The Land-Use Trade-Offs Model Version 2 (LUTO2): Technical Manual

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1 Define Sets for Land Use and Land management

1.1. Define Sets for Land Uses:

This segment categorizes fundamental land use types, forming the foundation for subsequent analysis. Land uses are grouped into the following categories: natural land uses, modified land uses, cropping, intensive cropping, horticulture, and unallocated natural land.

21.1.1. Land Uses

This set encompasses all land use classes designated for crop, livestock, and unallocated purposes:

$\mathcal{L} = \left\{ \begin{array}{c} \text{Apples, Beef} - \text{Modified Land, Beef} - \text{Natural Land, Citrus, Cotton,} \\ \text{Dairy} - \text{modified land, Dairy} - \text{natural land, Grapes, Hay, Nuts,} \\ \text{Other Non} - \text{Cereal Crops, Pears, Plantation Fruit, Rice,} \\ \text{Sheep} - \text{modified land, Sheep} - \text{natural land, Stone Fruit, Sugar,} \\ \text{Summer Cereals, Summer Legumes, Summer Oilseeds, Tropical Stone Fruit,} \\ \text{Unallocated} - \text{modified land, Unallocated} - \text{natural land, Vegetables,} \\ \text{Winter Cereals, Winter Legumes, Winter Oilseeds} \end{array} \right\}$	Equation 1

21.1.1. Natural Land Uses

These include areas used for agricultural purposes without significant modification, such as beef, sheep, and dairy grazing.

$\mathcal{L}_{\text{Beef, natural}} = \{\text{Beef} - \text{natural land}\}$	Equation 2
$\mathcal{L}_{\text{Sheep, natural}} = \{\text{Sheep} - \text{natural land}\}$	Equation 3
$\mathcal{L}_{\text{Dairy, natural}} = \{\text{Dairy} - \text{natural land}\}$	Equation 4

21.1.1. Modified Land Uses

These represent land areas altered through agricultural practices to enhance productivity, such as beef, sheep, and dairy farming under modified conditions.

$\mathcal{L}_{\text{Beef, modified}} = \{\text{Beef} - \text{modified land}\}$	Equation 5
$\mathcal{L}_{\text{Sheep, modified}} = \{\text{Sheep} - \text{modified land}\}$	Equation 6
$\mathcal{L}_{\text{Dairy,modified}} = \{\text{Dairy} - \text{modified land}\}$	Equation 7

21.1.1. Cropping Land Uses

This category represents land allocated for growing various crops in a rotational system.

$\mathcal{L}_{\text{Cropping}} = \left\{ \begin{array}{c} \text{Hay, Summer cereals, Summer legumes, Summer oilseeds,} \\ \text{Winter cereals, Winter legumes, Winter oilseeds} \end{array} \right\}$	Equation 8

21.1.1. Intensive Cropping Land Uses

Intensive cropping refers to land use dedicated to resource-intensive crops.

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$\mathcal{L}_{\text{Intensive Cropping}} = \{\text{Cotton, Other non} - \text{cereal crops, Rice, Sugar, Vegetables}\}$	Equation 9

21.1.1. Horticulture Land Uses

This category encompasses land used for cultivating fruits, nuts, and other horticultural products.

$\mathcal{L}_{\text{Horticulture}} = \left\{\begin{matrix}\text{Apples, Citrus, Grapes, Nuts, Pears, Plantation fruit, Stone fruit,} \\ \text{Tropical stone fruit}\end{matrix}\right\}$	Equation 10

21.1.1. Unallocated Natural Land

This set includes natural land that remains unallocated for specific agricultural practices.

$\mathcal{L}_{\text{Unallocated} - \text{natural land}} = \{\text{Unallocated} - \text{natural land}\}$	Equation 11

1.2. Agricultural and non-Agricultural Land Use

This section groups land uses into two broad categories: agricultural and non-agricultural, followed by the combination of both.

21.1.1. Agricultural Land Use

This set includes all land used for agricultural purposes, combining natural, modified, cropping, intensive cropping, and horticultural land uses.

$\mathcal{L}_{\text{AgrLand}} = \mathcal{L}_{\text{Beef, natural}} \cup \mathcal{L}_{\text{Beef, modified}} \cup \mathcal{L}_{\text{Sheep, natural}} \cup \mathcal{L}_{\text{Sheep, modified}} \cup \mathcal{L}_{\text{Dairy, natural}} \cup \mathcal{L}_{\text{Dairy,modified}} \cup \mathcal{L}_{\text{Cropping}} \cup \mathcal{L}_{\text{Intensive Cropping}} \cup \mathcal{L}_{\text{Horticulture}}$	Equation 12

21.1.1. Non-Agricultural Land Use

This set represents land used for non-agricultural purposes, such as environmental plantings and agroforestry.

$\mathcal{L}_{\text{NonAgrLand}} = \left\{\begin{matrix}\text{Environmental Plantings, Riparian Plantings, Sheep Agroforestry,} \\ \text{Beef Agroforestry, Carbon Plantings, Sheep Carbon Plantings,} \\ \text{Beef Carbon Plantings, Bioenergy with Carbon Capture and Storage}\end{matrix}\right\}$	Equation 13

21.1.1. All Agricultural and Non-Agricultural Land Use

This equation captures the union of agricultural and non-agricultural land uses.

$\mathcal{L}_{\text{AgNonAgLand}} = \mathcal{L}_{\text{AgrLand}} \cup \mathcal{L}_{\text{NonAgrLand}}$	Equation 14

1.3. Define Sets for Crops, Livestock, and Other Uses

This section focuses on categorizing crops, livestock, and unallocated land to clearly define agricultural outputs and other land classifications.

21.1.1. Crops

This set includes all crops cultivated within the defined land use types.

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$\mathcal{L}_{\text{Crops}} = \left\{ \begin{array}{c} \text{Apples, Citrus, Cotton, Grapes, Hay, Nuts, Other Non} - \text{Cereal Crops,} \\ \text{Pears, Plantation Fruit, Rice, Stone Fruit, Sugar, Summer Cereals,} \\ \text{Summer Legumes, Summer Oilseeds, Tropical Stone Fruit,} \\ \text{Vegetables, Winter Cereals, Winter Legumes, Winter Oilseeds} \end{array} \right\}$	Equation 15

21.1.1. Livestock

This set defines all livestock categories classified under natural or modified land use.

$\mathcal{L}_{\text{Livestock}} = \left\{ \begin{array}{c} \text{Beef} - \text{Modified Land, Sheep} - \text{modified land, Dairy} - \text{modified land,} \\ \text{Beef} - \text{Natural Land, Sheep} - \text{natural land, Dairy} - \text{natural land} \end{array} \right\}$	Equation 16

21.1.1. Unallocated Land

This set includes land, both natural and modified, that has not been allocated for specific use.

$\mathcal{L}_{\text{Unalloc-Land}} = \{\text{Unallocated} - \text{natural land, Unallocated} - \text{modified land}\}$	Equation 17

1.4. Define Natural and Modified Land Use

This section provides a focused definition of land that is either natural or modified for agricultural purposes.

21.1.1. Natural Land Use

This set includes all natural land uses in agricultural production, such as livestock and unallocated natural land.

$\mathcal{L}_{\text{NatAgLu}} = \left\{ \begin{array}{c} \text{Beef} - \text{natural land, Dairy} - \text{natural land, Sheep} - \text{natural land,} \\ \text{Unallocated} - \text{natural land} \end{array} \right\}$	Equation 18

21.1.1. Natural Livestock Land Use

This subset focuses specifically on livestock raised on natural land.

$\mathcal{L}_{\text{NatLivestock}} = \{\text{Beef} - \text{natural land, Dairy} - \text{natural land, Sheep} - \text{natural land}\}$	Equation 19

21.1.1. Modified Land Use

This set includes all land that has been altered for agricultural purposes, encompassing a wide range of agricultural products and unallocated modified land.

$\mathcal{L}_{\text{ModifiedLU}} = \left\{ \begin{array}{c} \text{Apples, Beef} - \text{Modified Land, Citrus, Cotton, Dairy} - \text{Modified Land,} \\ \text{Grapes, Hay, Nuts, Other Non} - \text{Cereal Crops, Pears, Plantation Fruit,} \\ \text{Rice, Sheep} - \text{Modified Land, Stone Fruit, Sugar, Summer Cereals,} \\ \text{Summer Legumes, Summer Oilseeds, Tropical Stone Fruit,} \\ \text{Unallocated} - \text{modified land, Vegetables, Winter Cereals,} \\ \text{Winter Legumes, Winter Oilseeds} \end{array} \right\}$	Equation 20

1.5. Land Management and Agricultural Practices

This section covers the land management practices applied to agricultural land and their relation to various land use types

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21.1.1. Land Management

This section categorizes agricultural land management systems based on water availability.

$\mathcal{M} = \{\text{Dryland, Irrigation}\}$	Equation 21

21.1.1. Agricultural Management Practices

This set defines the agricultural management practices applied to different land use types.

$\mathcal{K} = \left\{\begin{matrix}\text{Asparagopsis taxiformis, Precision Agriculture, Ecological Grazing,} \\ \text{Savanna Burning, AgTech EI}\end{matrix}\right\}$	Equation 22

1.6. Mapping of Agricultural Practices

This equation establishes a mapping between agricultural management practices and relevant land use types

$\phi: \mathcal{K} \longrightarrow 2^{\mathcal{L}}$	Equation 23

where,

- ϕ is a rule or mapping that relates elements from the set of agricultural management practices (the domain $\mathcal{K}$) to the power set of land uses (the codomain $2^{\mathcal{L}}$). Henec, it indicates how each management practice relates to different land use types.
- $\mathcal{K}$ represents the set of agricultural management practices.
- $2^{\mathcal{L}}$ denotes the power set of $\mathcal{L}$. The power set is the set of all possible combinations of these land uses ($\mathcal{L}$).
- $\mathcal{L}$ is the set of all land uses categorized under different types of agricultural practices.

Therefore, Equation 23 means that for each agricultural management practice $k \in \mathcal{K}$, $\phi(k)$ is a subset of land uses from $\mathcal{L}$. In other words, ϕ assigns to each management practice a set of land uses that are relevant or applicable to that practice.

21.1.1. Asparagopsis Taxiformis

This practice applies to livestock on both natural and modified land.

$\phi(\text{Asparagopsis taxiformis}) = \mathcal{L}_{\text{Beef, natural}} \cup \mathcal{L}_{\text{Beef, modified}} \cup \mathcal{L}_{\text{Sheep, natural}} \cup \mathcal{L}_{\text{Sheep, modified}} \cup \mathcal{L}_{\text{Dairy, natural}} \cup \mathcal{L}_{\text{Dairy,modified}}$	Equation 24
$\phi(\text{Asparagopsis taxiformis}) = \left\{\begin{matrix}\text{Beef} - \text{natural land, Beef} - \text{modified land, Sheep} - \text{natural land,} \\ \text{Sheep} - \text{modified land, Dairy} - \text{natural land, Dairy} - \text{modified land}\end{matrix}\right\}$	Equation 25

This practice affects beef, sheep, and dairy production across both natural and modified land.

21.1.1. Precision Agriculture

Applied to cropping, intensive cropping, and horticulture.

$\phi(\text{Precision Agriculture}) = \mathcal{L}_{\text{Cropping}} \cup \mathcal{L}_{\text{Intensive Cropping}} \cup \mathcal{L}_{\text{Horticulture}}$	Equation 26
$\phi(\text{Precision Agriculture}) = \left\{\begin{matrix}\text{Hay, Summer cereals, Summer legumes, Summer oilseeds,} \\ \text{Winter cereals, Winter legumes, Winter oilseeds, Cotton,} \\ \text{Other non} - \text{cereal crops, Rice, Sugar, Vegetables, Apples, Citrus,} \\ \text{Grapes, Nuts, Pears, Plantation fruit, Stone fruit, Tropical stone fruit}\end{matrix}\right\}$	Equation 27

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21.1.1. Ecological Grazing

Focused on livestock in modified land.

$\phi(\text{Ecological Grazing}) = \mathcal{L}_{\text{Beef, modified}} \cup \mathcal{L}_{\text{Sheep, modified}} \cup \mathcal{L}_{\text{Dairy,modified}}$	Equation 28
$\phi(\text{Ecological Grazing}) = \{\text{Beef} - \text{modified land}, \text{Sheep} - \text{modified land}, \text{Dairy} - \text{modified land}\}$	Equation 29

21.1.1. Savan Burning

This practice is typically applied to livestock on natural land, as well as unallocated natural land.

$\phi(\text{Savanna Burning}) = \mathcal{L}_{\text{Beef, natural}} \cup \mathcal{L}_{\text{Sheep, natural}} \cup \mathcal{L}_{\text{Dairy, natural}} \cup \{\text{Unallocated} - \text{natural land}\}$	Equation 30
$\phi(\text{Savanna Burning}) = \left\{\begin{matrix}\text{Beef} - \text{natural land}, \text{Sheep} - \text{natural land}, \text{Dairy} - \text{natural land}, \\ \text{Unallocated} - \text{natural land}\end{matrix}\right\}$	Equation 31

21.1.1. AgTech EI

This is applied similarly to precision agriculture, affecting cropping, intensive cropping, and horticulture.

$\phi(\text{AgTech EI}) = \mathcal{L}_{\text{Cropping}} \cup \mathcal{L}_{\text{Intensive Cropping}} \cup \mathcal{L}_{\text{Horticulture}}$	Equation 32
$\phi(\text{AgTech EI}) = \left\{\begin{matrix}\text{Hay, Summer cereals, Summer legumes, Summer oilseeds,} \\ \text{Winter cereals, Winter legumes, Winter oilseeds, Cotton,} \\ \text{Other non} - \text{cereal crops, Rice, Sugar, Vegetables, Apples, Citrus,} \\ \text{Grapes, Nuts, Pears, Plantation fruit, Stone fruit, Tropical stone fruit}\end{matrix}\right\}$	Equation 33

1.7. Filtered Mapping

Let $\mathcal{S} \subset \mathcal{K}$ be the subset of management practices enabled in the settings. The filtered mapping ϕ' is defined as:

$\phi' = \{(k, \phi(k)) \mid k \in \mathcal{S}\}$	Equation 34

21.1.1. Agricultural Practice

This is applied similarly to precision agriculture, affecting cropping, intensive cropping, and horticulture.

$\phi(\text{Agricultural Practice}) = \phi(\text{Asparagopsis taxiformis}) \cup \phi(\text{Precision Agriculture}) \cup \phi(\text{Ecological Grazing}) \cup \phi(\text{Savanna Burning}) \cup \phi(\text{AgTech EI})$	Equation 35

1.8. Define Commodities and Products

This section defines the agricultural outputs, commodities, and products derived from the land uses and management practices.

21.1.1. Commodities

This set defines all commodities produced from agricultural land use, including crops, livestock, and derived goods like wool and meat.

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$\mathcal{L}_{\text{Commodities}} = \left\{ \begin{array}{c} \text{Apples, Beef Lexp, Beef Meat, Citrus, Cotton, Dairy, Grapes, Hay, Nuts,} \\ \text{Other Non} - \text{Cereal Crops, Pears, Plantation Fruit, Rice, Sheep Lexp,} \\ \text{Sheep Meat, Sheep Wool, Stone Fruit, Sugar, Summer Cereals,} \\ \text{Summer Legumes, Summer Oilseeds, Tropical Stone Fruit,} \\ \text{Vegetables, Winter Cereals, Winter Legumes, Winter Oilseeds} \end{array} \right\}$	Equation 36

21.1.1. Products

This set provides a more granular categorization of products derived from agricultural activities, including fruits, grains, and livestock products.

$\mathcal{L}_{\text{Products}} = \left\{ \begin{array}{c} \text{Apples, Beef} - \text{Modified Land Lexp, Beef} - \text{Modified Land Meat,} \\ \text{Beef} - \text{Natural Land Lexp , Beef} - \text{Natural Land Meat,} \\ \text{Citrus, Cotton, Dairy} - \text{Modified Land, Dairy} - \text{Natural Land,} \\ \text{Grapes, Hay, Nuts, Other Non} - \text{Cereal Crops, Pears, Plantation Fruit,} \\ \text{Rice, Sheep} - \text{Modified Land Lexp, Sheep} - \text{Modified Land Meat} \\ \text{, Sheep} - \text{Modified Land Wool, Sheep} - \text{Natural Land Lexp,} \\ \text{Sheep} - \text{Natural Land Meat, Sheep} - \text{Natural Land Wool,} \\ \text{Stone Fruit, Sugar, Summer Cereals, Summer Legumes, Summer Oilseeds,} \\ \text{Tropical Stone Fruit, Vegetables, Winter Cereals, Winter Legumes,} \\ \text{Winter Oilseeds} \end{array} \right\}$	Equation 37

21.1.1. Livestock Commodities

This subset defines the commodities specifically derived from livestock, categorized by livestock type (Equation 36).

$\mathcal{L}^{\text{Livestock}}_{\text{Commodities}} = \{\text{Sheep Wool, Sheep Meat, Sheep Lexp, Dairy, Beef Meat, Beef Lexp}\}$	Equation 38

Regardless of livestock type, the general livestock commodities are:

$\mathcal{L}^{LS}_{\text{Commodities}} = \{\text{Meat, Lexp, Wool, Dairy}\}$	Equation 39

For each livestock type, the corresponding commodities are:

$\mathcal{L}^{\text{Sheep}}_{\text{Commodities}} = \{\text{Sheep Meat, Sheep Wool, Sheep Lexp }\}$	Equation 40
$\mathcal{L}^{\text{Beef}}_{\text{Commodities}} = \{\text{Beef Meat, Beef Lexp}\}$	Equation 41
$\mathcal{L}^{\text{Dairy}}_{\text{Commodities}} = \{\text{Dairy}\}$	Equation 42

1.9. Define the set of Land Uses based on Root depth

21.1.1. Deep rooted plantes

This category includes plants with deep root systems, often requiring significant water resources.

$\mathcal{L}_{\text{DR}} = \left\{ \begin{array}{c} \text{Apples, Citrus, Grapes, Nuts, Pears, Plantation Fruit,} \\ \text{Stone Fruit, Sugar, Tropical Stone Fruit} \end{array} \right\}$	Equation 43

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21.1.1. Shallow Rooted Plantes

This category includes plants with shallow root systems, typically more adaptable to water-limited conditions.

$\mathcal{L}_{\mathrm{SR}} = \left\{ \begin{array}{c} \text{Beef} - \text{Modified Land, Cotton, Dairy} - \text{modified land, Hay,} \\ \text{Other Non} - \text{Cereal Crops, Rice, Sheep} - \text{modified land,} \\ \text{Summer Cereals, Summer Legumes, Summer Oilseeds,} \\ \text{Unallocated} - \text{modified land, Vegetables, Winter Cereals,} \\ \text{Winter Legumes, Winter Oilseeds} \end{array} \right\}$	Equation 44

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2 Agricultural Production Cost in LUTO

2.1. Crop Production Cost

2.1.1. Total Crop Production Cost

The total crop production cost, $\mathbf{TCPC}_{mr\ell}^{AG}(y)$, for each year y , is calculated as:

$\mathbf{TCPC}_{mr\ell}^{AG}(y) = \mathbf{QDC}_{mr\ell}^{AG}(y) + \mathbf{ADC}_{mr\ell}^{AG}(y) + \mathbf{FC}_{mr\ell}^{AG}(y) + \mathbf{WDC}_{mr\ell}^{AG}(y)$	Equation 45

where:

- m: Land management type ($m \in \mathcal{M}$) (Equation 31).
- ℓ: Crop type ($\ell \in \mathcal{L}_{Crops}$) (Equation 15) .
- $\mathbf{QDC}_{mr\ell}^{AG}(y)$: Quantity dependence cost (Equation 46 and Figure 4).
- $\mathbf{ADC}_{mr\ell}^{AG}(y)$: Area dependence cost (Equation 47 and Figure 6).
- $\mathbf{FC}_{mr\ell}^{AG}(y)$: Fixed cost (Equation 48 and Figure 13).
- $\mathbf{WDC}_{mr\ell}^{AG}(y)$: Water dependence cost (Equation 52 and Figure 16).

2.1.2. Quantity Dependent Costs

The quantity dependent costs, $\mathbf{QDC}_{mr\ell}^{AG}(y)$, associated with crop ℓ under land management m for year y, are calculated as:

$\mathbf{QDC}_{mr\ell}^{AG}(y) = \mathbf{CPT}_{mr\ell}^{AG} \times \mathbf{TPC}_{mr\ell}^{AG}(y) \times QCM_{\ell}^{AG}(y) \times \mathbf{RA}_{r}$	Equation 46

where,

- $\mathbf{CPT}_{mr\ell}^{AG}$: Cost per tonne of crop ℓ (Figure 1 and Figure 3)
- $\mathbf{TPC}_{mr\ell}^{AG}(y)$: Total production of crop ℓ, in tonnes (Figure 2)
- $QCM_{\ell}^{AG}(y)$: Quantity cost multiplier
- $\mathbf{RA}_{r}$: Real area multiplier (Figure 5)

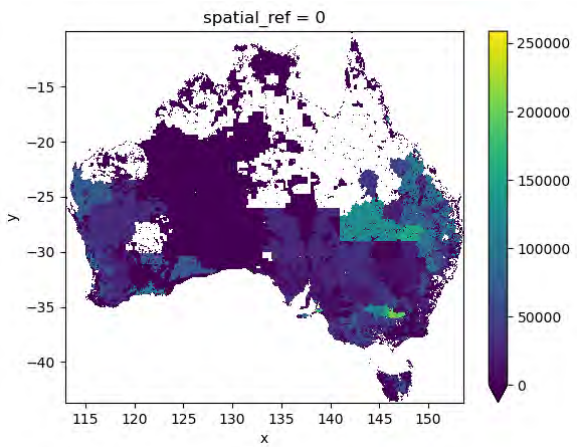

Figure 1: Cost per tonne for winter cereal $\mathbf{CPT}_{mr\ell}^{AG}$

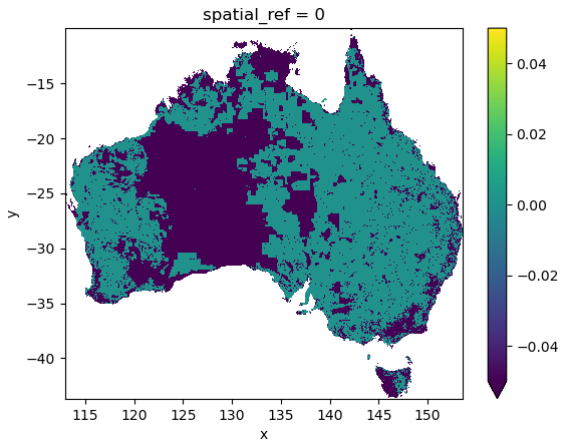

Figure 2 Total production for winter wereal $\mathbf{TPC}_{mr\ell}^{AG}$

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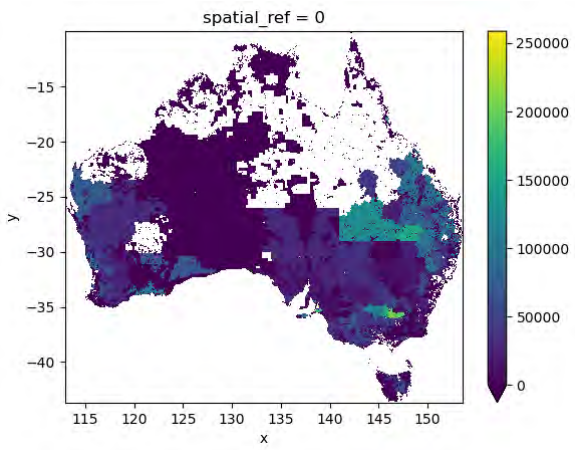

Figure 3 Quantity costs for winter cereal $\mathbf{CPT}_{mr\ell}^{AG}$

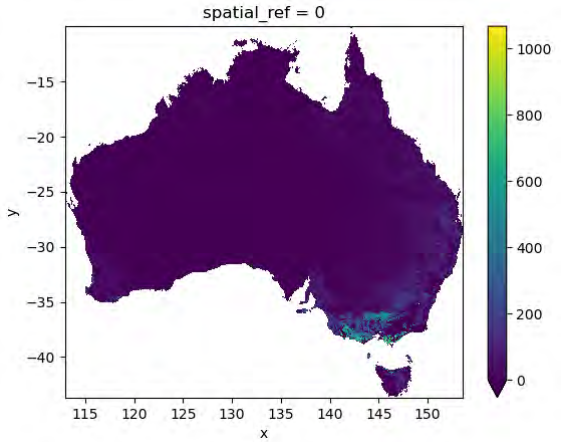

Figure 4 Quantity dependent costs for winter cereal $\mathbf{QDC}_{mr\ell}^{AG}(y)$

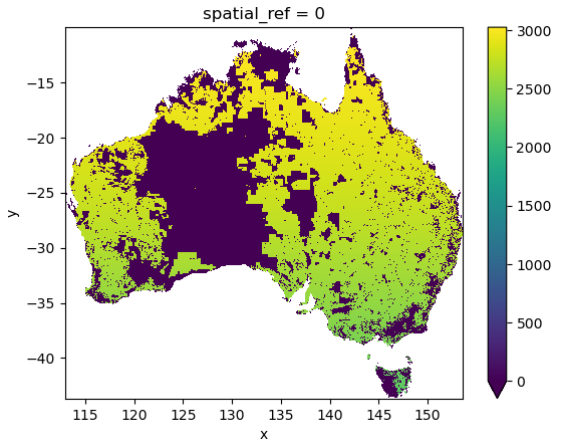

Figure 5 Real area $\mathbf{RA}_r$

2.1.3. Area Dependent Cost

The area dependent costs, $\mathbf{ADC}_{mr\ell}^{AG}$, are given by:

$$\mathbf{ADC}_{mr\ell}^{AG}(y) = \mathbf{APC}_{mr\ell}^{AG} \times ACM_{\ell}^{AG}(y) \times \mathbf{RA}_r \qquad \text{Equation 47}$$

where,

- $\mathbf{APC}_{mr\ell}^{AG}$: Area-based cost per hectare (Figure 8).
- $ACM_{\ell}^{AG}(y)$: Area cost multiplier (Figure 7).
- $\mathbf{RA}_r$: Real area multiplier (Figure 5).

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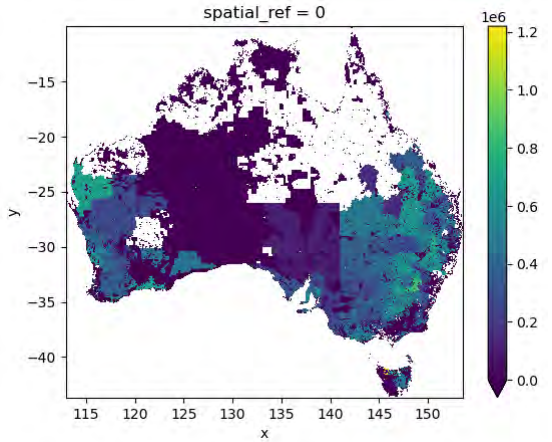

Figure 6: Area dependent costs for winter cereals $\mathbf{ADC}_{mr\ell}^{AG}(y)$

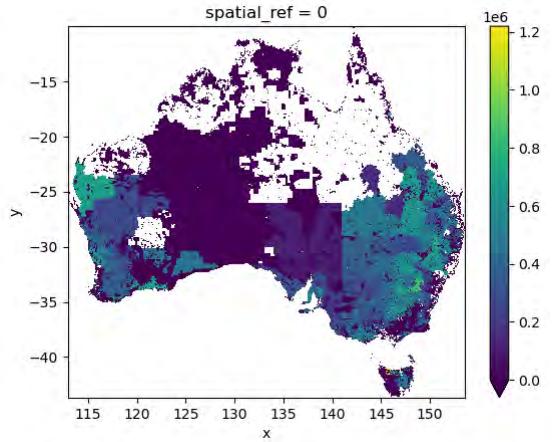

Figure 7: Area cost multiplier $ACM_{\ell}^{AG}(y)$

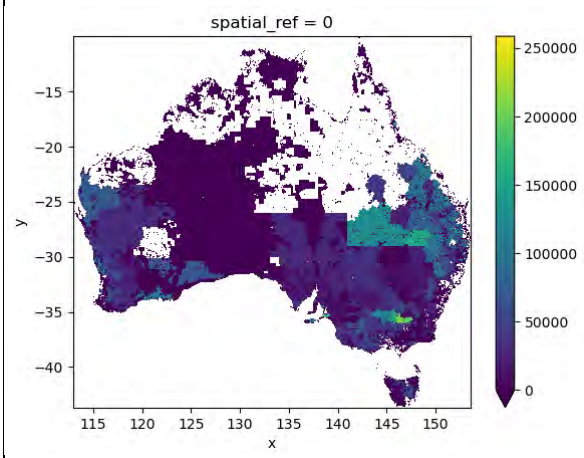

Figure 8: Cost per tonne for winter cereal data.AGEC_CROPS['QC', lm, lu] of Winter cereals $\mathbf{CPT}_{mr\ell}^{AG}(y)$

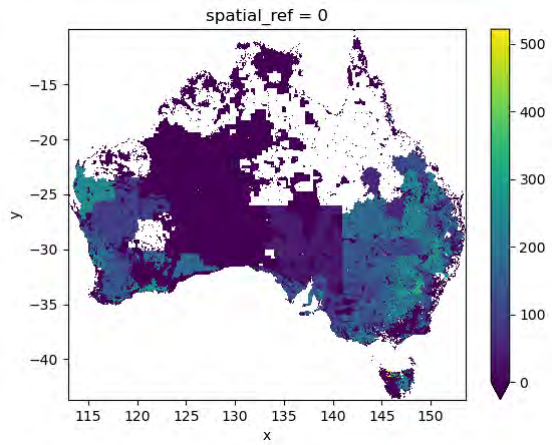

Figure 9: Area-based cost per hectare $\mathbf{APC}_{mr\ell}^{AG}$

2.1.4. Fixed Costs

The fixed costs, $\mathbf{FC}_{mr\ell}^{AG}(y)$, are computed as:

$\mathbf{FC}_{mr\ell}^{AG}(y) = \mathbf{FLC}_{mr\ell}^{AG}(y) + \mathbf{FOC}_{mr\ell}^{AG}(y) + \mathbf{FDC}_{mr\ell}^{AG}(y)$	Equation 48

where,

- $\mathbf{FLC}_{mr\ell}^{AG}(y)$: Fixed labour costs (Equation 49 and Figure 10)
- $\mathbf{FOC}_{mr\ell}^{AG}(y)$: Fixed operating costs (Equation 50 and Figure 11)
- $\mathbf{FDC}_{mr\ell}^{AG}(y)$: Fixed depreciation costs (Equation 51 and Figure 12)

$\mathbf{FLC}_{mr\ell}^{AG}(y) = \mathbf{CPT}_{mr\ell}^{AG,FLC} \times LCM_{\ell}^{AG}(y) \times \mathbf{RA}_r$	Equation 49
$\mathbf{FOC}_{mr\ell}^{AG}(y) = \mathbf{CPT}_{mr\ell}^{AG,FOC} \times OCM_{\ell}^{AG}(y) \times \mathbf{RA}_r$	Equation 50
$\mathbf{FDC}_{mr\ell}^{AG}(y) = \mathbf{CPT}_{mr\ell}^{AG,FDC} \times DCM_{\ell}^{AG}(y) \times \mathbf{RA}_r$	Equation 51

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where,

- $LCM_{\ell}^{AG}(y)$: Labor cost multiplier.
- $OCM_{\ell}^{AG}(y)$: Operating cost multiplier.
- $DCM_{\ell}^{AG}(y)$: Depreciation cost multiplier.
- $\mathbf{CPT}_{mr\ell}^{AG,FLC}(y)$: Cost per tonne for labor.
- $\mathbf{CPT}_{mr\ell}^{AG,FOC}(y)$: Cost per tonne for operating costs.
- $\mathbf{CPT}_{mr\ell}^{AG,FDC}(y)$: Cost per tonne for depreciation.
- $\mathbf{RA}_{r}$: Real area multiplier (Figure 5).

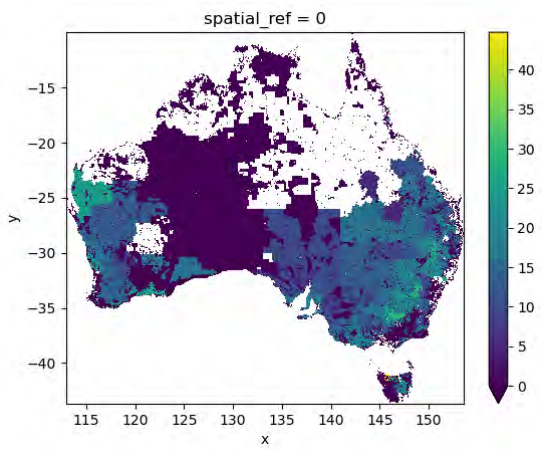

Figure 10: Fixed labour costs for winter cereals $\mathbf{FLC}_{lm,c}^{AG}(y)$.

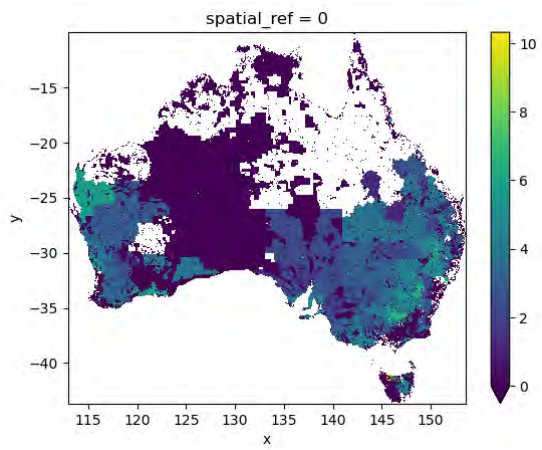

Figure 11: Fixed operating costs for winter cereals $\mathbf{FOC}_{lm,c}^{AG}(y)$.

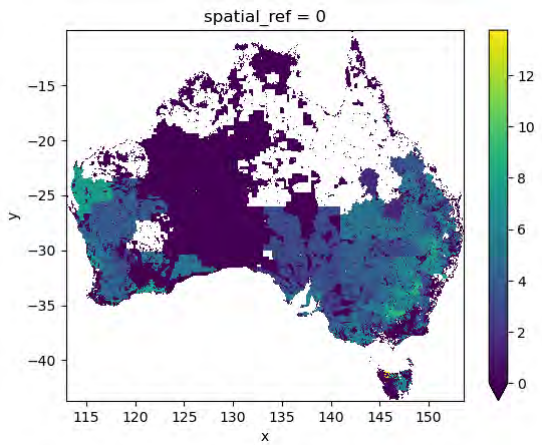

Figure 12: Fixed depreciation costs for winter cereals $\mathbf{FDC}_{lm,c}^{AG}(y)$.

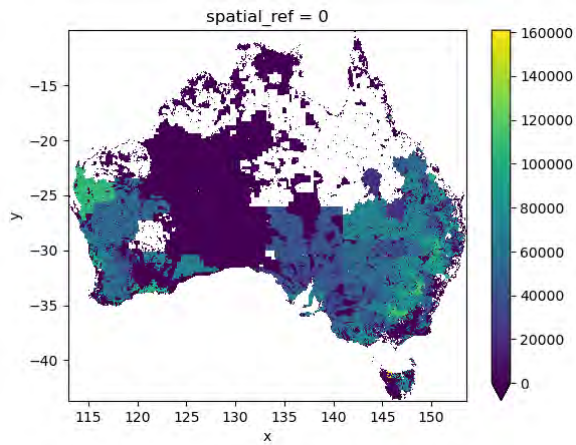

Figure 13: Fixed costs for winter cereals $\mathbf{FC}_{lm,c}^{AG}(y)$.

2.1.5. Water Dependent Costs

The water dependent costs, $\mathbf{WDC}_{mr\ell}^{AG}(y)$, are calculated as:

$$\mathbf{WDC}_{mr\ell}^{AG}(y) = \begin{cases} \mathbf{WR}_{mr\ell}^{AG} \times \mathbf{DP}_{mr\ell}^{AG} \times WPCM_{\ell}^{AG}(y) \times \mathbf{RA}_{r}, & \text{if} \quad m = Irrigation \\ 0, & \text{if} \quad m = Dry \end{cases} \qquad \text{Equation 52}$$

where,

- $\mathbf{WR}_{mr\ell}^{AG}$: Water requirement per hectare (ML/ha) (Figure 14).

- $\mathbf{DP}_{mr\ell}^{AG}$: Delivery price per megalitre (ML) of water (Figure 15).
- $WPCM_{\ell}^{AG}(y)$: Water price cost multiplier.
- $\mathbf{RA}_{r}$: Real area multiplier (Figure 5).

As Equation 52 shows, in the case of non-Irrigated land, the water dependent costs are considered as zero ($\mathbf{WDC}_{mr\ell}^{AG}(y) = 0, m = 0$).

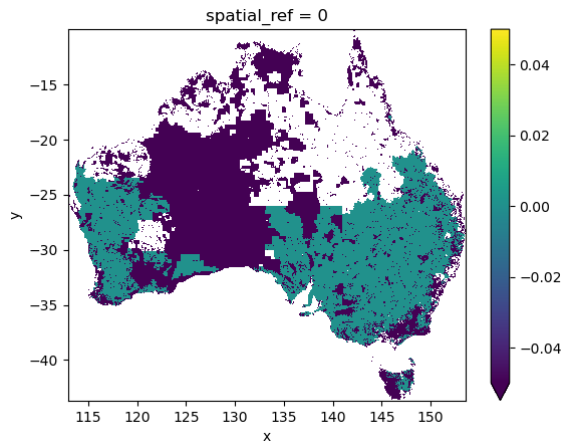

Figure 14: Water requirments of winter cereals $\mathbf{WR}_{mr\ell}^{AG}$.

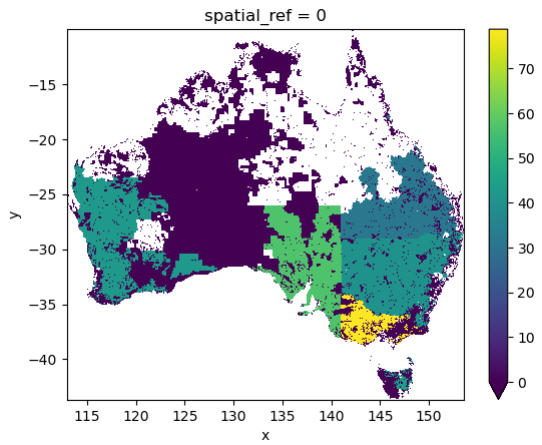

Figure 15: delivery price of water $\mathbf{DP}_{mr\ell}^{AG}$.

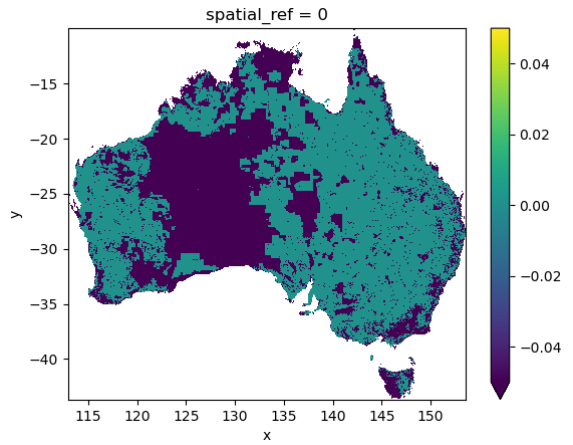

Figure 16: Water dependent costs $\mathbf{WDC}_{mr\ell}^{AG}(y)$.

2.2. Livestock Production Cost

2.2.1. Total Livestock Production Cost

The total livestock production cost, $\mathbf{TLPC}_{mr\ell}^{LS}(y)$, for each livestock type ℓ for year y, is calculated as:

$\mathbf{TLPC}_{mr\ell}^{LS}(y) = \mathbf{QDC}_{mr\ell}^{LS}(y) + \mathbf{ADC}_{mr\ell}^{LS}(y) + \mathbf{FC}_{mr\ell}^{LS}(y) + \mathbf{WDC}_{mr\ell}^{LS}(y)$	Equation 53

where:

- ℓ: Livestock type ($\ell \in \mathcal{L}_{\text{Livestock}}$) (Equation 16).
- $\mathbf{ADC}_{mr\ell}^{LS}(y)$: Area dependent costs (Equation 55 and Figure 20).
- $\mathbf{QDC}_{mr\ell}^{LS}(y)$: Quantity dependent costs (Equation 54 and Figure 18).

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- $\mathbf{FC}_{mr\ell}^{LS}(y)$: Fixed costs (Equation 56 and Figure 24).
- $\mathbf{WDC}_{mr\ell}^{LS}(y)$: Water dependent costs (Equation 60).

2.2.2. Quantity Dependent Costs

The quantity dependent costs, $\mathbf{QDC}_{mr\ell}^{LS}(y)$, associated with livestock ℓ for year y, are calculated as:

$\mathbf{QDC}_{mr\ell}^{LS}(y) = \mathbf{CPH}_{mr\ell}^{LS} \times \mathbf{YPot}_{mr\ell}^{LS}(y) \times QCM_{mr\ell}^{LS}(y) \times \mathbf{RA}_r$	Equation 54

where,

- $\mathbf{CPH}_{mr\ell}^{LS}$: Cost per head of livestock ℓ (Figure 17).
- $\mathbf{YPot}_{mr\ell}^{LS}(y)$: Yield potential or the number of heads per hectare (Equation 113 and Figure 117-Figure 128).
- $QCM_{mr\ell}^{LS}(y)$: Quantity cost multiplier.
- $\mathbf{RA}_r$: Real area multiplier (Figure 5).

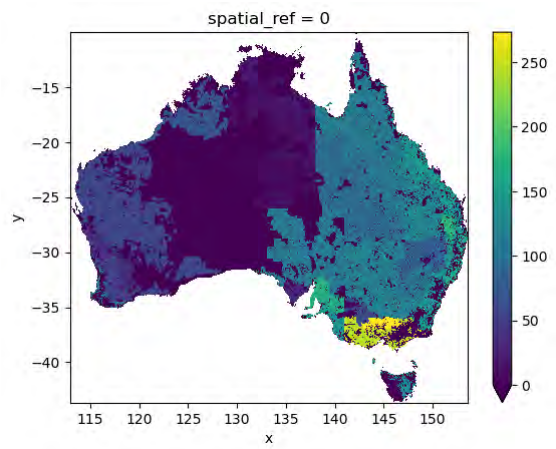

Figure 17: Cost per head for livestock $\mathbf{CPH}_{\ell}^{LS}$.

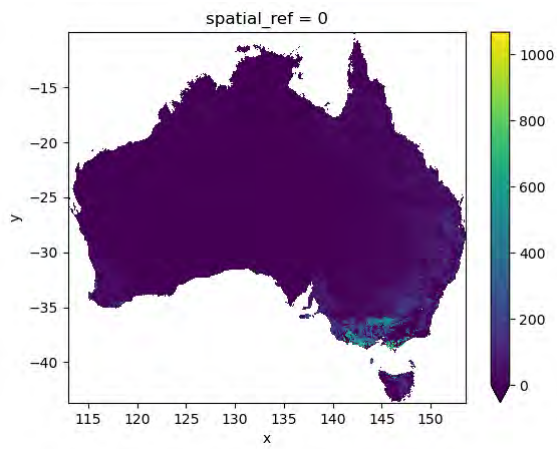

Figure 18: Quantity dependent costs for livestock $\mathbf{QDC}_{mr\ell}^{LS}(y)$.

2.2.3. Area Dependent Cost

The area dependent costs, $\mathbf{ADC}_{mr\ell}^{LS}(y)$, are calculated as:

$\mathbf{ADC}_{mr\ell}^{LS}(y) = \mathbf{CPT}_{mr\ell}^{LS,AC} \times ACM_{\ell}^{LS}(y) \times \mathbf{RA}_r$	Equation 55

where,

- $ACM_{\ell}^{LS}(y)$: Area cost multiplier.
- $\mathbf{RA}_r$: Real area multiplier (Figure 5).
- $\mathbf{CPT}_{mr\ell}^{LS,AC}$: Cost per tonne based on area cost.

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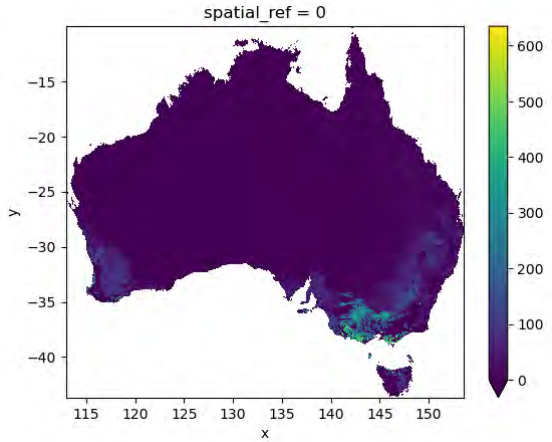

Figure 19: Cost per tonne based on area cost $\mathbf{CPT}_{mr\ell}^{LS,AC}$.

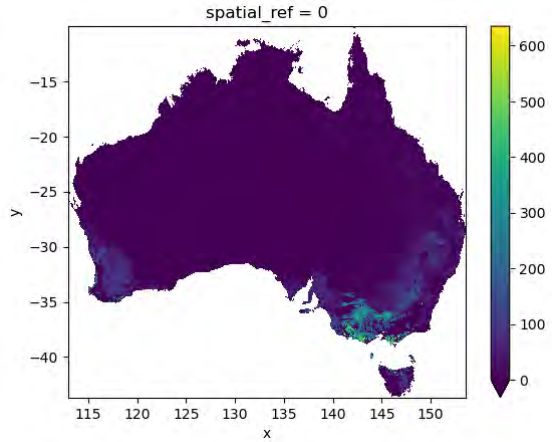

Figure 20: Area dependent costs $\mathbf{ADC}_{mr\ell}^{LS}(y)$.

2.2.4. Fixed Costs

The fixed costs, $\mathbf{FC}_{mr\ell}^{LS}(y)$, for livestock ℓ are computed as:

$\mathbf{FC}_{mr\ell}^{LS}(y) = \mathbf{FLC}_{mr\ell}^{LS}(y) + \mathbf{FOC}_{mr\ell}^{LS}(y) + \mathbf{FDC}_{mr\ell}^{LS}(y)$	Equation 56

where,

- $\mathbf{FLC}_{mr\ell}^{LS}(y)$: Fixed labour costs for livestock (Equation 57 and Figure 22).
- $\mathbf{FOC}_{mr\ell}^{LS}(y)$: Fixed operating costs for livestock (Equation 58 and Figure 21).
- $\mathbf{FDC}_{mr\ell}^{LS}(y)$: Fixed depreciation costs for livestock (Equation 59 and Figure 23).

$\mathbf{FLC}_{mr\ell}^{LS}(y) = \mathbf{CPT}_{mr\ell}^{LS,FLC} \times LCM_{\ell}^{LS}(y) \times \mathbf{RA}_r$	Equation 57
$\mathbf{FOC}_{mr\ell}^{LS}(y) = \mathbf{CPT}_{mr\ell}^{LS,FOC} \times OCM_{\ell}^{LS}(y) \times \mathbf{RA}_r$	Equation 58
$\mathbf{FDC}_{mr\ell}^{LS}(y) = \mathbf{CPT}_{mr\ell}^{LS,FDC} \times DCM_{\ell}^{LS}(y) \times \mathbf{RA}_r$	Equation 59

where,

- $LCM_{\ell}^{LS}(y)$: Labour costs multiplier.
- $OCM_{\ell}^{LS}(y)$: Operating costs multiplier.
- $DCM_{\ell}^{LS}(y)$: Depreciation costs multiplier.
- $\mathbf{RA}_r$: Real area multiplier (Figure 5).

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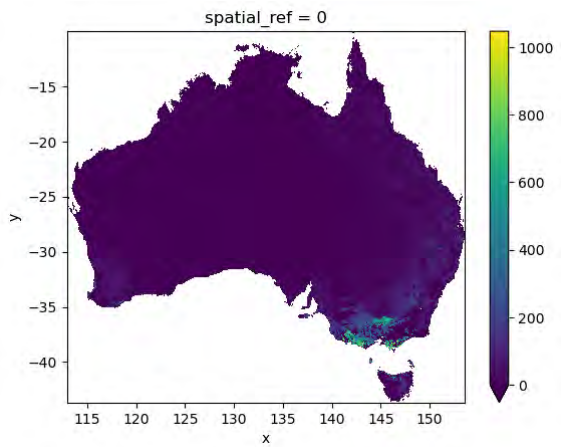

Figure 21: Fixed operation cost $\mathbf{FOC}_{mr\ell}^{LS}(y)$.

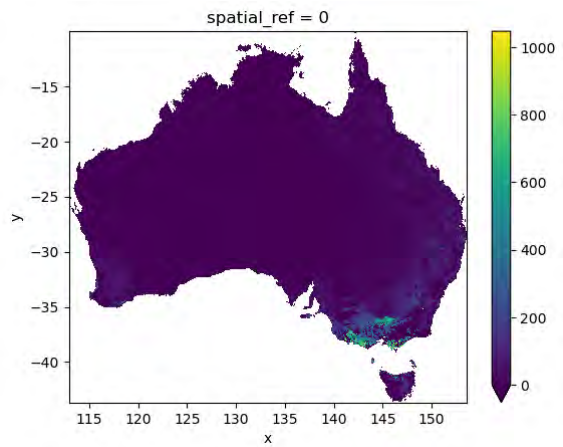

Figure 22: Fixed labor cost $\mathbf{FLC}_{mr\ell}^{LS}(y)$.

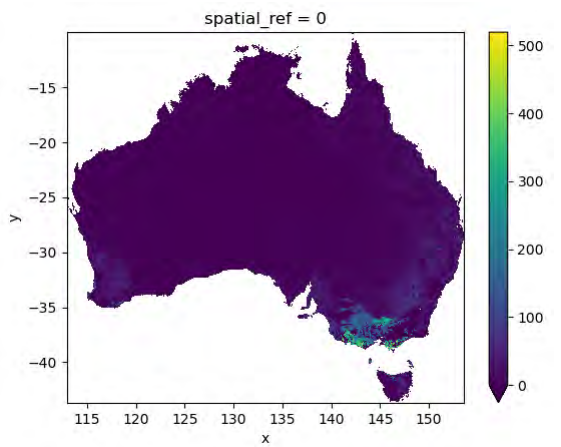

Figure 23: Fixed depreciation cost $\mathbf{FDC}_{mr\ell}^{LS}(y)$.

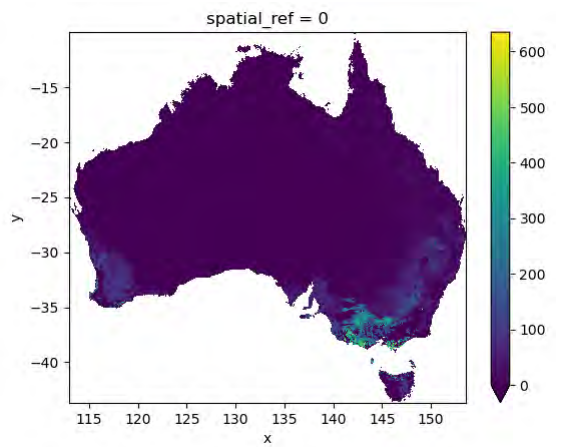

Figure 24: Fixed cost $\mathbf{FC}_{mr\ell}^{LS}(y)$.

2.2.5. Water Dependent Costs

The water dependent costs, $\mathbf{WDC}_{mr\ell}^{LS}(y)$, for livestock ℓ are calculated as:

$$\mathbf{WDC}_{mr\ell}^{LS}(y) = \begin{cases} \left[\left(LDW_{\ell}^{LS} \times \mathbf{DWR}_{r\ell}^{LS}\right) + \mathbf{IWR}_{mr\ell}^{LS}\right] \times \mathbf{YPot}_{mr\ell}^{LS}(y) \times \mathbf{WDP}_{r}^{LS} \times WCM_{\ell}^{LS}(y) \times \mathbf{RA}_{r} \\ 0 \qquad \text{if} \quad m = Dry \end{cases} \tag{60}$$

where,

- $\mathbf{DWR}_{r\ell}^{LS}$: Drinking water requirement per head (Figure 25)
- $\mathbf{IWR}_{mr\ell}^{LS}$: Irrigation water requirement per head which is zero for the dryland (Figure 26)
- $\mathbf{YPot}_{mr\ell}^{LS}(y)$: Yield potential or number of heads per hectare (Equation 113 and Figure 117-Figure 128)
- $\mathbf{WDP}_{r}^{LS}$: Water delivery price per ML (Figure 27)
- $WCM_{\ell}^{LS}(y)$: Water costs multiplier
- LDW_{ℓ}^{LS}: Livestock drinking water (ML/head)
- $\mathbf{RA}_{r}$: Real area multiplier (Figure 5)

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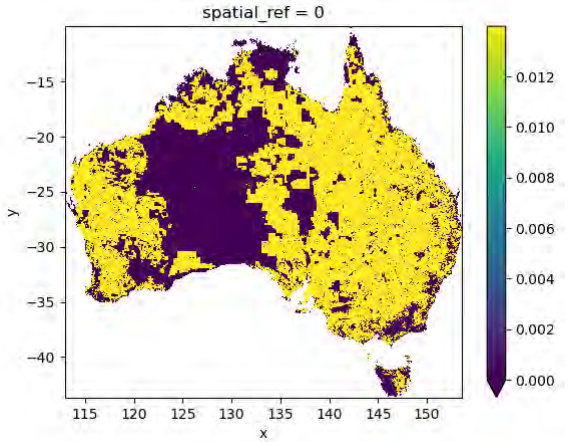

Figure 25: Drinking water requirement per head $\mathbf{DWR}_{r\ell}^{LS}$.

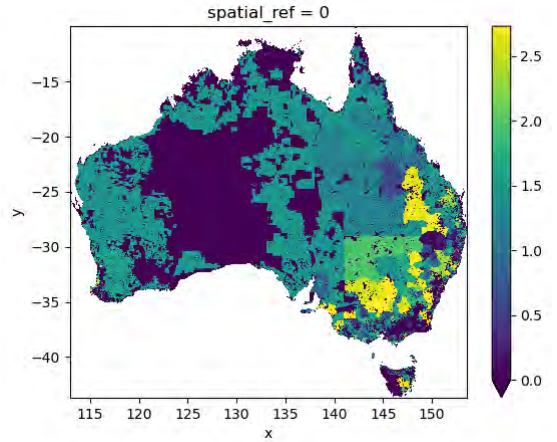

Figure 26: Irrigation water requirement per head, which is zero for the dryland $\mathbf{IWR}_{mr\ell}^{LS}$.

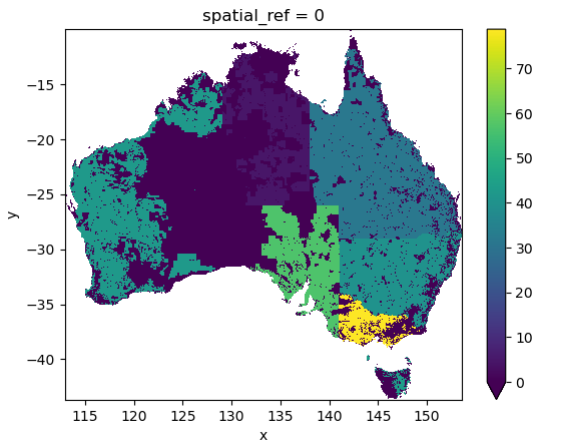

Figure 27 : Water delivery price per megalitre (ML) $\mathbf{WDP}_{r}^{LS}$.

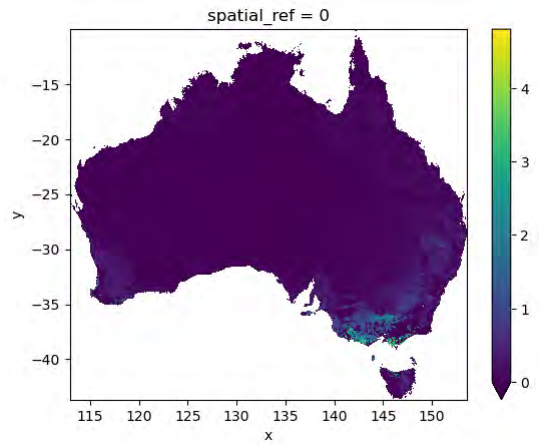

Figure 28: Water dependent costs for Livestock $\mathbf{WDC}_{mr\ell}^{LS}(y)$

2.2.6. Total Cost Matrix

To total cost matrix, $\mathbf{Cost}_{mr\ell}$, which incorporates both crop cost (Equation 45) and livestock cost (Equation 53), is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 61
$\mathbf{Cost}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21), hence $N_k = 2$.
- N_{lu}: Total number of land use classes, $N_{lu} = 28$, as the set $\mathcal{L}$ includes all land use classes assigned to crop, livestock, and unallocated land purposes (Equation 1).

Additionally:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell \mid \ell \in \mathcal{L}$	Equation 62
$\mathbf{Cost}_{mr\ell}(y) = \begin{cases} \mathbf{TCPC}^{AG}_{mr\ell}(y), & \text{if } \ell_{mr} \in \mathcal{L}_{\text{Crops}} \\ \mathbf{TLPC}^{LS}_{mr\ell}(y), & \text{if } \ell_{mr} \in \mathcal{L}_{\text{Livestock}} \end{cases}$	

where,

- $\mathbf{TCPC}^{AG}_{mr\ell}(y)$: Crops cost (Equation 45) for the set of $\mathcal{L}_{\text{Crops}} - \{\text{Pears}, \text{Rice}\}$.
- $\mathbf{TLPC}^{LS}_{mr\ell}(y)$: Livestock cost matrix (Equation 53) for all products $\ell \in \mathcal{L}_{\text{Livestock}}$.
- $\mathcal{L}_{\text{Crops}}$: Set including all crops grown across the land-use types (Equation 15).
- $\mathcal{L}_{\text{Livestock}}$: Set including all livestock categories, classified by natural or modified land-use types (Equation 16).

2.3. Impacts of Agricultural Management Practices on Cost

2.3.1. Asparagopsis Taxiformis Effects to the Cost for all Relevant Land Use Classes

The updated cost matrix, $\mathbf{UCM}^{\text{AspTaxifor}}_{mr\ell}$, after integrating Asparagopsis taxiformis into agricultural land management, is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Asparagopsis taxiformis})$	Equation 63
$\mathbf{UCM}^{\text{AspTaxifor}}_{mr\ell} = 0_{\left(N_k \times N_c \times N^{\text{AspTaxifor}}_{lu}\right)}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21), hence $N_k = 2$.
- $N^{\text{AspTaxifor}}_{lu}$ is 6, as Asparagopsis taxiformis practice affects beef, sheep, and dairy production across both natural and modified land, $N_{lu} = 6$ (Equation 25).

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Asparagopsis taxiformis})$	Equation 64
$\mathbf{UCM}^{\text{AspTaxifor}}_{mr\ell}(y) = CPA^{\text{AspTaxifor}}_{\ell}(y) \times \mathbf{YPot}^{LS}_{mr\ell}(y) \times \mathbf{RA}_r$	

where,

- $\mathbf{YPot}^{LS}_{mr\ell}(y)$: Yield potential or number of heads per hectare (Figure 117-Figure 128 and Equation 113)
- $\mathbf{RA}_r$: Real area multiplier (Figure 5)
- $CPA^{\text{AspTaxifor}}_{\ell}(y)$: Cost per animal.

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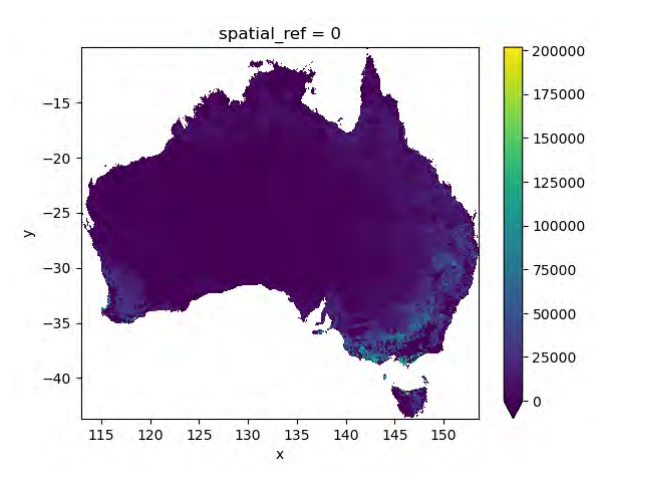

Figure 29: Updated cost matrix by integrating Asparagopsis taxiformis $\mathbf{UCM}_{mr\ell}^{\text{AspTaxifor}}$.

2.3.2. The Precision Agriculture Effects to the Cost for all Relevant Land Use Classes

The updated cost matrix, $\mathbf{UCM}_{mr\ell}^{\text{PrecAgric}}$, after integrating precision agriculture into agricultural land management, is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 65
$\mathbf{UCM}_{mr\ell}^{\text{PrecAgric}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{PrecAgric}}\right)}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21), hence $N_k = 2$.
- $N_{lu}^{\text{PrecAgric}}$ is 20, as precision agriculture practice affects 20 land use classes (Equation 27), $N_{lu} = 20$

The updated cost matrix, $\mathbf{UCM}_{mr\ell}^{\text{PrecAgric}}$, after integrating precision agriculture into land management strategies, is given by:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 66
$\mathbf{UCM}_{mr\ell}^{\text{PrecAgric}}(y) = CPH_{\ell}^{\text{PrecAgric}}(y) \times \mathbf{RA}_r$	

where,

- $CPH_{\ell}^{\text{AspTaxifor}}(y)$: Cost per hectare for precision agriculture.
- $\mathbf{RA}_r$: Real area multiplier (Figure 5)

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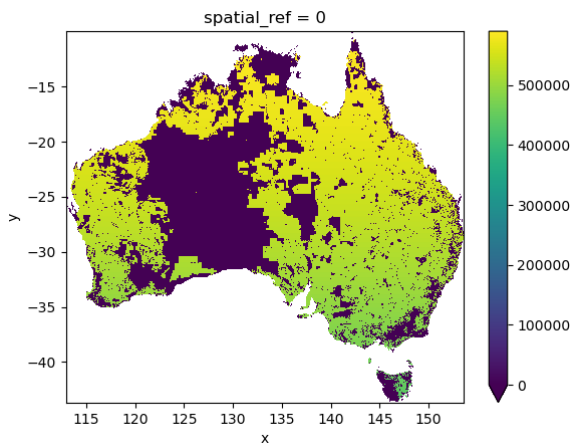

Figure 30: Updated cost matrix by integrating precision aAgriculture $\mathbf{UCM}_{mr\ell}^{\text{PrecAgric}}$.

2.3.3. The ecological grazing Effects to the Cost for all Relevant Land Use Classes

The updated cost matrix, $\mathbf{UCM}_{mr\ell}^{\text{EcolGrazing}}$, after integrating ecological grazing into agricultural land management, is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell\ , \ell \in \phi(\text{Ecological Grazing})$	Equation 67
$\mathbf{UCM}_{mr\ell}^{\text{EcolGrazing}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{EcolGrazing}}\right)}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21), hence $N_k = 2$.
- $N_{lu}^{\text{EcolGrazing}}$ is 3, as ecological grazing practice affects beef, sheep, and dairy production across modified land (Equation 29), $N_{lu} = 3$.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell\ , \ell \in \phi(\text{Ecological Grazing})$	Equation 68
$\mathbf{UCM}_{mr\ell}^{\text{EcolGrazing}}(y) = \mathbf{OCE}_{mr\ell}^{\text{EcolGrazing}}(y) + \mathbf{LCE}_{mr\ell}^{\text{EcolGrazing}}(y)$	
$\mathbf{OCE}_{mr\ell}^{\text{EcolGrazing}}(y) = \mathbf{FOC}_{mr\ell}^{LS} \times \left(OM_{\ell}^{\text{EcolGrazing}}(y) - 1\right) \times \mathbf{RA}_r$	
$\mathbf{LCE}_{mr\ell}^{\text{EcolGrazing}}(y) = \mathbf{FLC}_{mr\ell}^{LS} \times \left(LM_{\ell}^{\text{EcolGrazing}}(y) - 1\right) \times \mathbf{RA}_r$	

where,

- $OM_{\ell}^{\text{EcolGrazing}}(y)$: Operating multiplier.
- $LM_{\ell}^{\text{EcolGrazing}}(y)$: Labour multiplier
- $\mathbf{FOC}_{mr\ell}^{LS}$: Fixed operating costs (Equation 58)

- $\mathbf{FLC}_{mr\ell}^{LS}$: Fixed labour cost (Equation 57)
- $\mathbf{OCE}_{mr\ell}^{\text{EcolGrazing}}(y)$: Operating cost effects (Figure 31)
- $\mathbf{LCE}_{mr\ell}^{\text{EcolGrazing}}(y)$: Labour cost effects of ecological grazing practice (Figure 32)
- $\mathbf{RA}_r$: Real area multiplier (Figure 5)

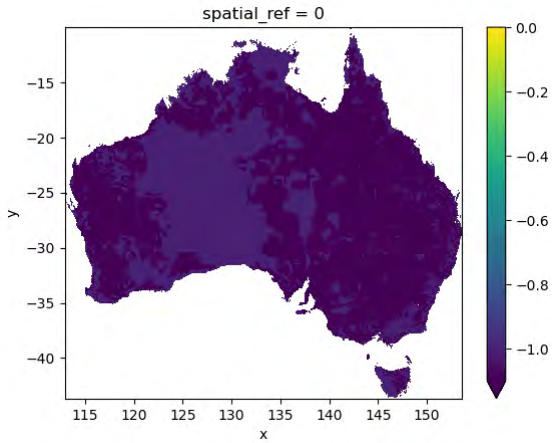

Figure 31 Operating cost effects of ecological grazing practice $\mathbf{OCE}_{mr\ell}^{\text{EcolGrazing}}$

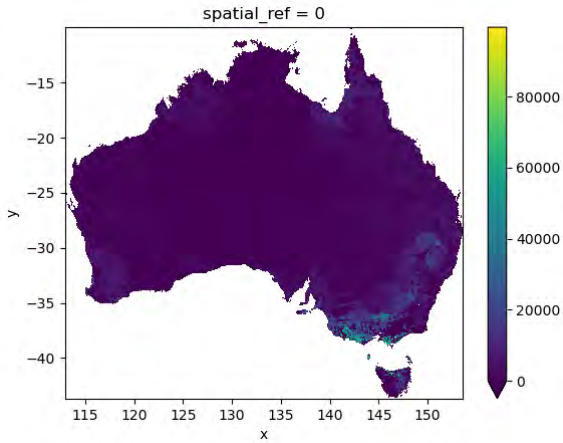

Figure 32 Labour cost effects of ecological grazing practice $\mathbf{LCE}_{mr\ell}^{\text{EcolGrazing}}$

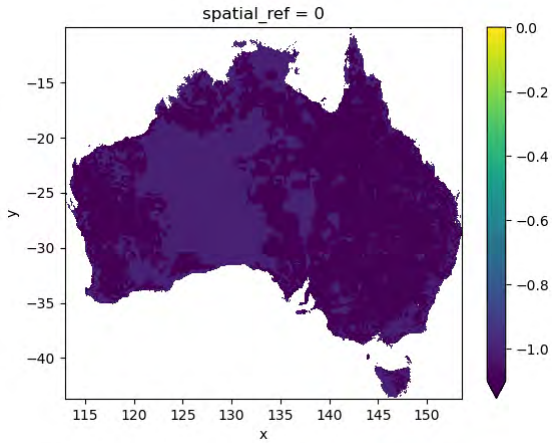

Figure 33 The updated cost matrix by integrating ecological grazing $\mathbf{UCM}_{mr\ell}^{\text{EcolGrazing}}$

2.3.4. The Savana burning Effects to the Cost for all Relevant Land Use Classes

The updated cost matrix, $\mathbf{UCM}_{mr\ell}^{\text{SavBurn}}$, after integrating Savana burning into agricultural land management, is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 69
$\mathbf{UCM}_{mr\ell}^{\text{SavBurn}} = 0_{(N_k \times N_c \times N_{lu}^{\text{SavBurn}})}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21), hence $N_k = 2$.

- N_{lu}^{SavBurn} is 4, as Savana burning practice affects beef, sheep, and dairy production across natural land as well as unallocated natural land (Equation 31), $N_{lu} = 4$

The updated $\mathbf{UCM}_{mr\ell}^{\text{SavBurn}}(y)$, after integrating Savanna burning practices, is given as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 70
$\mathbf{UCM}_{mr\ell}^{\text{SavBurn}}(y) = CPH_{\ell}^{\text{SavBurn}} \times CM_{\ell}^{\text{SavBurn}}(y) \times \mathbf{RA}_r$	

where,

- $CPH_{\ell}^{\text{SavBurn}}$: Cost per hectare for Savanna burning.
- $CM_{\ell}^{\text{SavBurn}}(y)$: Savanna burning cost multiplier.
- $\mathbf{RA}_r$: Real area multiplier (Figure 5)

$\mathbf{UCM}_{mr\ell}^{\text{SavBurn}}(y)$ represents the actual cost values for cells where Savanna burning is eligible, as illustrated in Figure 35. For all other pixels, a very large placeholder value, such as 999999999999, is assigned to indicate ineligibility. This approach ensures that the cost matrix accurately differentiates between eligible and ineligible regions, where:

- **Eligible Cells**: Contain real cost values calculated for Savanna burning activities.
- **Ineligible Cells**: Are assigned a large value to effectively exclude them from cost calculations or optimization processes.

The high placeholder value ensures that ineligible pixels do not interfere with subsequent analyses or decision-making processes.

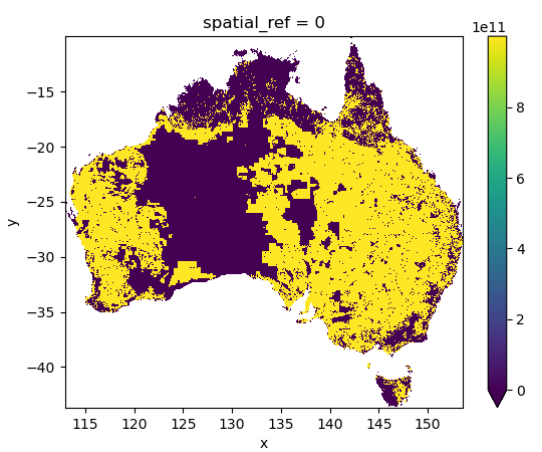

Figure 34: Updated cost matrix by integrating Savana burning practice $\mathbf{UCM}_{mr\ell}^{\text{SavBurn}}(y)$

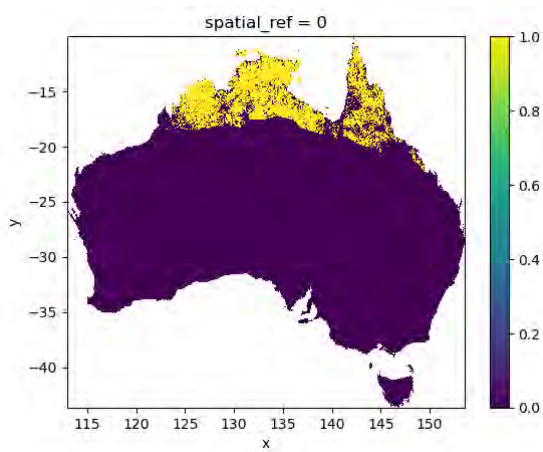

Figure 35: Eligible cells for Savana burning

2.3.5. The AgTech EI Effects to the Cost for all Relevant Land Use Classes

The updated cost matrix, $\mathbf{UCM}_{mr\ell}^{\text{AgTech EI}}$, after integrating AgTech EI into agricultural land management, is defined as:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 71
$\mathbf{UCM}_{mr\ell}^{\text{AgTech EI}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AgTech EI}}\right)}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21), hence $N_k = 2$.
- $N_{lu}^{\text{AgTech EI}}$ is 20, as AgTech EI practice affects 20 land use classes (Equation 33), $N_{lu} = 20$

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 72
$\mathbf{UCM}_{mr\ell}^{\text{AgTech EI}}(y) = CPH_{\ell}^{\text{AgTech EI}}(y) \times \mathbf{RA}_r$	

where,

- $CPH_{\ell}^{\text{AgTech EI}}(y)$: Cost per hectare for AgTech EI
- $\mathbf{RA}_r$: Real area multiplier (Figure 5)

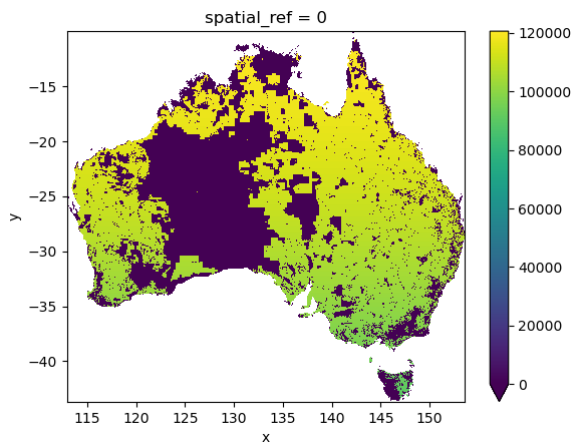

Figure 36 Updated cost matrix by integrating AgTech EI practice $\mathbf{UCM}_{mr\ell}^{\text{AgTech EI}}$

2.3.6. Agricultural Management Practices Effects to the Cost for all Relevant Land Use Classes

To represent the effects of all agricultural management practices, the variable $\mathbf{Cost}^{\text{AGMP}}$ is defined as a dictionary mapping practices k to their respective updated cost matrices $\mathbf{UCM}_{mr\ell}^{k}$:

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$\mathbf{Cost}^{\mathrm{AGMP}} = \left\{ k \rightarrowtail \mathbf{UCM}^{k}_{mr\ell}(y) \middle| r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}, \mathbf{UCM}^{k}_{mr\ell}(y) \in \mathbb{R}^{N_k \times N_c \times N^k_{lu}} \right\}$	Equation 73

where,

- $\mathcal{K}$: Set of agricultural management practices (Equation 22)
- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21), hence $N_k = 2$.
- N^k_{lu} is the number of land-use in each of the agricultural management practices $k \in \mathcal{K}$ (Equation 24-Equation 32)
- $\mathbb{R}$: The real number
- $\mathbf{UCM}^{k}_{mr\ell}(y)$: Updated cost matrix by integrating k-th agricultural management practice.

Regarding the agricultural management practices, $\mathcal{K}$ is the set lists agricultural management practices that can be applied to different land use types (Equation 22). As mentioned in Equation 23, there is a rule or mapping ϕ that relates elements from the set of agricultural management practices (the domain $\mathcal{K}$) to the set of land uses $\mathcal{L}$ (Equation 1) that are relevant or applicable to that practice. The practices related to each agricultural management practices are mentioned in Equation 24-Equation 32.

Then, the initialized $\mathbf{Cost}^{\mathrm{AGMP}}$ (Equation 73) is updated, as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists k\ , k \in \mathcal{K}$	Equation 74
$\mathbf{Cost}^{\mathrm{AGMP}}(y) = \left\{ \begin{array}{lll} k \rightarrowtail \mathbf{UCM}^{\mathrm{AspTaxifor}}_{mr\ell}(y) & if & k \in \phi(\text{Asparagopsis taxiformis}) \\ k \rightarrowtail \mathbf{UCM}^{\mathrm{PrecAgric}}_{mr\ell}(y) & if & k \in \phi(\text{Precision Agriculture}) \\ k \rightarrowtail \mathbf{UCM}^{\mathrm{EcolGrazing}}_{mr\ell}(y) & if & k \in \phi(\text{Ecological Grazing}) \\ k \rightarrowtail \mathbf{UCM}^{\mathrm{SavBurn}}_{mr\ell}(y) & if & k \in \phi(\text{Savanna Burning}) \\ k \rightarrowtail \mathbf{UCM}^{\mathrm{AgTech\ EI}}_{mr\ell}(y) & if & k \in \phi(\text{AgTech EI}) \end{array} \right\}$	

where,

- $\mathcal{K}$ is the set lists agricultural management practices that can be applied to different land use types (Equation 22)
- k *is* the agricultural management practice type
- $\mathbf{UCM}^{\mathrm{AspTaxifor}}_{mr\ell}(y)$ is the updated cost matrix by integrating Asparagopsis taxiformis into agricultural land management strategies (Equation 64)
- $\mathbf{UCM}^{\mathrm{PrecAgric}}_{mr\ell}(y)$ is the updated cost matrix by integrating precision agriculture into agricultural land management strategies (Equation 66)
- $\mathbf{UCM}^{\mathrm{EcolGrazing}}_{mr\ell}(y)$ is the updated cost matrix by integrating ecological grazing into agricultural land management strategies (Equation 68)
- $\mathbf{UCM}^{\mathrm{SavBurn}}_{mr\ell}(y)$ is the updated cost matrix by integrating Savanna burning into agricultural land management strategies (Equation 70)
- $\mathbf{UCM}^{\mathrm{AgTech\ EI}}_{mr\ell}(y)$ is the updated cost matrix by integrating AgTech EI into agricultural land management strategies (Equation 72)
- $\phi(\text{Asparagopsis taxiformis})$ is the Asparagopsis taxiformis practice that primarily affecting livestock on natural and modified land (Equation 25)

- $\phi(\text{Precision Agriculture})$ is the precision agriculture practice that primarily applied to cropping, intensive cropping, and horticulture (Equation 27)
- $\phi(\text{Ecological Grazing})$ is the ecological grazing practice that primarily applied to livestock on modified land (Equation 29)
- $\phi(\text{Savanna Burning})$ is the Savanna burning practice that primarily related to livestock on natural land, as well as unallocated natural land (Equation 31)
- $\phi(\text{AgTech EI})$ is the AgTech EI practice that primarily affecting cropping, intensive cropping, and horticulture (Equation 33)

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3 Agricultural Greenhous Gas (GHG) Emissions

3.1. GHG Emission of Crops

This section computes the GHG emissions for crops in land use set $\mathcal{L}_{\text{Crops}}^{\text{GHG}}$ (Equation 75) based on different sources.

$\mathcal{L}_{\text{Crops}}^{\text{GHG}} = \mathcal{L}_{\text{Crops}} - \{\text{Rice, Pears}\}$	Equation 75
$\mathcal{L}_{\text{Crops}}^{\text{GHG}} = \left\{ \begin{matrix} \text{Apples, Citrus, Cotton, Grapes, Hay, Nuts, Other Non} - \text{Cereal Crops,} \\ \text{Plantation Fruit, Stone Fruit, Sugar, Summer Cereals,} \\ \text{Summer Legumes, Summer Oilseeds, Tropical Stone Fruit,} \\ \text{Vegetables, Winter Cereals, Winter Legumes, Winter Oilseeds} \end{matrix} \right\}$	

where, $\mathcal{L}_{\text{Crops}}$ introduced in Equation 15.

The GHG emissions of each crop consists of 9 different sources as:

1. Greenhouse gas emissions from the application of chemicals (e.g., pesticides, herbicides) per hectare, which is known as CO2E_KG_HA_CHEM_APPL in Luto 2.
2. Greenhouse gas emissions from general crop management practices per hectare, which is known as CO2E_KG_HA_CROP_MGT in Luto 2.
3. Greenhouse gas emissions from cultivation activities, such as plowing and tilling, per hectare, which is known as CO2E_KG_HA_CULTIV in Luto 2.
4. Greenhouse gas emissions from the production of fertilizers used in crop production per hectare, which is known as CO2E_KG_HA_FERT_PROD in Luto 2.
5. Greenhouse gas emissions from harvesting activities per hectare, which is known as CO2E_KG_HA_HARVEST in Luto 2.
6. Greenhouse gas emissions from irrigation practices per hectare, which is known as CO2E_KG_HA_IRRIG in Luto 2.
7. Greenhouse gas emissions from the production of pesticides used in crop production per hectare, which is known as CO2E_KG_HA_PEST_PROD in Luto 2.
8. Greenhouse gas emissions from soil management practices, such as soil amendments and treatments, per hectare, which is known as CO2E_KG_HA_SOIL in Luto 2.
9. Greenhouse gas emissions from sowing activities per hectare, which is known as CO2E_KG_HA_SOWING in Luto 2.

Therefore, GHG sources can be defined as:

$S^{\text{Crops}} = \left\{ \begin{matrix} \text{CO2E_KG_HA_CHEM_APPL, CO2E_KG_HA_CROP_MGT, CO2E_KG_HA_CULTIV,} \\ \text{CO2E_KG_HA_FERT_PROD, CO2E_KG_HA_HARVEST, CO2E_KG_HA_IRRIG,} \\ \text{CO2E_KG_HA_PEST_PROD,CO2E_KG_HA_SOIL, CO2E_KG_HA_SOWING} \end{matrix} \right\}$	Equation 76

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The amount of greenhouse gas emission for each source s, $s \in S^{\text{Crops}}$, is defined as $\mathbf{CGHGE}^{AG}_{m,r,\ell,s}$. Therefore, the total greenhouse gas emission of each given cell r considering the crop type ℓ, $\ell \in \mathcal{L}^{\text{GHG}}_{\text{Crops}}$ and land management m can be written as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, s \in S^{\text{Crops}} \ \exists \ell, \ell \in \mathcal{L}^{\text{GHG}}_{\text{Crops}}$	Equation 77
$$\mathbf{GHGE}^{AG}_{mr\ell} = \sum_{s=1}^{S^{\text{Crops}}} \frac{\mathbf{CGHGE}^{AG}_{m,r,\ell,s} \times \mathbf{RA}_r}{1000}$$	

where,

- $\mathbf{CGHGE}^{AG}_{m,r,\ell,s}$ represents the amount of greenhouse gas emission from each source s, $s \in S^{\text{Crops}}$ for cell r under land management type m which cultivated by crop ℓ, $\ell \in \mathcal{L}^{\text{GHG}}_{\text{Crops}}$ (Figure 38 - Figure 46)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- 1000 is the conversion factor from kg to tonnes.

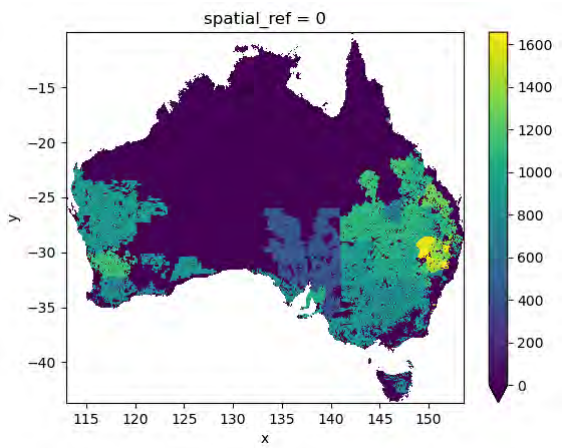

Figure 37 GHG emission for winter cereals under dry land management $\mathbf{CGHGE}^{AG}_{mr\ell}$

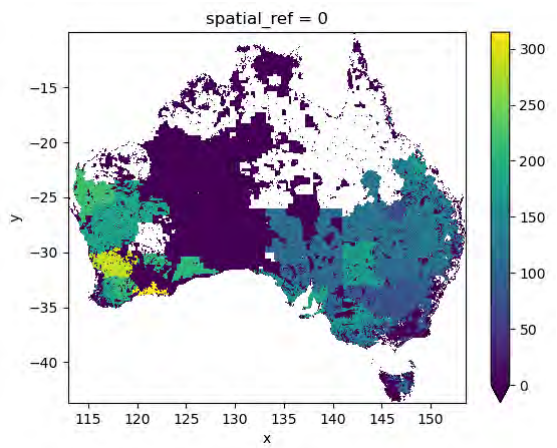

Figure 38 GHG emission for source of 'CO2E_KG_HA_CHEM_APPL'

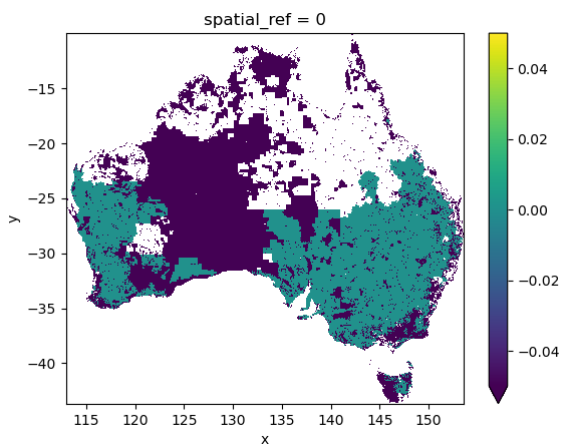

Figure 39 GHG emission for source of CO2E_KG_HA_CROP_MGT

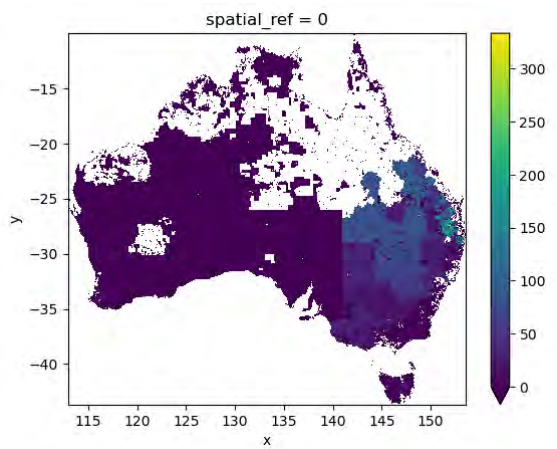

Figure 40 GHG emission for source of CO2E_KG_HA_CULTIV

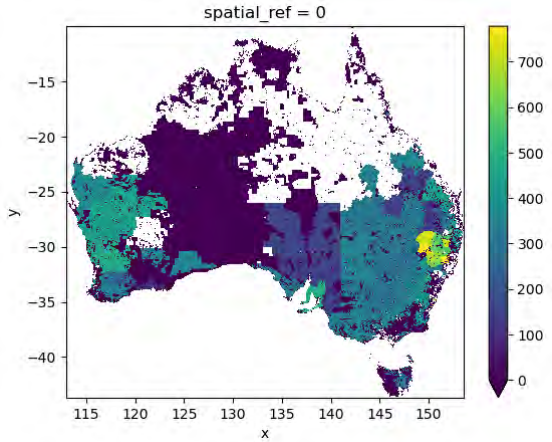

Figure 41 GHG emission for source of CO2E_KG_HA_FERT_PROD

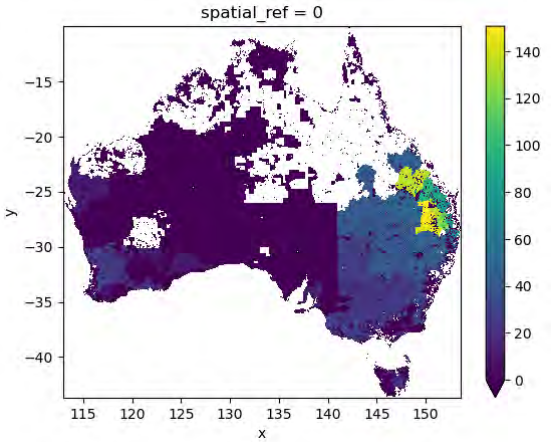

Figure 42 GHG emission for source of CO2E_KG_HA_HARVEST

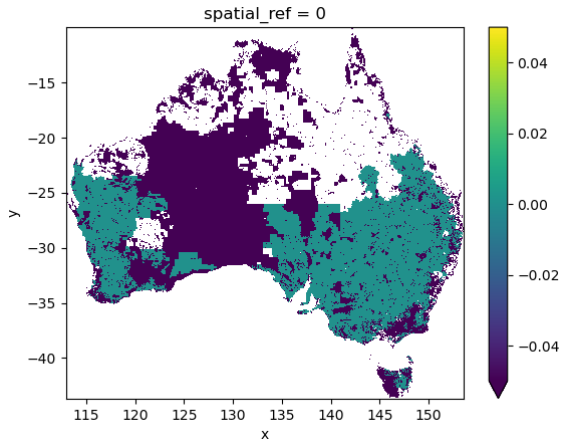

Figure 43 GHG emission for source of CO2E_KG_HA_IRRIG

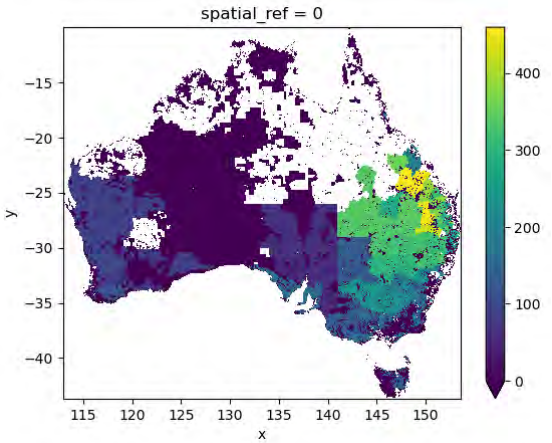

Figure 44 GHG emission for source of CO2E_KG_HA_PEST_PROD

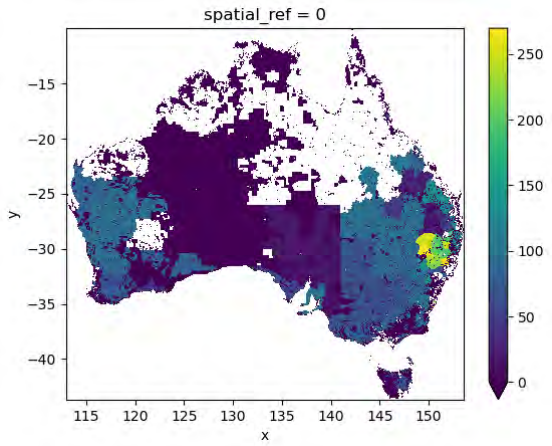

Figure 45 GHG emission for source of CO2E_KG_HA_SOIL

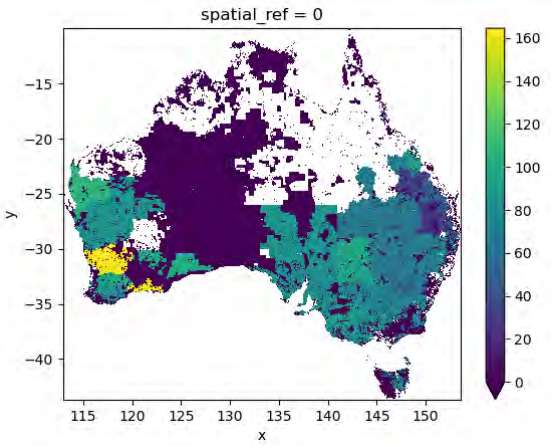

Figure 46 GHG emission for source of CO2E_KG_HA_SOWING

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3.2. GHG Emission of Livestock farming

The GHG emission of livestock farming consists of two parts, including GHG emission from livestock and GHG emission from lands.

3.2.1. GHG Emission from Livestock

This section computes the GHG emissions for livestock in land use set $\mathcal{L}^{\text{GHG}}_{\text{Livestock}}$ (Equation 78) based on different sources.

$\mathcal{L}^{\text{GHG}}_{\text{Livestock}} = \{\text{Beef}, \text{Dairy}, \text{Sheep}\}$	Equation 78

The GHG emissions of each livestock consists of 8 different sources ($S^{\text{Livestock}}$) as:

1. The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock due to dung and urine. This includes methane (CH4) and nitrous oxide (N2O) emissions from the decomposition of dung and urine. It is known as CO2E_KG_HEAD_DUNG_URINE in Luto 2.
2. The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock from electricity usage associated with livestock management and operations. It is known as CO2E_KG_HEAD_ELEC in Luto 2.
3. The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock from enteric fermentation. Enteric fermentation is a digestive process in ruminants that produces methane (CH4) as a by-product. It is known as CO2E_KG_HEAD_ENTERIC in Luto 2.
4. The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock from the production and transport of fodder (animal feed). It is known as CO2E_KG_HEAD_FODDER in Luto 2.
5. The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock from fuel usage, including fuel for machinery and transport related to livestock management. It is known as CO2E_KG_HEAD_FUEL in Luto 2.
6. The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock from indirect leaching and runoff. This includes nitrous oxide (N2O) emissions from nitrogen leached from manure and urine into water bodies. It is known as CO2E_KG_HEAD_IND_LEACH_RUNOFF in Luto 2.
7. The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock from manure management. This includes emissions from manure storage, treatment, and application to fields. It is known as CO2E_KG_HEAD_MANURE_MGT in Luto 2.
8. The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock from the production of seeds used to grow feed crops for livestock. It is known as CO2E_KG_HEAD_SEED in Luto 2.

Therefore, GHG sources can be defined as:

$S^{\text{Livestock}} = \left\{ \begin{array}{c} \text{CO2E_KG_HEAD_DUNG_URINE, CO2E_KG_HEAD_ELEC,} \\ \text{CO2E_KG_HEAD_ENTERIC,CO2E_KG_HEAD_FODDER,} \\ \text{CO2E_KG_HEAD_FUEL,CO2E_KG_HEAD_IND_LEACH_RUNOFF,} \\ \text{CO2E_KG_HEAD_MANURE_MGT, CO2E_KG_HEAD_SEED} \end{array} \right\}$	Equation 79

The GHG emission maps for beef farming which are corresponded to each GHG sources $S^{\text{Livestock}}$ are illustrated in Figure 47- Figure 55. To explain the implementation in LUTO 2.0, let $\mathbf{RGHGM}^{LS}_{r\ell s}$ be the raw form of GHG emission matrix for cell r that farming livestock ℓ. This matrix consists of 8 values for each livestock type ℓ, that each value represents GHG emission of a given source s, $s \in S^{\text{Livestock}}$. In the general form, for a given cell r this matrix can be written as:

$$\mathbf{RGHGM}_{r\ell s}^{LS} = \begin{bmatrix} \mathrm{CO2E}_{\ell=Beef,s=1} & \mathrm{CO2E}_{\ell=Beef,s=2} & \cdots & \mathrm{CO2E}_{\ell=Beef,s=8} \\ \mathrm{CO2E}_{\ell=Sheep,s=1} & \mathrm{CO2E}_{\ell=Sheep,s=2} & \cdots & \mathrm{CO2E}_{\ell=Sheep,s=8} \\ \mathrm{CO2E}_{\ell=Dairy,s=1} & \mathrm{CO2E}_{\ell=Dairy,s=2} & \cdots & \mathrm{CO2E}_{\ell=Dairy,s=8} \end{bmatrix} \quad \text{Equation 80}$$

where,

- $\mathrm{CO2E}_{\ell,s}$ is the CO2 equivalent for the source s of livestock type ℓ
- $r = 1$

This matrix ($\mathbf{RGHGM}_{r\ell s}^{LS}$) can be vectorized as a 1-D vector for a given cell r, where each row of $\mathbf{RGHGM}_{r\ell s}^{LS}$ becomes a segment of the $\mathbf{RGHGV}_{r\ell s}^{LS}$. Therefore, regarding the number of members in sets $\mathcal{L}_{\mathrm{Livestock}}^{\mathrm{GHG}}$ and $S^{\mathrm{Livestock}}$; this vector consists of $n = 3 \times 8 = 24$ columns, as:

$$\mathbf{RGHGV}_{r\ell s}^{LS} = [\mathrm{CO2E}_{\ell=Beef,s=1}, \ldots \mathrm{CO2E}_{\ell=Beef,s=8} \quad \mathrm{CO2E}_{\ell=Sheep,s=1} \ldots \mathrm{CO2E}_{\ell=Sheep,s=8} \quad \mathrm{CO2E}_{\ell=Dairy,s=1} \ldots \mathrm{CO2E}_{\ell=Dairy,s=8}] \quad \text{Equation 81}$$

The vectorized 1-D vector form ($\mathbf{RGHGV}_{r\ell s}^{LS}$) can be arranged into a 2D tensor ($\mathbf{RGHG}_{r\ell s}^{LS}$) by concatenating it for all cells ($r \in \{1, \ldots, N_r\}$). Therefore, $\mathbf{RGHG}_{r\ell s}^{LS}$ has n columns ($n = 24$), where each column corresponds to the different GHG emission source ($s \in S^{\mathrm{Livestock}}$) and each row correspond to a different cell of the studying area's grid. The unit of each value in $\mathbf{RGHG}_{r\ell s}^{LS}$ is $\mathrm{kgCO_2e/head}$; therefore, it must be converted to $\mathrm{kgCO_2e}$ per hectare ($\mathrm{kgCO_2e/ha}$) using Equation 82:

$$\mathbf{LGHGE}_{mr\ell}^{LS}(y) = \sum_{s=1}^{S^{\mathrm{Livestock}}} \frac{\mathbf{RGHG}_{r\ell s}^{LS} \times \mathbf{YPot}_{mr\ell}^{LS}(y) \times \mathbf{RA}_r}{1000} \quad \text{Equation 82}$$

where,

- $\mathbf{YPot}_{mr\ell}^{LS}(y)$ represents the yield potential for livestock ℓ (Figure 117-Figure 128). This parameter is computed by Equation 113.
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{LGHGE}_{mr\ell}^{LS}$ represents the GHG emitted from all sources $S^{\mathrm{Livestock}}$ per hectare (in tonnes of CO2e/ha)

The produced map of $\mathbf{LGHGE}_{mr\ell}^{LS}$ for beef farming is illustrated in Figure 55.

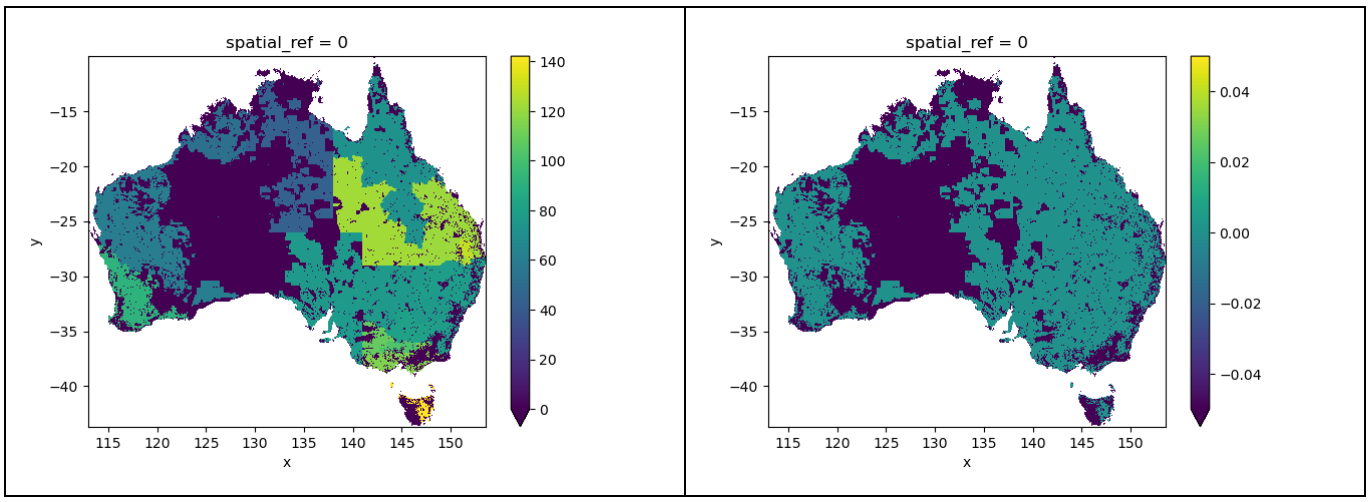

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Figure 47 GHG emission from beef farming for source of CO2E_KG_HEAD_DUNG_URINE

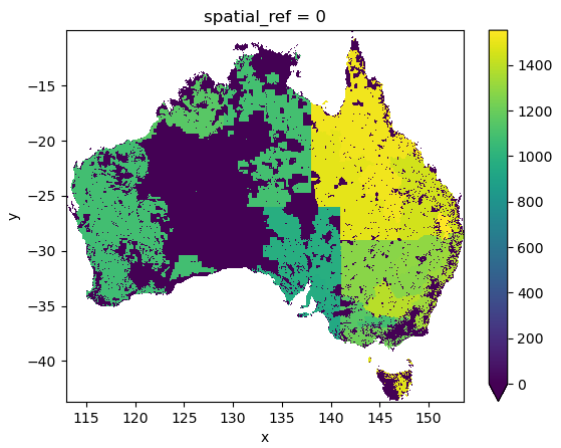

Figure 48 GHG emission from beef farming for source of CO2E_KG_HEAD_ELEC

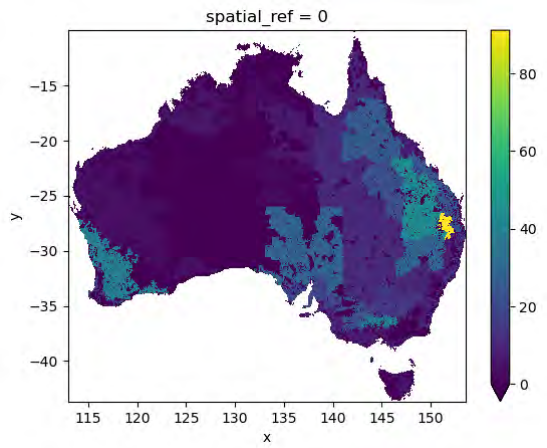

Figure 49 GHG emission from the scenario of beef farming for source of CO2E_KG_HEAD_ENTERIC

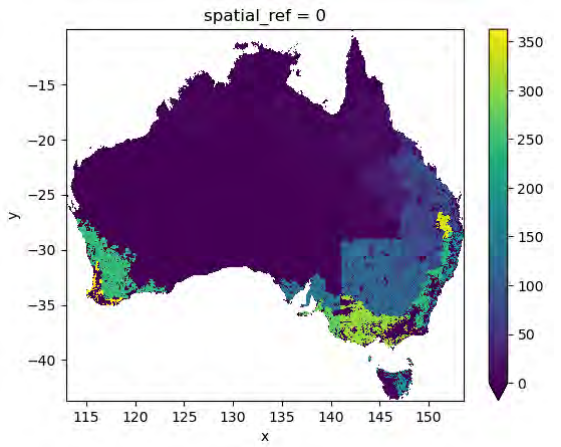

Figure 50 GHG emission from the scenario of beef farming for source of CO2E_KG_HEAD_FODDER

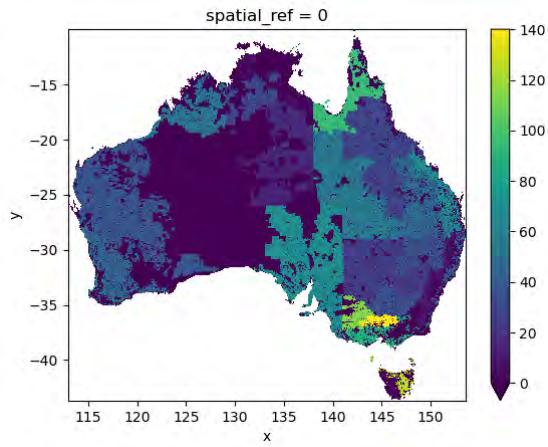

Figure 51 GHG emission from the scenario of beef farming for source of CO2E_KG_HEAD_FUEL

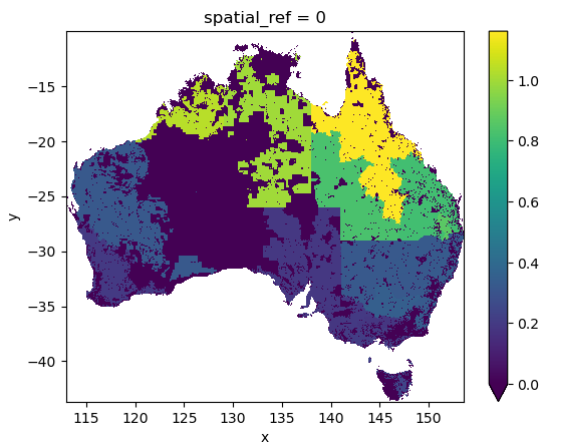

Figure 52 GHG emission from the scenario of beef farming for source of CO2E_KG_HEAD_IND_LEACH_RUNOFF

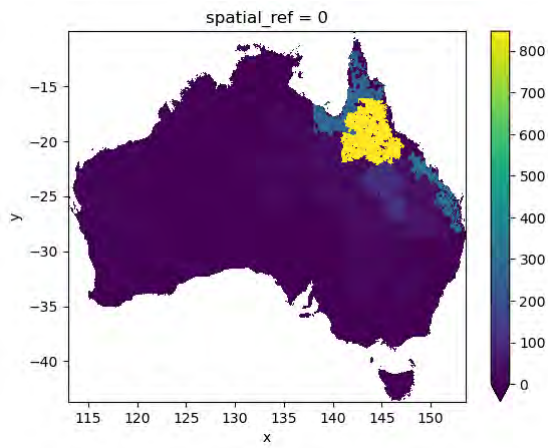

Figure 53 GHG emission from the scenario of beef farming for source of CO2E_KG_HEAD_MANURE_MGT

Figure 54 GHG emission from the scenario of beef farming for source of CO2E_KG_HEAD_SEED

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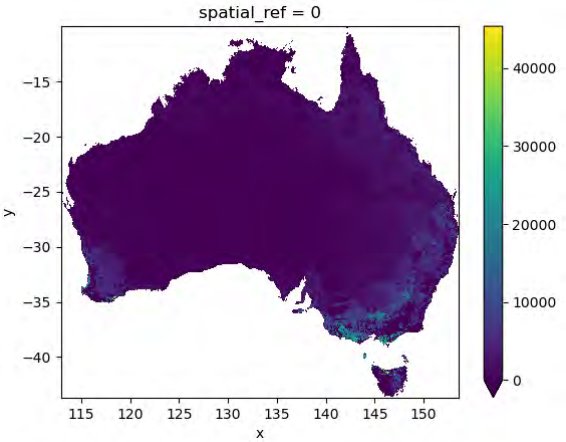	
Figure 55 The summation of GHG emitted from the scenario of beef farming for all beef farming sources $S^{\text{Livestock}}$ per hectare (in tonnes of CO2e/ha) $\mathbf{LGHGE}_{r\ell}^{LS}$	

3.2.2. GHG Emission from Lands

In LUTO 2.0, the assigned pasture lands to livestock industries are divided into natural and modified lands, where a proportion of the modified lands are under an irrigated land management system. They have the same greenhouse gas emissions sources s as those mentioned in S^{Crops} (see Equation 76). Therefore, if the land management system of a pasture lands is irrigated ($m = 'irr'$), the emissions data related to the irrigation of pasture lands ($\mathbf{PGHGE}_{m,r,\ell,s}^{LS,Irr}$) also considered as another source of GHG emissions from Livestock. Therefore, for each given cell r, $\mathbf{RGHGE}_{m,r,\ell,s}^{LS,Irr}$ can be written as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, s \in S^{\text{Crops}} \exists \ell, \ell \in \mathcal{L}_{\text{Livestock}}^{Irr}$	Equation 83
$\mathbf{RGHGE}_{r,\ell}^{LS,Irr} = \begin{cases} \mathbf{PGHGE}_{m,r,\ell,s}^{LS,Irr} & \text{if} \quad m = 1 \\ 0 & \text{otherwise} \end{cases}$	

where,

- $\mathcal{L}_{\text{Livestock}}^{Irr}$ is a set of livestock that are farming under an irrigated land management system (Equation 84)
- $\mathbf{PGHGE}_{m,r,\ell,s}^{LS,Irr}$ is the emissions data related to the irrigation of pasture lands
- $\mathbf{RGHGE}_{m,r,\ell,s}^{LS,Irr}$ is raw GHG emission.

$\mathcal{L}_{\text{Livestock}}^{Irr} = \mathcal{L}_{\text{Livestock}} - \mathcal{L}_{\text{NatLivestock}}$ $= \{\text{Beef} - \text{Modified Land}, \text{Sheep} - \text{modified land}, \text{Dairy} - \text{modified land}\}$	Equation 84

Each column of $\mathbf{RGHGE}_{m,r,\ell,s}^{LS,Irr}$ corresponds to different types of GHG measurements expressed in terms of CO2 equivalents (CO2E) for each cell r, as:

$\mathbf{RGHGE}_{r,\ell,s}^{LS,Irr} = [\mathrm{CO2E}_{m=irr,s=1} \quad , \mathrm{CO2E}_{m=irr,s=2}, \quad \cdots, \mathrm{CO2E}_{m=irr,s=9}]$	Equation 85

where,

- $m = 1$, m represents the irrigated land management
- $\mathrm{CO2E}_{m=irr,s=1}$ represents CO2e produced by each GHG emission source s, $s \in S^{\mathrm{Crops}}$ (Equation 76)

$\mathbf{GHGE}_{r\ell}^{LS,Irr} = \sum_{s=1}^{S^{\mathrm{Crops}}} \frac{\mathbf{RGHGE}_{r,\ell,s}^{LS,Irr} \times \mathbf{RA}_r}{1000}$	Equation 86

where,

- $\mathbf{RA}_r$ represents the real area (Figure 5)
- 1000 is the conversion factor from kg to tonnes.
- $\mathbf{GHGE}_{r\ell}^{LS,Irr}$ represents GHG emitted from all sources S^{Crops} of irrigated land management per hectare (in tonnes of CO2e/ha)

3.2.3. GHG Emission from Livestock and Land

The GHG emission of livestock farming which is from livestock and irrigated pasture ($\mathbf{GHGE}_{mr\ell}^{LS}$) can be computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, s \in S^{\mathrm{Crops}} \exists \ell, \ell \in \mathcal{L}_{\mathrm{Livestock}}^{Irr}$	Equation 87
$\mathbf{GHGE}_{mr\ell}^{LS} = \begin{cases} \mathbf{LGHGE}_{mr\ell}^{LS} & \text{if} \quad m = 0 \\ \mathbf{LGHGE}_{mr\ell}^{LS} + \mathbf{GHGE}_{mr\ell}^{LS,Irr} & \text{if} \quad m = 1 \end{cases}$	

where,

- $\mathbf{LGHGE}_{mr\ell}^{LS}$ was computed by Equation 82
- $\mathbf{GHGE}_{mr\ell}^{LS,Irr}$ was computed by Equation 86

In Figure 65, the total GHG Emission of beef farming which is from beef's GHG emission source and irrigated pasture that assigned to beef farming is illustrated.

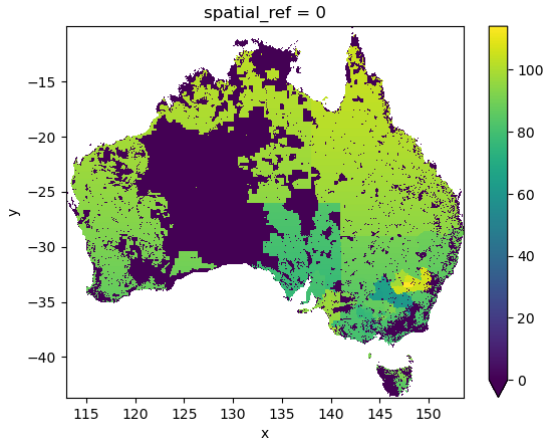

Figure 56 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_CHEM_APPL

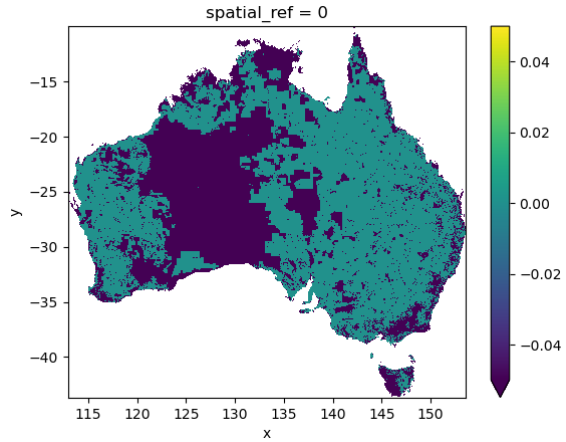

Figure 57 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_CROP_MGT

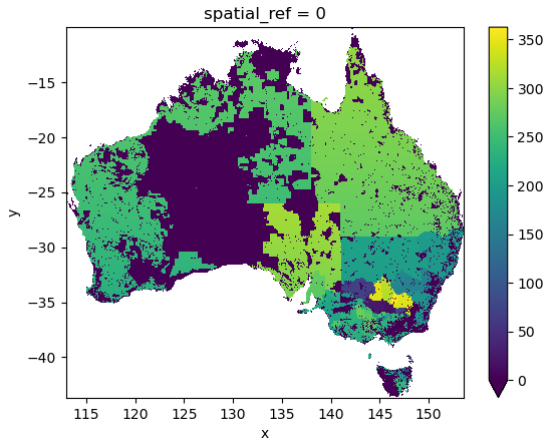

Figure 58 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_CULTIV

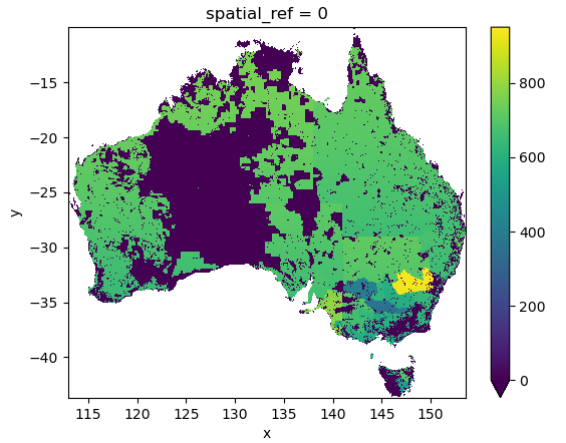

Figure 59 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_FERT_PROD

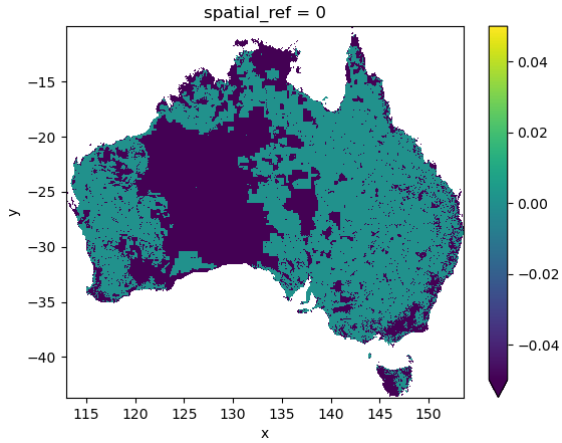

Figure 60 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_HARVEST

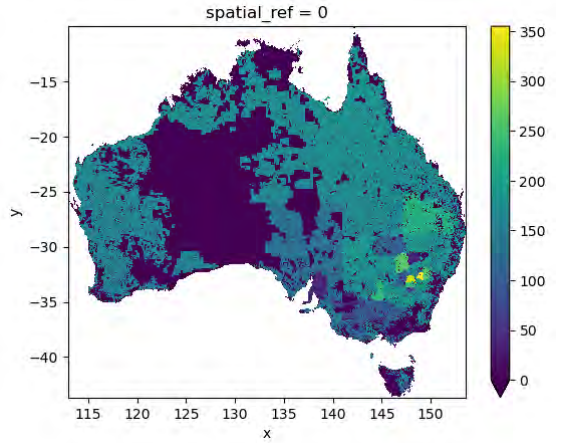

Figure 61 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_IRRIG

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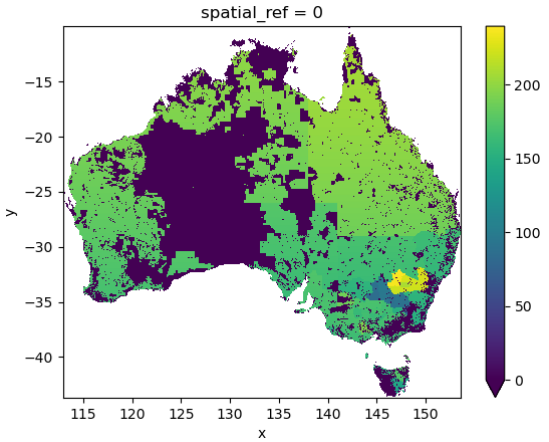
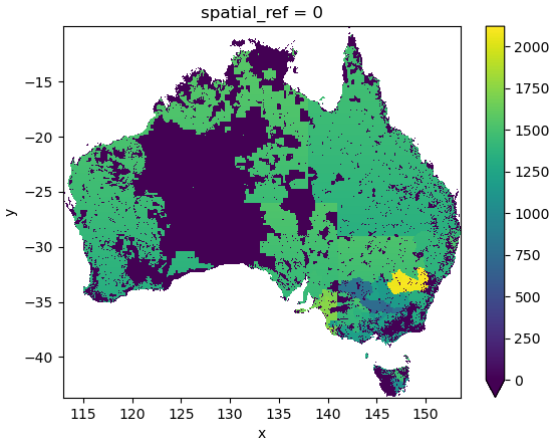
	

Figure 62 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_PEST_PROD	Figure 63 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_SOIL

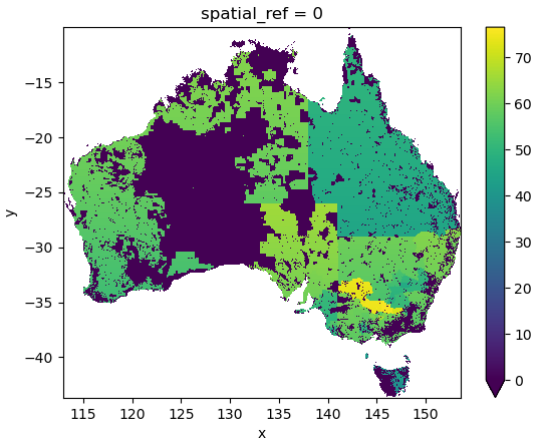
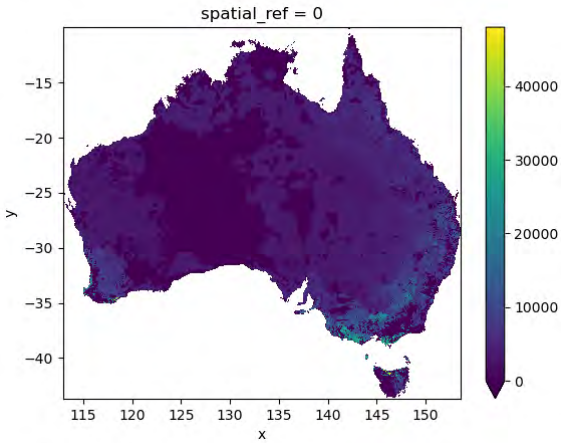

	

Figure 64 GHG emission from the pasture lands scenario that could be assigned to livestock industries for source of CO2E_KG_HA_SOWING	Figure 65 The GHG emission of livestock farming which is from livestock and irrigated pasture that could be assigned to beef farming

3.3. The GHG Emission Matrix from all and use classes

Let $\mathbf{GHGE}_{mr\ell}^{AG,LS}$ be a tensor that represents the GHG emissions for both crop and livestock products under dry and irrigation land management systems. At first step, $\mathbf{GHGE}_{mr\ell}^{AG,LS}$ must be initialized as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 88
$\mathbf{GHGE}_{mr\ell}^{AG,LS} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- N_{lu} is the number of agricultural land-use categories; hence, $N_{lu} = 28$ (Equation 1).

This tensor ($\mathbf{GHGE}_{mr\ell}^{AG,LS}$) should be updated using $\mathbf{CQY}_{mr\ell}^{AG}(y)$ and $\mathbf{LQY}_{mr\ell}^{LS}(y)$ values, which computed in Equation 121 and Equation 114 respectively.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 89
$\mathbf{GHGE}_{mr\ell}^{AG,LS}(y) = \begin{cases} \mathbf{CQY}_{mr\ell}^{AG}(y) & \text{if } \ell \in \mathcal{L}_{\text{Crops}} \\ \mathbf{LQY}_{mr\ell}^{LS}(y) & \text{if } \ell \in \mathcal{L}_{\text{Commodities}}^{\text{Livestock}} \end{cases}$	

where,

- $\mathbf{CQY}_{mr\ell}^{AG}(y)$ is GHG emissions for crops computed by Equation 121
- $\mathbf{LQY}_{mr\ell}^{LS}(y)$ is GHG emissions for livestock computed by Equation 114

For example, to compare the total GHG emission from different livestock land uses scenarios, Figure 66, Figure 68, and Figure 70 illustrate the GHG emission from beef, sheep, and diary under irrigated land management system, and Figure 67, Figure 69, and Figure 71 illustrate the GHG emission from beef, sheep, and diary under dry land management system.

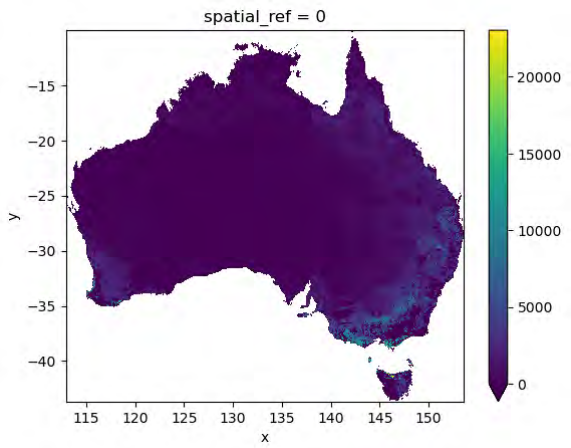


Figure 66 The GHG emission of 'Beef-Modified Land' scenario under dry land management system

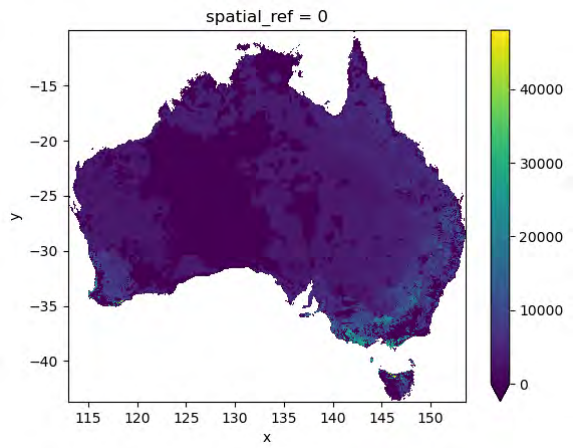
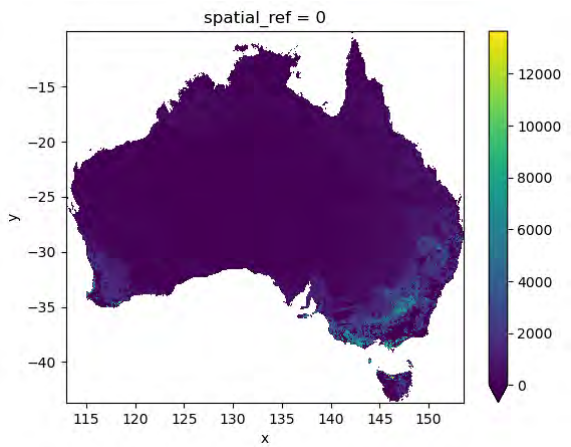


Figure 67 The GHG emission of 'Beef-Modified Land' scenario under irrigated land management system



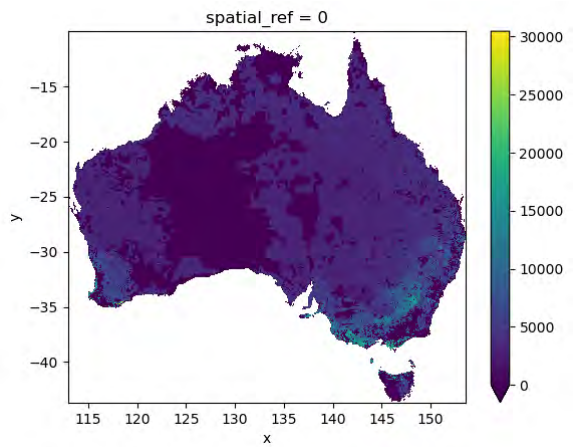


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Figure 68 The GHG emission of 'Sheep-Modified Land' scenario under dry land management system	Figure 69 The GHG emission of 'Sheep-Modified Land' scenario under irrigated land management system
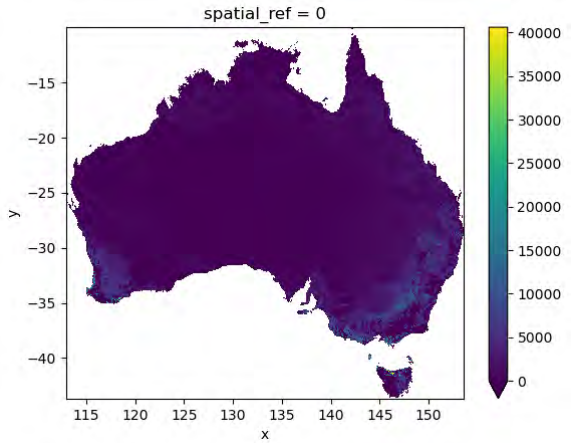	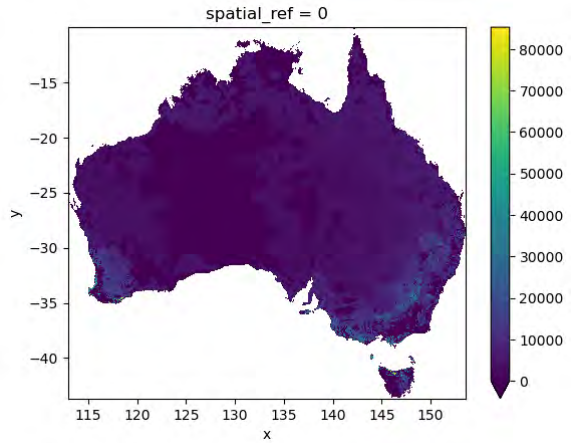
Figure 70 The GHG emission of 'Dairy-Modified Land' scenario under dry land management system	Figure 71 The GHG emission of 'Dairy-Modified Land' scenario under irrigated land management system

Another examples are the total GHG emission from winter and summer cereals which are cultivated under dry and irrigated land management system scenarios, see Figure 72 - Figure 75 .

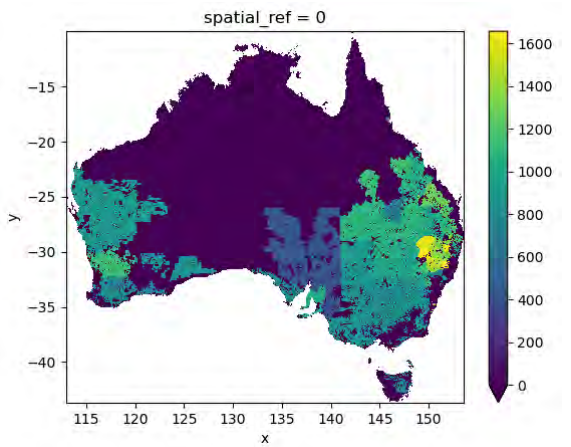	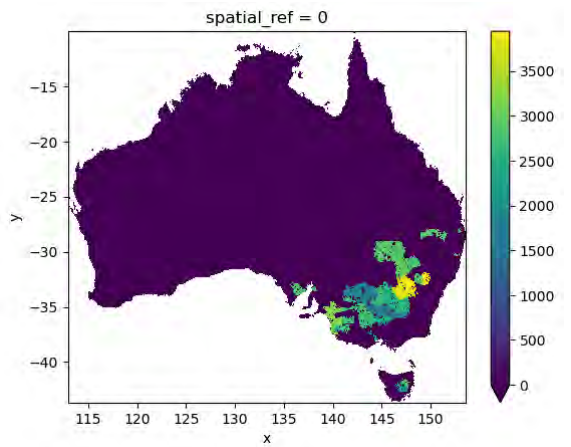
Figure 72 The GHG emission of winter cereals cultivated under dry land management system scenario	Figure 73 The GHG emission of winter cereals cultivated under irrigated land management system scenario

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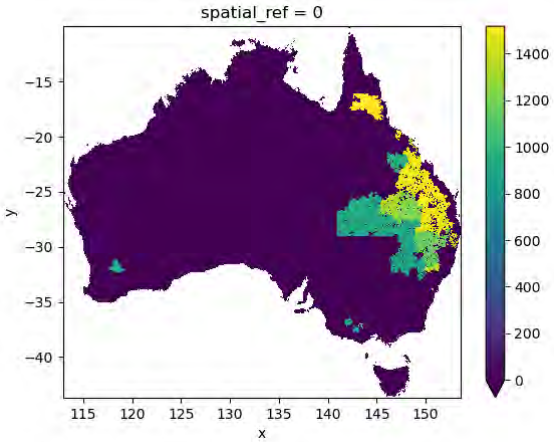	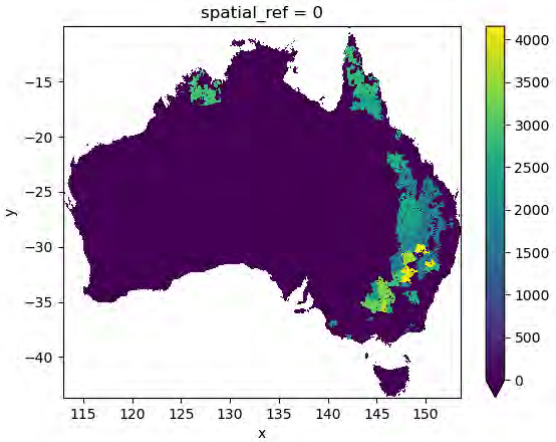
Figure 74 The GHG emission of summer cereals cultivated under dry land management system scenario	Figure 75 The GHG emission of summer cereals cultivated under irrigated land management system scenario

3.4. Greenhouse Gas Emission Penalties for Land-Use Transitions

Let $\mathbf{CEP}^{\mathrm{NLtoML}}$ be the carbon emission penalty for transition from class ℓ_i of the natural land use to class ℓ_j of the modified land use. It is defined as a matrix with size $N_c \times N_{lu}$, where each element of $\mathbf{CEP}^{\mathrm{NLtoML}}_{\ell_i,\ell_j}$ represents the penalties from class ℓ_i into ℓ_j, and $\ell_i \in \mathcal{L}_{\mathrm{NatAgLu}}$ (Equation 18), $\ell_j \in \mathcal{L}_{\mathrm{ModifiedLu}}$ (Equation 20). First, initialize the $\mathbf{CEP}^{\mathrm{NLtoML}}$ as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 90
$\mathbf{CEP}^{\mathrm{NLtoML}} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- N_{lu} is the number of agricultural land-use categories; hence, $N_{lu} = 28$.

The values of $\mathbf{CEP}^{\mathrm{NLtoML}}$ is dependent to the remnant vegetation carbon data ($\mathbf{CEF}_r^{\mathrm{rem}}$) of cell r and its correspondence fire risk probability ($\mathbf{FRP}_r$) of cell r, as:

$\forall r \in \{1, \dots, N_r\}$	Equation 91
$\mathbf{CEF}_r^{\mathrm{adj}} = \dfrac{\mathbf{CEF}_r^{\mathrm{rem}} \times \mathbf{FRP}_r}{100}$	

where

- $\mathbf{CEF}_r^{\mathrm{adj}}$ is the fire-adjusted emissions factor for cell r, in tonnes of CO_2 per hectare (Figure 80).
- $\mathbf{CEF}_r^{\mathrm{rem}}$ is the initial emissions factor for remnant vegetation in cell r before adjustment (Figure 79).
- $\mathbf{FRP}_r$ is the fire risk probability for cell r (Figure 76-Figure 78)

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As $\mathbf{CEP}^{\mathrm{NLtoML}}$ is computed for the cells that assigned to natural land use; hence, the list of cells representing the natural land use in $\mathbf{LUM}_{mr}^{\mathrm{BYear}}$ must be identified, as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \exists \ell, \ell = \mathrm{LUM}_{mr}^{\mathrm{BYear}}$	Equation 92
$\mathcal{N}_{\mathrm{NatAgLu}} = \{r \mid \ell_{mr} \in \mathcal{L}_{\mathrm{NatAgLu}}\}$	

where,

- $\mathcal{L}_{\mathrm{NatAgLu}}$ is the set of all natural land uses in agricultural production, including livestock and unallocated natural land (Equation 18).

Then, for all the cells indexed by $\mathcal{N}_{\mathrm{NatAgLu}}$, $\mathbf{CEP}^{\mathrm{NLtoML}}$ is computed as

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L} \exists\, r \in \mathcal{N}_{\mathrm{NatAgLu}}$	Equation 93
$\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}} = \begin{cases} \mathbf{CEF}_r^{\mathrm{adj}} \times \mathbf{RA}_r & \text{if } , m \in \{0,1\}, r \in \mathcal{N}_{\mathrm{NatAgLu}} \\ 0 & \text{otherwise} \end{cases}$	

Where

- $\mathbf{CEF}_r^{\mathrm{adj}}$ the fire-adjusted emissions factor for cell r, in tonnes of CO_2 per hectare (Equation **91** and Figure 80)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

Regarding Equation 93, the value of $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$ for all land uses ℓ are same; hence, to illustrate $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$, two land use classes of Beef Modified-land (Figure 82) and Beef Natural land (Figure 83) were selected. The map of $\mathbf{CEP}_{r\ell}^{\mathrm{NLtoML}}$ for all the classes available in $\mathcal{L}_{\mathrm{NatAgLu}}$ (Figure 18) is same as Figure 83, and for other land use classes available in the set $\mathcal{L} - \mathcal{L}_{\mathrm{NatAgLu}}$, the map of $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$ is same as Figure 82.

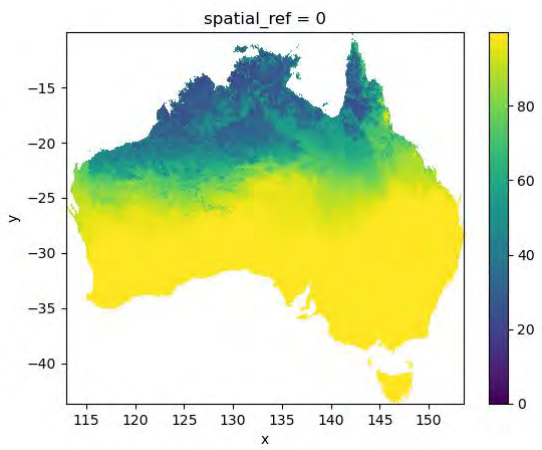	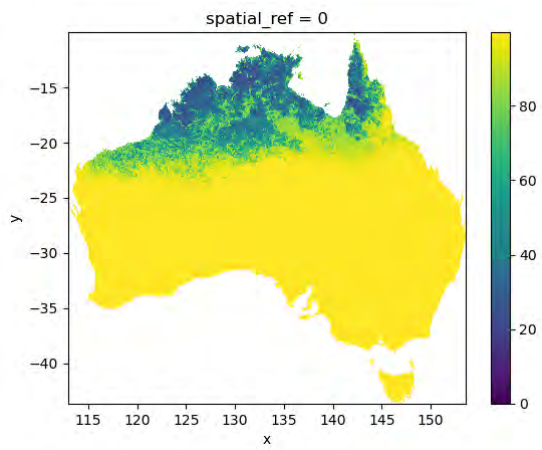
Figure 76 Fire risk probability (low level) $\mathbf{FRP}_r$	Figure 77 Fire risk probability (median level) $\mathbf{FRP}_r$

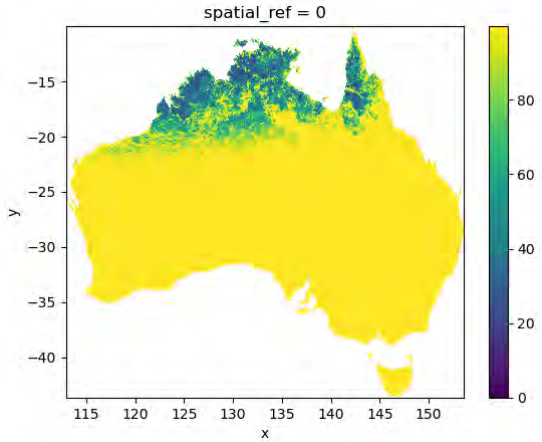

Figure 78 Fire risk probability (high level) $\mathbf{FRP}_r$

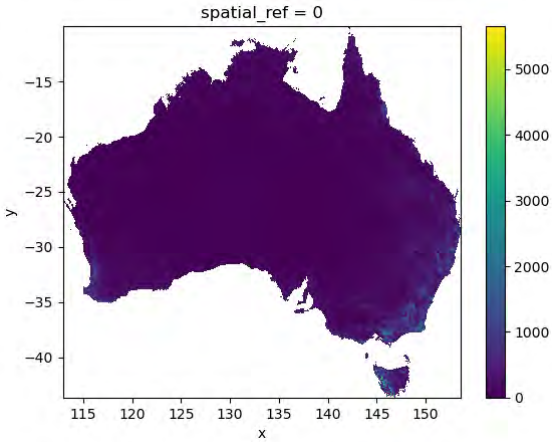

Figure 79 The is the initial CO2 emissions factor for remnant vegetation $\mathbf{CEF}_r^{\mathrm{rem}}$

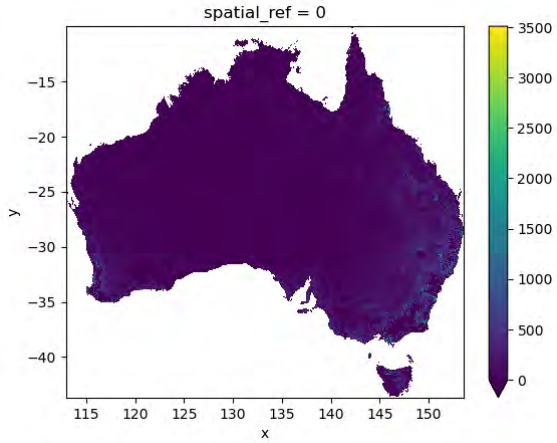

Figure 80 The fire-adjusted emissions factor based on the median fire risk in tonnes of CO_2 per hectare $\mathbf{CEF}_r^{\mathrm{adj}}$

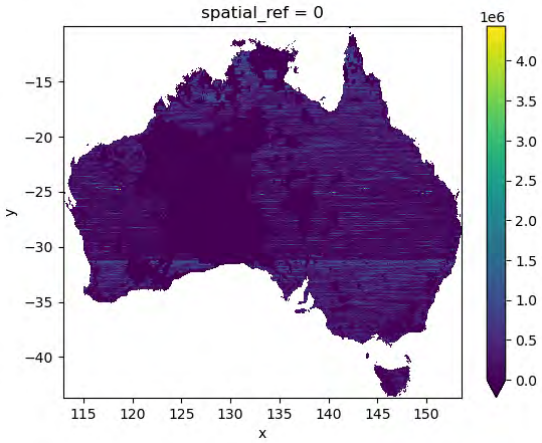

Figure 81 The computed penalties based on the median fire risk

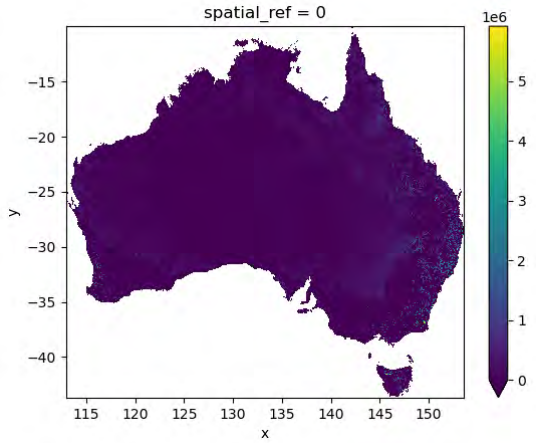

Figure 82 The carbon emission penalty for transition from natural land use to 'Beef - modified land' $\mathbf{CEP}^{\mathrm{NLtoML}}$

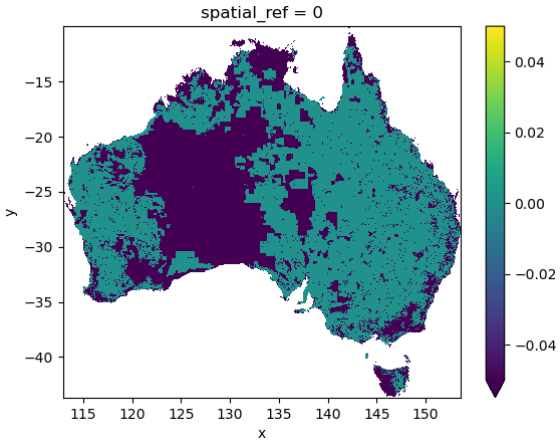

Figure 83 The carbon emission penalty for transition from natural land use to 'Beef - natural land' $\mathbf{CEP}^{\mathrm{NLtoML}}$

3.5. Greenhouse Gas Emission limit

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The greenhouse gas emissions limit in tonnes CO2e for the specified target year is illustrated in Figure 84. This graph is produced using the dataset provided by LUTO 2.0.

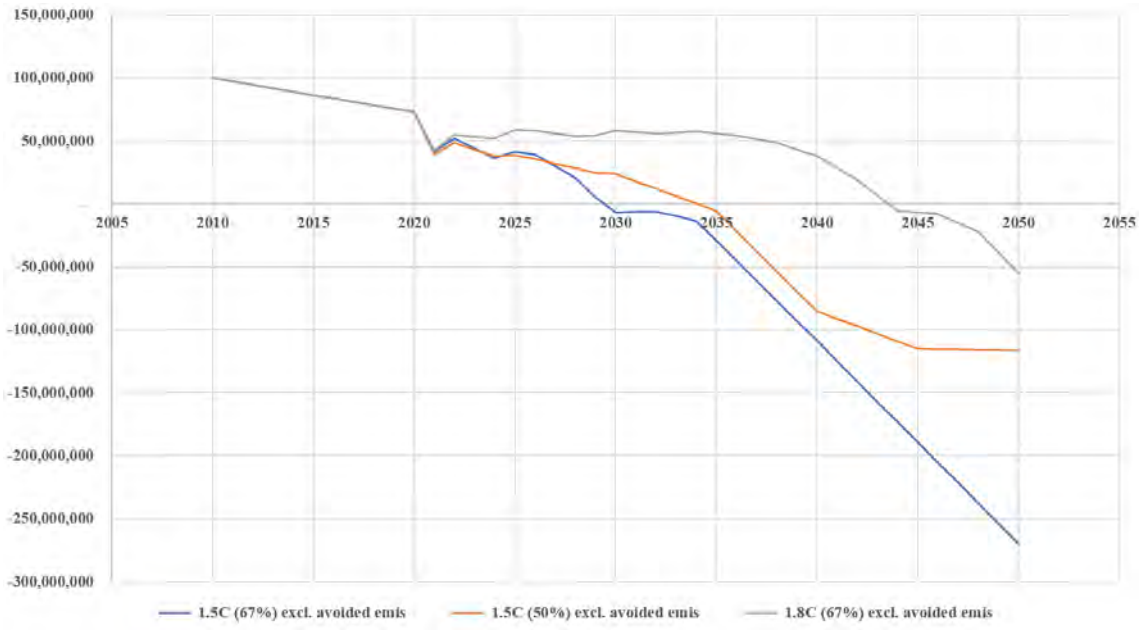

Figure 84 The GHG emissions limits in tonnes CO2e from year target

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4. The impacts of Agricultural Management Practices on the GHG emission of Agricultural Land uses

4.1. Asparagopsis Taxiformis Effects to the GHG emissions for all relevant agricultural land use

In this section the effects of using Asparagopsis taxiformis practice to the GHG data for all relevant agricultural land uses is discussed.

The Asparagopsis taxiformis practice is primarily related to livestock on natural and modified land. The set of classes is called $\phi(\text{Asparagopsis taxiformis})$ which introduced in Equation 25. Therefore, let $\mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}}$ be the updated GHG emission Matrix by integrating Asparagopsis taxiformis into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Asparagopsis taxiformis})$	Equation 94
$\mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{AspTaxifor}}$ is 6, as Asparagopsis taxiformis practice affects beef, sheep, and dairy production across both natural and modified land, $N_{lu} = 6$ (Equation 25).

As mentioned in Equation 79, there are several GHG emission sources from livestock ($S^{\text{Livestock}}$). One of these sources s that affected by implementing Asparagopsis taxiformis practice is $s = \text{'CO2E_KG_HEAD_ENTERIC'}$, $s \in S^{\text{Livestock}}$, which is mapped for the scenario of beef farming in Figure 49. Therefore, here, same as Section 10345021.0.21.1.1, we also employ the same term of $\mathbf{RGHG}_{r\ell s}^{LS}$ to represents the GHG emission of the given source s in $\text{kgCO}_2\text{e/head}$.

By implementing Asparagopsis taxiformis practice, the amount of enteric fermentation emissions ($\mathbf{RGHG}_{r\ell s}^{LS}$) is affected by a multiplier $\delta_{\text{CH}_4}^{\text{AspTaxifor}}(y)$, and , $0.1 \leq \delta_{\text{CH}_4}^{\text{AspTaxifor}}(y) \leq 1$. For example, for $y = 2050$; the values of $\delta_{\text{CH}_4}^{\text{AspTaxifor}}$ are presented in Table 1:

Table 1 The values of $\delta_{CH_4}^{AspTaxifor}(y)$ for all the classes available in $\phi(Asparagopsis\ taxiformis)$ for $y = 2050$

$\phi(\text{Asparagopsis taxiformis})$	Natural Land			Modified Land		
	Beef	Sheep	Dairy	Beef	Sheep	Dairy
$\delta_{\text{CH}_4}^{\text{AspTaxifor}}$	0.52	0.52	0.52	0.51	0.52	0.52

Therefore, for the year y that the value of $\delta_{\text{CH}_4}^{\text{AspTaxifor}}(y) \neq 1$, the amount of enteric fermentation emissions is reduced by $1 - \delta_{\text{CH}_4}^{\text{AspTaxifor}}(y)$ percent.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, s \in S^{\text{Livestock}}\ \exists \ell, \ell \in \phi(\text{Asparagopsis taxiformis}), s = \text{'CO2E_KG_HEAD_ENTERIC'}$	Equation 95
$\mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}}(y) = -\left[\dfrac{\mathbf{RGHG}_{r\ell s}^{LS} \times \mathbf{YPot}_{mr\ell}^{LS}(y) \times \left(1 - \delta_{\text{CH}_4}^{\text{AspTaxifor}}(y)\right) \times \mathbf{RA}_r}{1000}\right]$	

where,

- $\mathbf{YPot}_{mr\ell}^{LS}(y)$ represents the yield potential or the number of heads per hectare (Equation 113 and Figure 117-Figure 128)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{RGHG}_{r\ell s}^{LS}$ represents the GHG emission of the given source s in $\text{kgCO}_2\text{e/head}$ (Figure 49)

For example, The impacts of Asparagopsis taxiformis practice on the GHG emission of Beef - natural land under dry and irrigation land management system are illustrated in Figure 85 and Figure 86; as well as the GHG emission of Beef - modified land under dry and irrigation land management system are illustrated in Figure 87 and Figure 88.

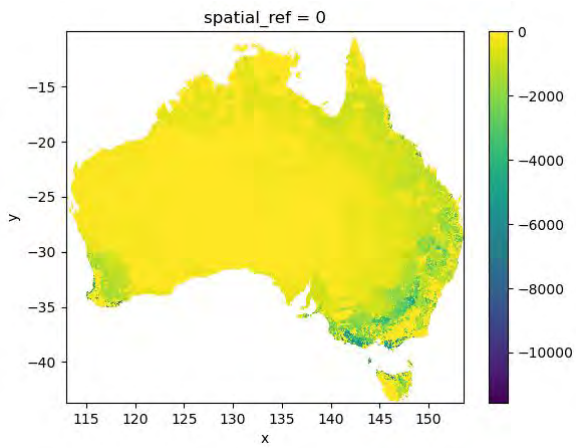


Figure 85 The impacts of Asparagopsis taxiformis practice on the GHG emission of Beef - natural land under dry land management system $\mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}}$

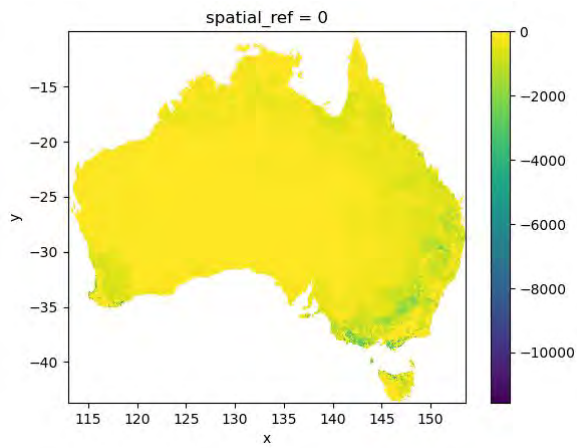
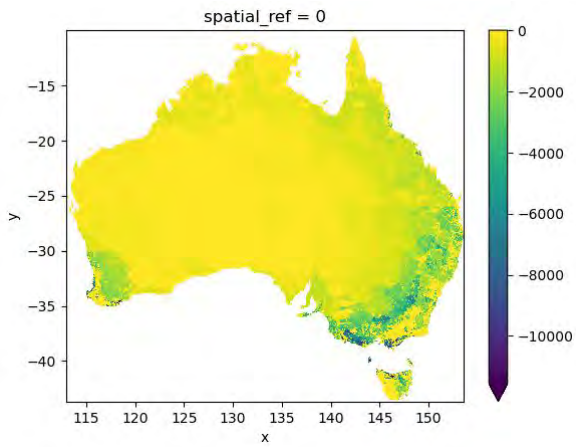


Figure 86 The impacts of Asparagopsis taxiformis practice on the GHG emission of Beef - natural land under irrigation land management system$\mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}}$



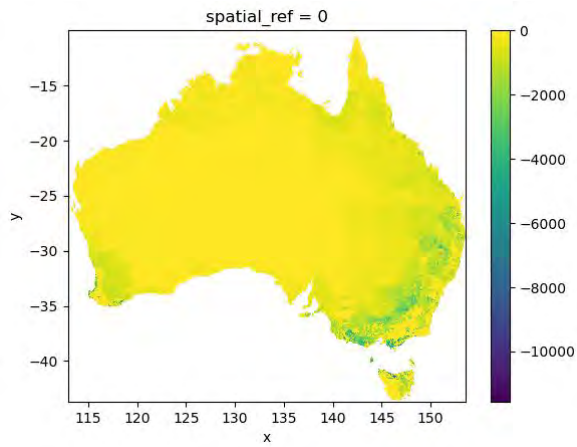


Figure 87 The impacts of Asparagopsis taxiformis practice on the GHG emission of Beef - modified land under dry land management system $\mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}}$	Figure 88 The impacts of Asparagopsis taxiformis practice on the GHG emission of Beef - modified land under irrigation land management system $\mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}}$

4.2. Precision Agriculture Effects to the GHG emissions for all relevant agricultural land use

In this section the effects of using precision agriculture practice to the GHG data for all relevant agricultural land uses is discussed.

The precision agriculture practice is primarily related to integrating precision agriculture into agricultural land management strategies. The set of classes is called $\phi(\text{Precision Agriculture})$ which introduced in Equation 27. Therefore, let $\mathbf{GEG}_{mr\ell}^{\text{PrecAgric}}$ be the updated GHG emission matrix by integrating precision agriculture into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 96
$\mathbf{GEG}_{mr\ell}^{\text{PrecAgric}} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{PrecAgric}}$ is 20, as precision agriculture practice affects 20 land use classes (Equation 27), $N_{lu} = 20$

As mentioned in Equation 76, there are 9 sources for GHG emission of crops (S^{Crops}); where 4 of them are considered as the GHG sources of precision agriculture practice ($S^{\text{PrecAgric}}$), as

$S^{\text{PrecAgric}} = \left\{ \begin{matrix} \text{CO2E_KG_HA_CHEM_APPL, CO2E_KG_HA_CROP_MGT,} \\ \text{CO2E_KG_HA_PEST_PROD,CO2E_KG_HA_SOIL} \end{matrix} \right\}$	Equation 97
$S^{\text{PrecAgric}} \subset S^{\text{Crops}}$	

where,

- CO2E_KG_HA_CHEM_APPL: Greenhouse gas emissions from the application of chemicals (e.g., pesticides, herbicides) per hectare.
- CO2E_KG_HA_CROP_MGT: Greenhouse gas emissions from general crop management practices per hectare.
- CO2E_KG_HA_PEST_PROD: Greenhouse gas emissions from the production of pesticides used in crop production per hectare.
- PROD,CO2E_KG_HA_SOIL: Greenhouse gas emissions from soil management practices, such as soil amendments and treatments.

In the current version of LUTO 2, by implementing precision agriculture practice on all land use classes ℓ, $\ell \in \phi(\text{Precision Agriculture})$, and for all GHG source s, $s \in S^{\text{PrecAgric}}$, the emitted GHG is affected by a

multiplier $\delta_s^{\text{PrecAgric}}(y)$, where $0 < \delta_s^{\text{PrecAgric}}(y) \leq 1$. Moreover, the assigned values to $\delta_s^{\text{PrecAgric}}$ do not change between year 2050-2100 (*Table 2*).

Table 2 The values of $\delta_s^{PrecAgric}(y)$ for all GHG sources $S^{PrecAgric}$, and land use classes $\phi(Precision\ Agriculture)$

$S^{\text{PrecAgric}}$	$\delta_s^{\text{PrecAgric}}$					
	2010	2020	2030	2040	2050	2100
s=CO2E_KG_HA_CHEM_APPL	0.8463	0.7964	0.7657	0.7491	0.7340	0.7340
s=CO2E_KG_HA_CROP_MGT	0.8463	0.7964	0.7657	0.7491	0.7340	0.7340
s=CO2E_KG_HA_PEST_PROD	0.8463	0.7964	0.7657	0.7491	0.7340	0.7340
s=CO2E_KG_HA_SOIL	0.8463	0.7964	0.7657	0.7491	0.7340	0.7340

Therefore, for the year y that the value of $\delta_s^{\text{PrecAgric}}(y) \neq 0$, the amount of GHG emissions is reduced by $1 - \delta_s^{\text{AspTaxifor}}(y)$ percent.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists s, \ell \mid \ell \in \phi(\text{Precision Agriculture}), s \in S^{\text{PrecAgric}}$	Equation 98
$\mathbf{GEG}_{mr\ell}^{\text{PrecAgric}}(y) = -\left[\dfrac{\mathbf{CGHGE}_{m,r,\ell,s}^{AG} \times \left(1 - \delta_s^{\text{PrecAgric}}(y)\right) \times \mathbf{RA}_r}{1000}\right]$	

where,

- $\mathbf{CGHGE}_{m,r,\ell,s}^{AG}$ represents the amount of greenhouse gas emission from each source s, $s \in S^{\text{Crops}}$ for cell r under land management type m which cultivated by crop ℓ, $\ell \in \mathcal{L}_{\text{Crops}}^{\text{GHG}}$ (Figure 38 - Figure 46)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- 1000 is the conversion factor from kg to tonnes.

For example, the impacts of precision agriculture practice on the GHG emission of the winter and summer cereals under dry and irrigation land management systems are illustrated in Figure 89 - Figure 92 .

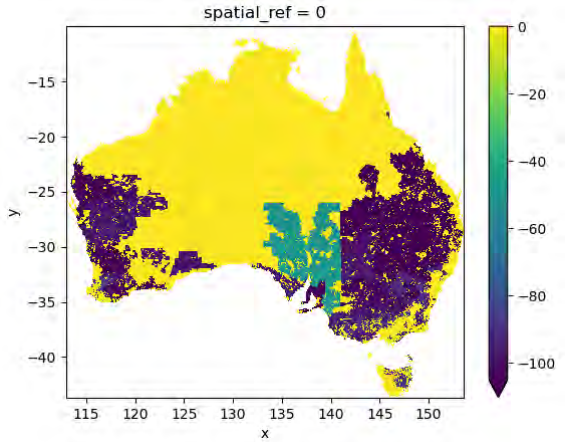


Figure 89 The impacts of precision agriculture practice on the GHG emission of winter cereals under dry land management system$\mathbf{GEG}_{mr\ell}^{\text{PrecAgric}}(y)$

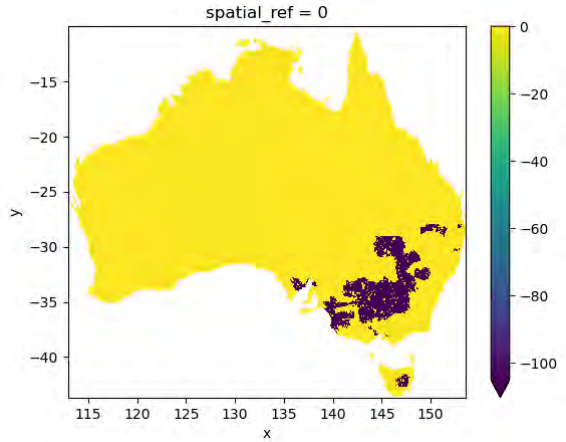


Figure 90 The impacts of precision agriculture practice on the GHG emission of winter cereals under irrigation land management system$\mathbf{GEG}_{mr\ell}^{\text{PrecAgric}}(y)$

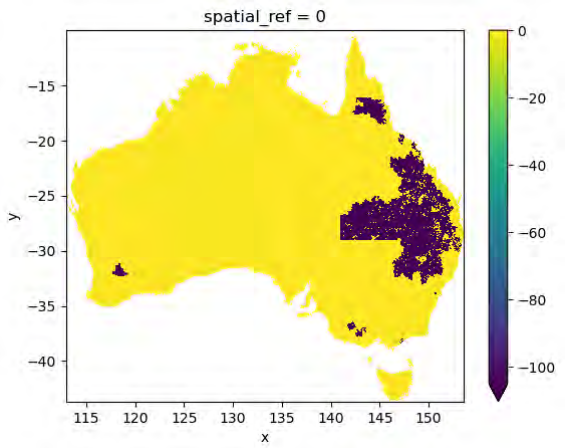


Figure 91 The impacts of precision agriculture practice on the GHG emission of summer cereals under dry land management system$\mathbf{GEG}_{mr\ell}^{\text{PrecAgric}}(y)$

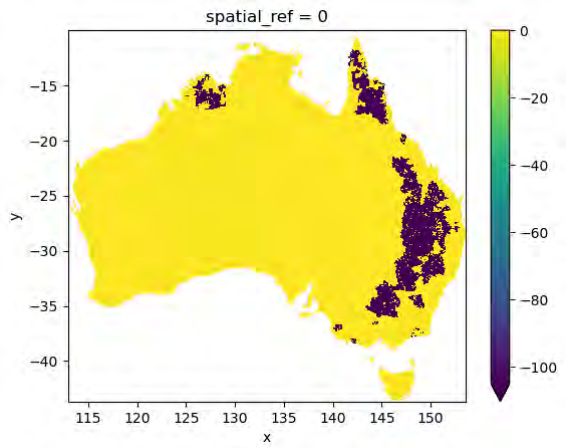


Figure 92 The impacts of precision agriculture practice on the GHG emission of summer cereals under irrigation land management system$\mathbf{GEG}_{mr\ell}^{\text{PrecAgric}}(y)$

4.3. Ecological Grazing Effects to the GHG emissions for all relevant agricultural land use

In this section the effects of using ecological grazing practice to the GHG data for all relevant agricultural land uses is discussed.

The ecological grazing practice is primarily related to livestock on modified land. The set of classes is called $\phi(\text{Ecological Grazing})$ which introduced in Equation 29. Therefore, let $\mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}}$ be the updated GHG emission matrix by implementing ecological grazing practice into livestock on modified land (Figure 95-Figure 100).

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell\ , \ell \in \phi(\text{Ecological Grazing})$	Equation 99

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$\mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{EcolGrazing}}$ is 3, as ecological grazing practice affects beef, sheep, and dairy production across modified land (Equation 29), $N_{lu} = 3$

As mentioned in Equation 79, there are 8 sources for GHG emission of livestock ($S^{\text{Livestock}}$); where one of them, entitled 'CO2E_KG_HEAD_IND_LEACH_RUNOFF', is considered as the GHG sources of ecological grazing practice ($S^{\text{EcolGrazing}}$), as

$S^{\text{EcolGrazing}} = \{\text{CO2E_KG_HEAD_IND_LEACH_RUNOFF}\}$	Equation 100
$S^{\text{EcolGrazing}} \subset S^{\text{Livestock}}$	

where,

- CO2E_KG_HEAD_IND_LEACH_RUNOFF: The greenhouse gas emissions (in kilograms of CO2 equivalent) per head of livestock from indirect leaching and runoff. This includes nitrous oxide (N2O) emissions from nitrogen leached from manure and urine into water bodies.

In the current version of LUTO 2, by implementing ecological grazing practice on livestock farming in modified land ϕ(Ecological Grazing), and for GHG source s, $s \in S^{\text{EcolGrazing}}$, the emitted GHG is affected by a multiplier $\delta_s^{\text{EcolGrazing}}(y)$, where$\delta_s^{\text{EcolGrazing}}(y) = 0.84$. Moreover, the assigned values to $\delta_s^{\text{EcolGrazing}}$ do not change between year 2050-2100.
Therefore, for the year y that the value of $\delta_{\text{CH}_4}^{\text{EcolGrazing}}(y) \neq 0$, the amount of GHG emission by leaching is reduced by $1 - \delta_s^{\text{EcolGrazing}}(y)$ percent.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, s \in S^{\text{EcolGrazing}}\ \exists s, \ell \mid \ell \in \phi(\text{Ecological Grazing}), s = \text{'CO2E_KG_HEAD_IND_LEACH_RUNOFF'}$	Equation 101
$\mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}}(y) = -\left[\dfrac{\mathbf{RGHG}_{r\ell s}^{LS} \times \mathbf{YPot}_{mr\ell}^{LS}(y) \times \left(1 - \delta_{\text{CH}_4}^{\text{AspTaxifor}}(y)\right) \times \mathbf{RA}_r}{1000}\right] - \mathbf{SCB}_r^{\text{EcolGrazing}}(y)$	

where,

- $\mathbf{YPot}_{mr\ell}^{LS}(y)$ represents the yield potential or the number of heads per hectare (Equation 113 and Figure 117-Figure 128)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{RGHG}_{r\ell s}^{LS}$ represents the GHG emission of the given source s in $\text{kgCO}_2\text{e/head}$ (Figure 49)
- $\mathbf{SCB}_r^{\text{EcolGrazing}}(y)$ represents the soil carbon benefit (Equation 102, and Figure 94)
- 1000 is the conversion factor from kg to tonnes.

As Ecological grazing practice has impacts on the average amount of soil carbon $\mathbf{SCA}_r$(Figure 93); hence $\mathbf{SCB}_r^{\text{EcolGrazing}}(y)$must be computed (Figure 94). This procedure requires a multiplier $\delta_s^{\text{SCI}}(y)$ which represents the impacts of ecological grazing practice on soil carbon.

$\forall r \in \{1, \dots, N_r\}, s \in S^{\text{EcolGrazing}}\ \exists \delta_s^{\text{SCI}}\ \lvert \delta_s^{\text{SCI}} \neq 1$	Equation 102
$\mathbf{SCB}_r^{\text{EcolGrazing}}(y) = -\left[\frac{\mathbf{SCA}_r \times (\delta_s^{\text{SCI}} - 1) \times \mathbf{RA}_r}{1000}\right]$	

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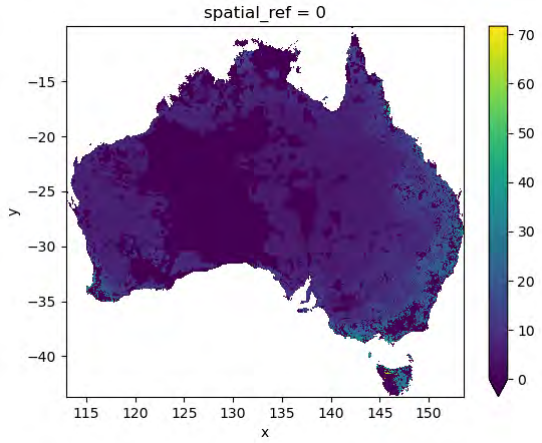


Figure 93 The average of soil carbon $\mathbf{SCA}_r$

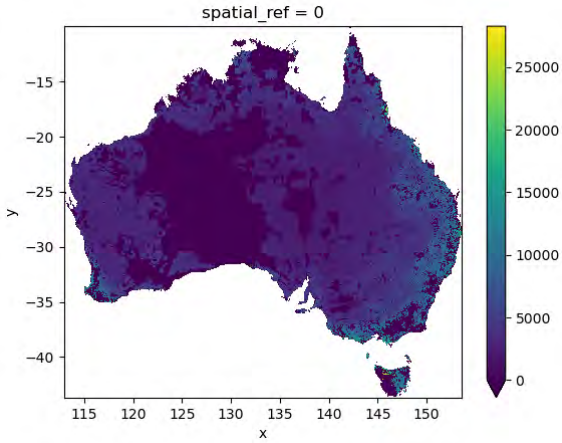


Figure 94 soil carbon benefit for 2050 $\mathbf{SCB}_r^{\mathrm{EcolGrazing}}(y)$

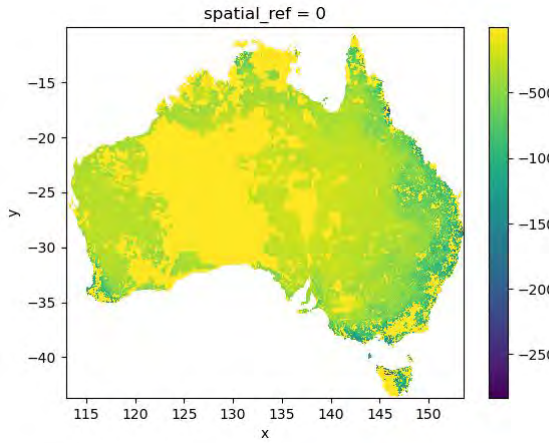


Figure 95 The impacts of ecological grazing practice on the GHG emission of Beef-modified land under dry land management $\mathbf{GEG}_{mr\ell}^{\mathrm{EcolGrazing}}(y)$

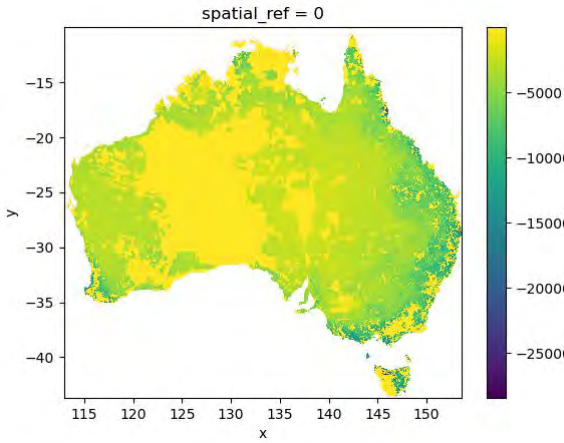
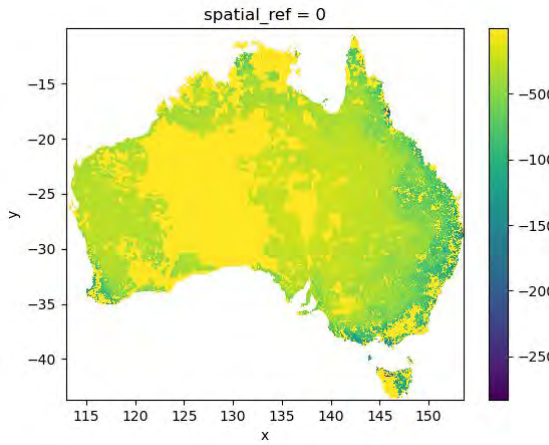


Figure 96 The impacts of ecological grazing practice on the GHG emission of Beef-modified land under irrigation land management $\mathbf{GEG}_{mr\ell}^{\mathrm{EcolGrazing}}(y)$



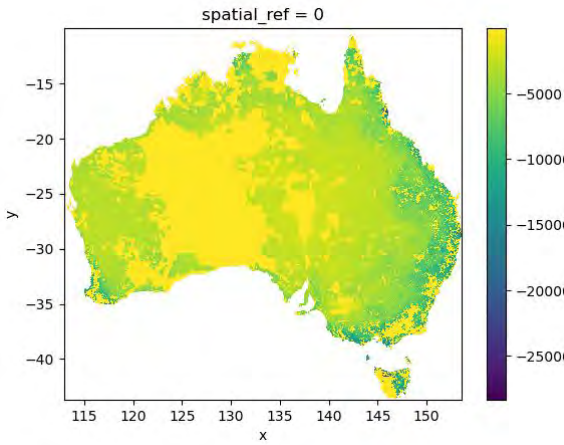


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Figure 97 The impacts of ecological grazing practice on the GHG emission of Sheep-modified land under dry land management $\mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}}(y)$	Figure 98 The impacts of ecological grazing practice on the GHG emission of Sheep-modified land under irrigation land management $\mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}}(y)$
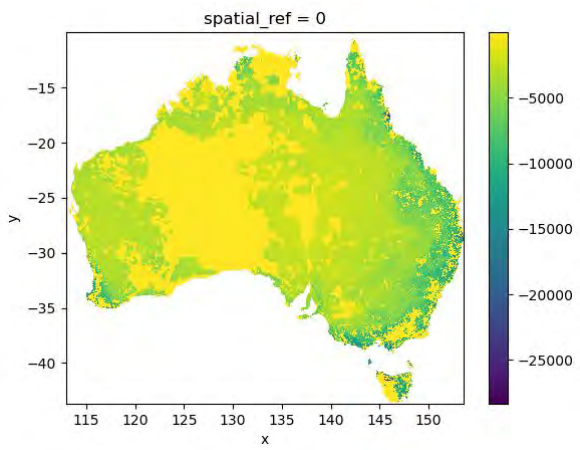	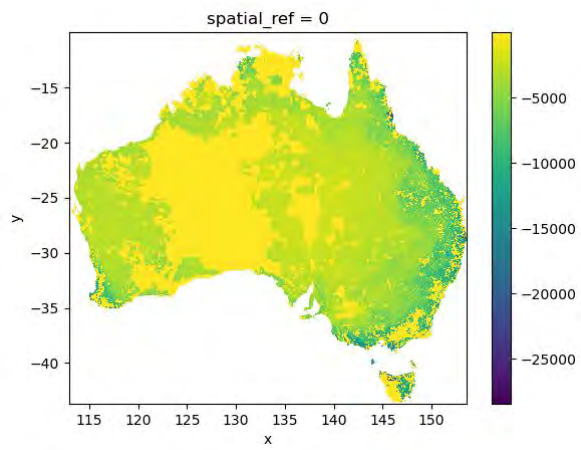
Figure 99 The impacts of ecological grazing practice on the GHG emission of Dairy-modified land under dry land management $\mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}}(y)$	Figure 100 The impacts of ecological grazing practice on the GHG emission of Dairy-modified land under irrigation land management $\mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}}(y)$

4.4. Savanna Burning Effects to the GHG emissions for all relevant agricultural land use

In this section the effects of using Savanna burning practice to the GHG data for all relevant agricultural land uses is discussed.

The Savanna burning practice is primarily related to livestock on natural land as well as unallocated-natural land. The set of classes is called $\phi(\text{Savanna Burning})$ which introduced in Equation 31. Therefore, let $\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}$ be the updated GHG emission matrix by implementing Savanna burning practice into livestock and unallocated natural land.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 103
$\mathbf{GEG}_{mr\ell}^{\text{SavBurn}} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- N_{lu}^{SavBurn} is 4, as Savanna burning practice affects beef, sheep, and dairy production across natural land as well as unallocated-natural land (Equation 31), $N_{lu} = 4$

Let $\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}$ be the updated GEG emission matrix by integrating Savana burning into livestock on natural land as well as unallocated-natural land management strategies.

In the current version of LUTO 2, by implementing Savana burning practice on the classes available in $\phi(\text{Savanna Burning})$, the emitted GHG do not change between year 2050-2100.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 104
$\mathbf{GEG}_{mr\ell}^{\text{SavBurn}} = \begin{cases} \mathbf{TotCO2e}_r^{\text{SavBurn}} \times \mathbf{RA}_r & \text{If Savana burning is eligible} \\ 0 & \text{otherwise} \end{cases}$	

where,

- $\mathbf{TotCO2e}_r^{\text{SavBurn}}$ is the total CO2e that can be produced by Savanna burning in each cell
- $\mathbf{RA}_r$ represents the real area (Figure 5)

$\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}(y)$ represent the real values, just for the cells that Savana burning is eligible (Figure 35). The other pixels assigned a value as 0.

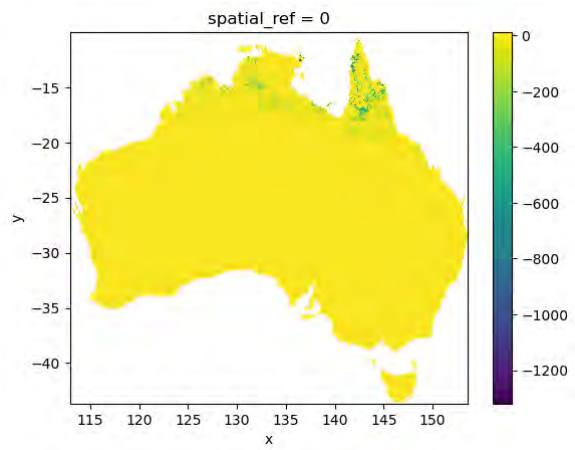

Figure 101 The impacts of Savana burning practice on the GHG emission of Beef-natural land under dry and irrigated land management $\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}$

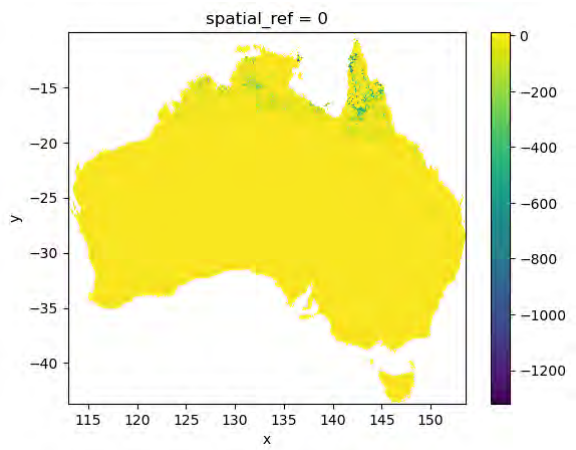

Figure 102 The impacts of Savana burning practice on the GHG emission of Sheep-natural land under dry and irrigated land management $\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}$

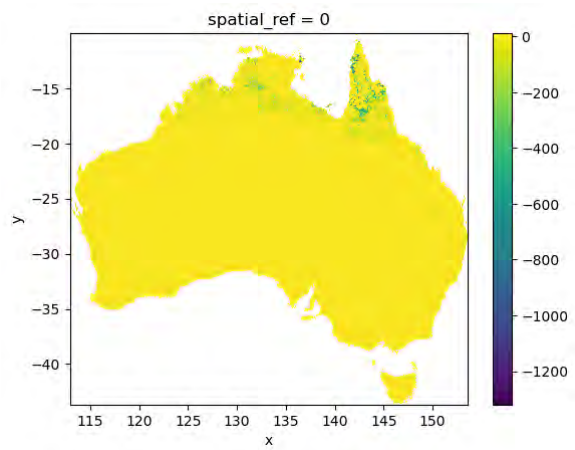

Figure 103 The impacts of Savana burning practice on the GHG emission of Dairy-natural land under dry and irrigated land management $\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}$

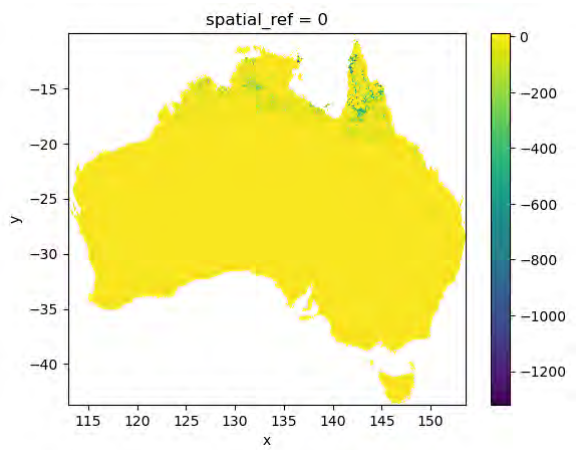

Figure 104 The impacts of Savana burning practice on the GHG emission of Unallocated-natural land under dry land management $\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}$

4.5. AgTech EI Effects to the GHG emissions for all relevant agricultural land use

This section examines the effects of applying AgTech EI (AgTech Emission-Intelligent) practices on greenhouse gas (GHG) emissions across all relevant agricultural land uses. Specifically, we consider the integration of AgTech EI into broader agricultural land management strategies and evaluate how it modifies the emissions profile of these systems.

The AgTech EI practice is conceptualised as a framework for incorporating advanced agricultural technologies into management decisions, aimed at reducing emissions and improving efficiency. We define a corresponding set of land use classes, denoted as $\phi(\text{AgTech EI})$, as introduced in Equation 33.

Let $\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}$ represent the updated GHG emission matrix after applying AgTech EI practices across land use categories defined by management region mmm, land use type r, and land class ℓ. This matrix reflects the emission reductions or changes resulting from AgTech EI integration.

Additionally, we define $\mathbf{GEGIrr}_{mr\ell}^{\text{AgTech EI}}$ as a matrix of the same dimensions as $\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}$, representing GHG emissions under irrigated conditions where AgTech EI practices are applied.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 105
$\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}} = 0_{(N_k \times N_c \times N_{lu})}$	
$\mathbf{GEGIrr}_{mr\ell}^{\text{AgTech EI}} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{AgTech EI}}$ is 20, as AgTech EI practice affects 20 land use classes (Equation 33), $N_{lu} = 20$

As mentioned in Equation 76, there are 9 sources for GHG emission of crops (S^{Crops}); where, same precision agriculture Equation 97, 4 of them are considered as the GHG sources of AgTech EI practice under dry land management system ($S_{\text{Dry}}^{\text{AgTech EI}}$), and 5 of them are considered as the GHG sources of AgTech EI practice under irrigation land management system ($S_{\text{Irrigation}}^{\text{AgTech EI}}$), as:

$S_{\text{Dry}}^{\text{AgTech EI}} = \left\{\begin{matrix}\text{CO2E_KG_HA_CHEM_APPL, CO2E_KG_HA_CROP_MGT,} \\ \text{CO2E_KG_HA_PEST_PROD,CO2E_KG_HA_SOIL}\end{matrix}\right\}$	Equation 106
$S_{\text{Irrigation}}^{\text{AgTech EI}} = \left\{\begin{matrix}\text{CO2E_KG_HA_CHEM_APPL, CO2E_KG_HA_CROP_MGT,} \\ \text{CO2E_KG_HA_PEST_PROD,CO2E_KG_HA_SOIL,CO2e_KG_HA_IRRIG}\end{matrix}\right\}$	Equation 107
$S_{\text{Dry}}^{\text{AgTech EI}} \subset S_{\text{Irrigation}}^{\text{AgTech EI}} \subset S^{\text{Crops}}$	

where,

- CO2E_KG_HA_CHEM_APPL: Greenhouse gas emissions from the application of chemicals (e.g., pesticides, herbicides) per hectare.

- CO2E_KG_HA_CROP_MGT: Greenhouse gas emissions from general crop management practices per hectare.
- CO2E_KG_HA_PEST_PROD: Greenhouse gas emissions from the production of pesticides used in crop production per hectare.
- PROD,CO2E_KG_HA_SOIL: Greenhouse gas emissions from soil management practices, such as soil amendments and treatments.
- CO2E_KG_HA_IRRIG: Greenhouse gas emissions from irrigation practices per hectare.

In the current version of LUTO 2, by implementing AgTech EI practice on all land use classes ℓ, $\ell \in \phi(\text{AgTech EI})$, and for all GHG source s, $s \in S_{\text{Dry}}^{\text{AgTech EI}}$, and $s \in S_{\text{Irrigation}}^{\text{AgTech EI}}$, the emitted GHG is affected by a multiplier $\delta_{\text{s}}^{\text{AgTech EI}}(y)$, where $0 < \delta_{\text{s}}^{\text{AgTech EI}}(y) \leq 1$. Moreover, the assigned values to $\delta_{\text{s}}^{\text{AgTech EI}}$ do not change between year 2050-2100 (Table 3).

Table 3 The values of $\delta_{s}^{AgTech\ EI}(y)$ for all GHG sources $s \in S_{Dry}^{AgTech\ EI}$, and $s \in S_{Irrigation}^{AgTech\ EI}$, and land use classes $\phi(AgTech\ EI)$

$S_{\text{Dry}}^{\text{AgTech EI}}$ and $S_{\text{Irrigation}}^{\text{AgTech EI}}$	$\delta_{\text{s}}^{\text{AgTech EI}}$					
	2010	2020	2030	2040	2050	2100
s=CO2E_KG_HA_CHEM_APPL	0.8658	0.8658	0.8522	0.8336	0.8192	0.8192
s=CO2E_KG_HA_CROP_MGT	0. 8658	0. 8658	0. 8522	0. 8336	0. 8192	0. 8192
s=CO2E_KG_HA_PEST_PROD	0.8533	0. 8533	0.8397	0.8211	0.8067	0. 8067
s=CO2E_KG_HA_SOIL	0.6322	0. 6322	0.6185	0.5999	0.5855	0. 5855
s=CO2e_KG_HA_IRRIG	0.5178	0.5178	0.4729	0.4118	0.3643	0.3643

As mentioned above, updating $\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}$ values depend to the land management system $m \in \{0,1\}$. In the case of land use classes which are under dry land management system ($m \in \{0\}$), for the year y that the value of $\delta_{\text{s}}^{\text{AgTech EI}}(y) \neq 0$, the amount of GHG emissions is reduced by $1 - \delta_{\text{s}}^{\text{AgTech EI}}(y)$ percent, as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}\ \exists s, \ell \mid \ell \in \phi(\text{AgTech EI}), s \in S_{\text{Dry}}^{\text{AgTech EI}}$	Equation 108
$\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}(y) = -\left[\dfrac{\mathbf{CGHGE}_{m,r,\ell,s}^{AG} \times \left(1 - \delta_{\text{s}}^{\text{AgTech EI}}(y)\right) \times \mathbf{RA}_r}{1000}\right]$	

where,

- $\mathbf{CGHGE}_{m,r,\ell,s}^{AG}$ represents the amount of greenhouse gas emission from each source s, $s \in S^{\text{Crops}}$ for cell r under land management type m which cultivated by crop ℓ, $\ell \in \mathcal{L}_{\text{Crops}}^{\text{GHG}}$ (Figure 38 - Figure 46)

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- $\mathbf{RA}_r$ represents the real area (Figure 5)
- 1000 is the conversion factor from kg to tonnes.

The $\mathbf{CGHGE}^{AG}_{m,r,\ell,s}$ maps for different GHG source of $S^{\text{AgTech EI}}_{\text{Irrigation}}$ for winter cereals under dry land management system are presented in Figure 38, Figure 39, Figure 41, Figure 43, and Figure 45.

As Equation 106 and Equation 107 show, $S^{\text{AgTech EI}}_{\text{Irrigation}}$ has all the members of $S^{\text{AgTech EI}}_{\text{Dry}}$ as well as a GHG emission source of CO2e_KG_HA_IRRIG. Therefore, in the case of cells that are under irrigation land management system, and $\ell_{mr} \in \phi(\text{AgTech EI})$, the computed $\mathbf{GEG}^{\text{AgTech EI}}_{mr\ell}(y)$ in Equation 108 must be updated based on GHG source of CO2e_KG_HA_IRRIG. For this purpose, we update $\mathbf{GEGIrr}^{\text{AgTech EI}}_{mr\ell}$ that was also initialized in Equation 105.

Same as Equation 108, in the case of land use classes which are under irrigation land management system ($m \in \{1\}$), for the year y, that the value of $\delta^{\text{AgTech EI}}_{\text{s}}(y) \neq 0$, the amount of GHG emissions is also reduced by $1 - \delta^{\text{AgTech EI}}_{\text{s}}(y)$ percent. Therefore, for each given cell r which is under irrigation land management system, $\delta^{\text{AgTech EI}}_{\text{s}}(y)$ of 'CO2e_KG_HA_IRRIG' is used to compute $\mathbf{GEGIrr}^{\text{AgTech EI}}_{mr\ell}(y)$ that represents the effects of using Irrigation in AgTech EI practice to the GHG data for all relevant agricultural land uses, as:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, s \in S^{\text{AgTech EI}}_{\text{Irrigation}}\ \exists s, \ell \mid \ell \in \phi(\text{AgTech EI}), \text{s=CO2e_KG_HA_IRRIG}$	Equation 109
$\mathbf{GEGIrr}^{\text{AgTech EI}}_{mr\ell}(y) = \left[\dfrac{\mathbf{CGHGE}^{AG}_{m,r,\ell,s} \times \left(1 - \delta^{\text{AgTech EI}}_{\text{s}}(y)\right) \times \mathbf{RA}_r}{1000}\right]$	

As the cells under irrigation land management system are $S^{\text{AgTech EI}}_{\text{Dry}}$ sources and the source of CO2e_KG_HA_IRRIG; therefore, the computed $\mathbf{GEG}^{\text{AgTech EI}}_{mr\ell}(y)$ values for irrigated cells should be updated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell \mid \ell \in \phi(\text{AgTech EI})$	Equation 110
$\mathbf{GEG}^{\text{AgTech EI}}_{mr\ell}(y) = \mathbf{GEG}^{\text{AgTech EI}}_{mr\ell}(y) - \mathbf{GEGIrr}^{\text{AgTech EI}}_{mr\ell}(y)$	

The $\mathbf{GEG}^{\text{AgTech EI}}_{mr\ell}$ maps for Winter and Summer Cereals under Dry and irrirrigation Land management system for year 2050 are presented in Figure 105 - Figure 108.

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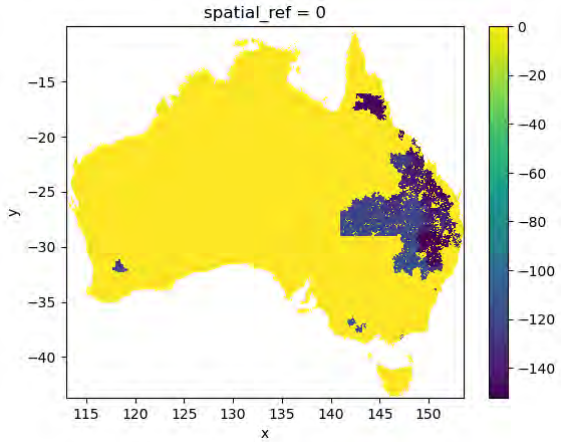

Figure 105 The impacts of AgTech EI practice on the GHG emission of summer Ccereals under dry land management $\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}$

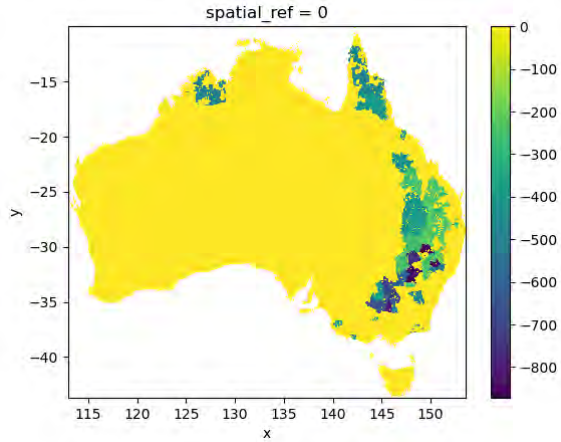

Figure 106 The impacts of AgTech EI practice on the GHG emission of summer cereals under irrigation land management $\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}$

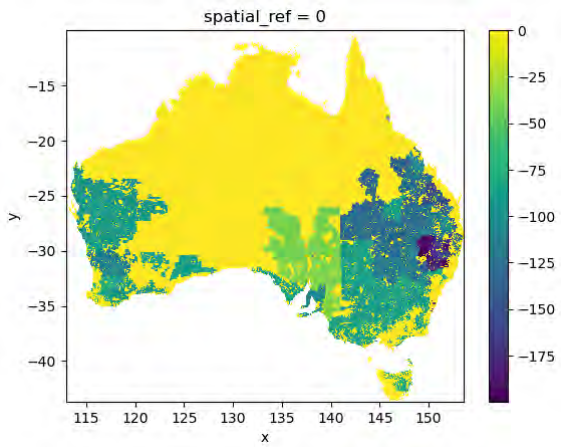

Figure 107 The impacts of AgTech EI practice on the GHG emission of winter cereals under dry land management $\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}$

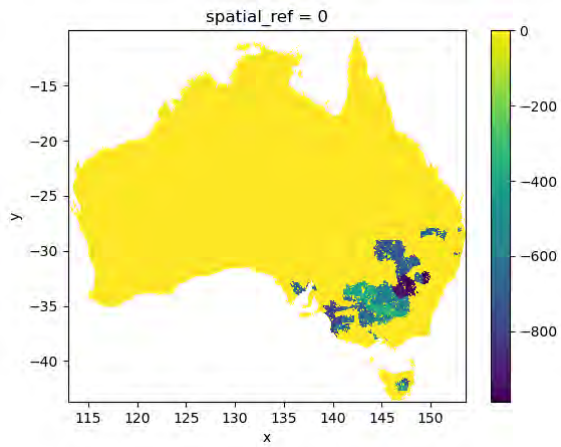

Figure 108 The impacts of AgTech EI practice on the GHG emission of winter cereals under irrigation land management $\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}$

4.6. Agricultural Management Practices Effects to the GHG for all relevant agricultural land use

Define the variable $\mathbf{GEG}^{\text{AGMP}}$, which represents a dictionary of agricultural management practice GHG variable that maps keys k to value $\mathbf{GEG}_{mr\ell}^{k}$, as:

$$\mathbf{GEG}^{\text{AGMP}} = \left\{ k \rightarrowtail \mathbf{GEG}_{mr\ell}^{k}(y) | r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}, \mathbf{GEG}_{mr\ell}^{k}(y) \in \mathbb{R}^{N_k \times N_c \times N_{lu}^{k}} \right\} \quad \text{Equation 111}$$

where,

- $\mathcal{K}$ is the set lists agricultural management practices that can be applied to different land use types (Equation 22)

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- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- N_{lu}^{k} represents the number of land-use in each of the agricultural management practices $\mathcal{K}$ (Equation 24-Equation 32)
- $\mathbb{R}$ represents the real number
- $\mathbf{GEG}_{mr\ell}^{k}(y)$ is the Updated GHG Matrix by integrating k-th agricultural management practice.

Regarding the agricultural management practices, $\mathcal{K}$ is the set lists agricultural management practices that can be applied to different land use types (Equation 22). As mentioned in Equation 23, there is a rule or mapping ϕ that relates elements from the set of agricultural management practices (the domain $\mathcal{K}$) to the set of land uses $\mathcal{L}$ (Equation 1) that are relevant or applicable to that practice. The practices related to each agricultural management practices are mentioned in Equation 24-Equation 32.

Then, the initialized $\mathbf{GEG}^{\text{AGMP}}$ (Equation 111) is updated, as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists k\ , k \in \mathcal{K}$	Equation 112
$\mathbf{GEG}^{\text{AGMP}}(y) = \left\{ \begin{array}{lll} k \rightarrowtail \mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}}(y) & if & k \in \phi(\text{Asparagopsis taxiformis}) \\ k \rightarrowtail \mathbf{GEG}_{mr\ell}^{\text{PrecAgric}}(y) & if & k \in \phi(\text{Precision Agriculture}) \\ k \rightarrowtail \mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}}(y) & if & k \in \phi(\text{Ecological Grazing}) \\ k \rightarrowtail \mathbf{GEG}_{mr\ell}^{\text{SavBurn}}(y) & if & k \in \phi(\text{Savanna Burning}) \\ k \rightarrowtail \mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}(y) & if & k \in \phi(\text{AgTech EI}) \end{array} \right\}$	

where,

- $\mathcal{K}$ is the set lists agricultural management practices that can be applied to different land use types (Equation 22)
- k *is* the agricultural management practice type
- $\mathbf{GEG}_{mr\ell}^{\text{AspTaxifor}}(y)$ is the updated GHG matrix by integrating Asparagopsis taxiformis into agricultural land management strategies (Equation 95)
- $\mathbf{GEG}_{mr\ell}^{\text{PrecAgric}}(y)$ is the updated GHG matrix by integrating precision agriculture into agricultural land management strategies (Equation 98)
- $\mathbf{GEG}_{mr\ell}^{\text{EcolGrazing}}(y)$ is the updated GHG matrix by integrating ecological grazing into agricultural land management strategies (Equation 101)
- $\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}(y)$ is the updated GHG matrix by integrating Savanna burning into agricultural land management strategies (Equation 104)
- $\mathbf{GEG}_{mr\ell}^{\text{AgTech EI}}(y)$ is the updated GHG matrix by integrating AgTech EI into agricultural land management strategies (Equation 110)
- $\phi(\text{Asparagopsis taxiformis})$ is the Asparagopsis taxiformis practice that primarily affecting livestock on natural and modified land (Equation 25)
- $\phi(\text{Precision Agriculture})$ is the precision agriculture practice that primarily applied to cropping, intensive cropping, and horticulture (Equation 27)
- $\phi(\text{Ecological Grazing})$ is the ecological grazing practice that primarily applied to livestock on modified land (Equation 29)
- $\phi(\text{Savanna Burning})$ is the Savanna burning practice that primarily related to livestock on natural land, as well as unallocated natural land (Equation 31)

- $\phi(\text{AgTech EI})$ is the AgTech EI practice that primarily affecting cropping, intensive cropping, and horticulture (Equation 33)

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5. The Quantity

5.1. Yield Potential for Livestock

The yield potential for livestock (head per hectare) is given by:

$$\mathbf{YPot}_{mr\ell}^{LS}(y) = \frac{\mathbf{FR}_r^{LS} \times \mathbf{DMP}_r^{Pasture} \times \mathbf{SUR}_{r\ell}^{Pasture} \times \mathbf{CCIM}_{mr\ell}^{LS}(y) \times IrF_m^{LS}}{365 \times DSE_\ell^{LS} \times \emptyset_\ell^{LS}}$$	Equation 113

where,

- $\mathbf{FR}_r^{LS}$ represents feed requirements (Figure 109).
- $\mathbf{DMP}_r^{Pasture}$ denotes estimated dry matter production by pasture per hectare (Figure 110).
- $\mathbf{SUR}_{r\ell}^{Pasture}$ is the safe pasture utilization rate (Figure 111 and Figure 112), defined as:
$$\mathbf{SUR}_{r\ell}^{Pasture} = \begin{cases} \mathbf{SUR}_{\ell=NL}^{Pasture} & \text{if } \ell = \text{Natural Land} \\ \mathbf{SUR}_{\ell=ML}^{Pasture} & \text{if } \ell = \text{Modified Land} \end{cases}$$
- DSE_ℓ^{LS} is the dry sheep equivalents (DSE) per livestock type (Table 4).
- $\emptyset_\ell^{LS}$ is the grass-fed factor per livestock type (Table 5).
- $\mathbf{CCIM}_{mr\ell}^{LS}(y)$ represents the climate change impact multiplier (Figure 113-Figure 116)
- IrF_m^{LS} is the irrigation factor, defined as:
$$IrF_m^{LS} = \begin{cases} 2, & \text{if } m = \text{Irrigation} \\ 1, & \text{otherwise} \end{cases}$$

Table 4 Dry sheep equivalents (DSE_ℓ^{LS}) per head by livestock type

Livestock type	Beef	Sheep	Dairy
DSE_ℓ^{LS}	8	1.5	7

Table 5 Grass-fed factor ($\emptyset_\ell^{LS}$) per head based by livestock type

Livestock type	Beef	Sheep	Dairy
$\emptyset_\ell^{LS}$	0.85	0.85	0.65

The computed yield potential for different livestock types on both natural land and modified land under dry and irrigation land management system is illustrated in Figure 117-Figure 128.

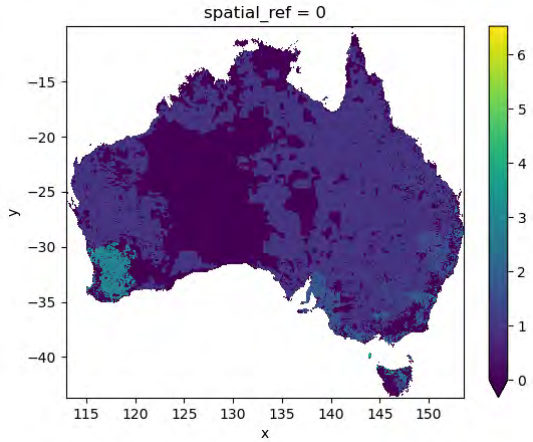

Figure 109 Feed requirements $\mathbf{FR}_r^{LS}$

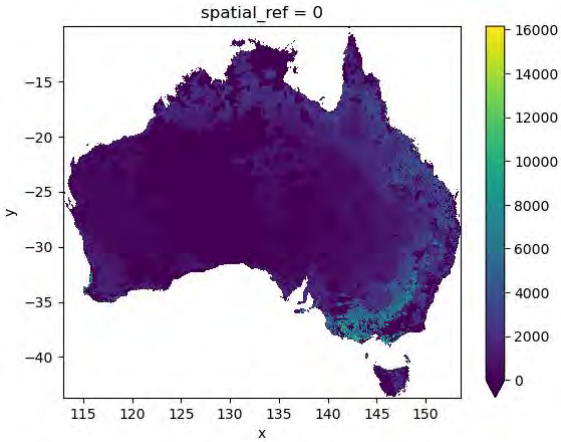

Figure 110 Estimated dry matter production by pasture per hectare $\mathbf{DMP}_r^{Pasture}$

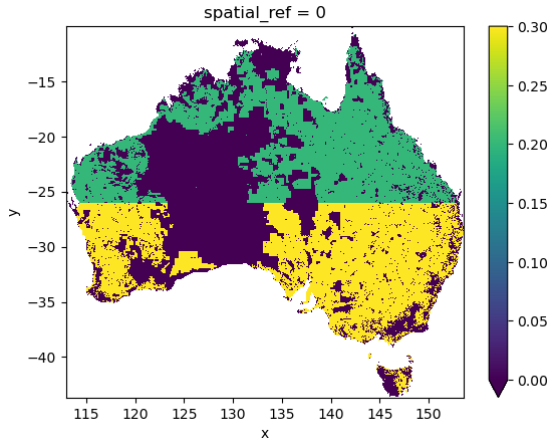

Figure 111 Safe pasture utilization rate for natural land $\mathbf{SUR}_{\ell=NL}^{Pasture}$

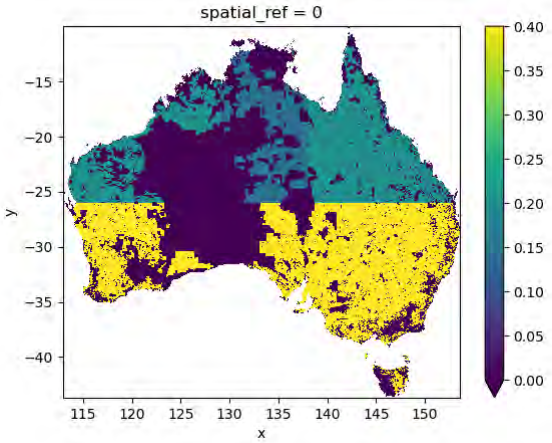

Figure 112 Safe pasture utilization rate for modified land $\mathbf{SUR}_{\ell=ML}^{Pasture}$

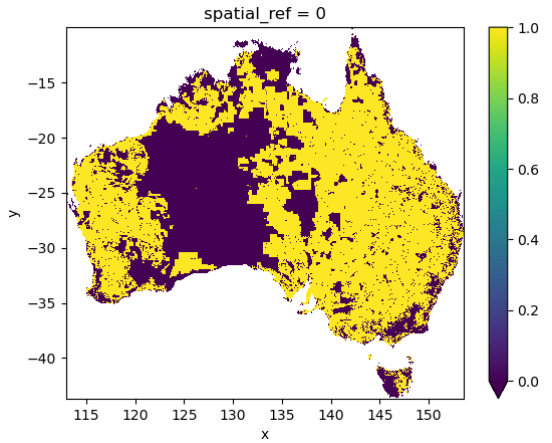

Figure 113 Climate change yield impact multiplier on Beef -Natural Land under irrigation land management system $\mathbf{CCIM}_{mr\ell}^{LS}(y)$

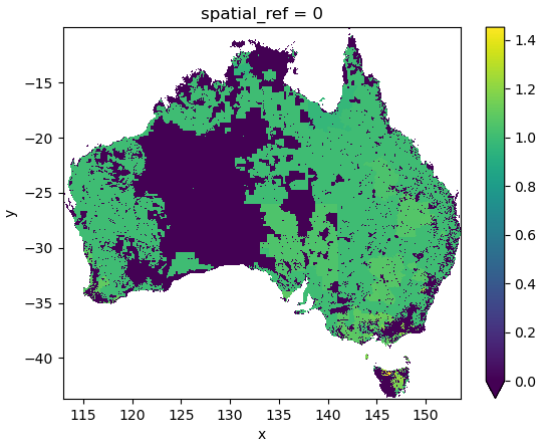

Figure 114 Climate change yield impact multiplier on Beef -Modified Land under irrigation land management system$\mathbf{CCIM}_{mr\ell}^{LS}(y)$

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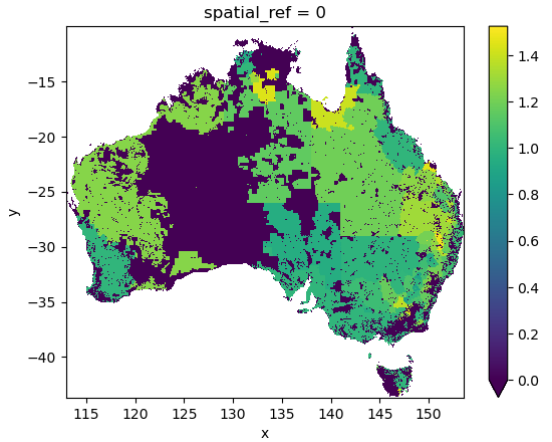

Figure 115 Climate change yield impact multiplier on Beef -Natural Land under dry land management system $\mathbf{CCIM}_{mr\ell}^{LS}(y)$

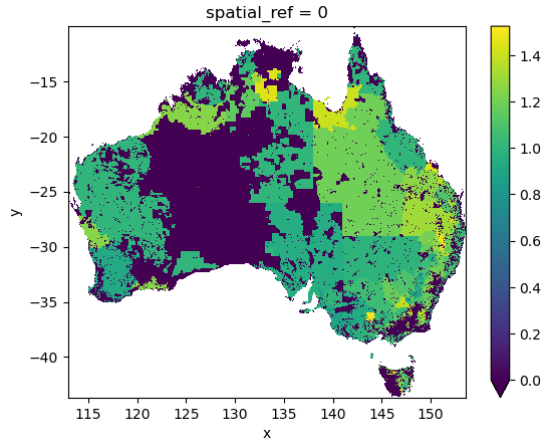

Figure 116 Climate change yield impact multiplier on Beef -Modified Land under dry land management system $\mathbf{CCIM}_{mr\ell}^{LS}(y)$

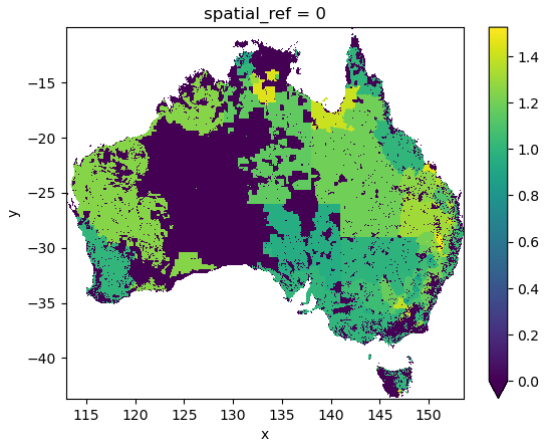

Figure 117 Yield potential of Beef -Natural Land under dry land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

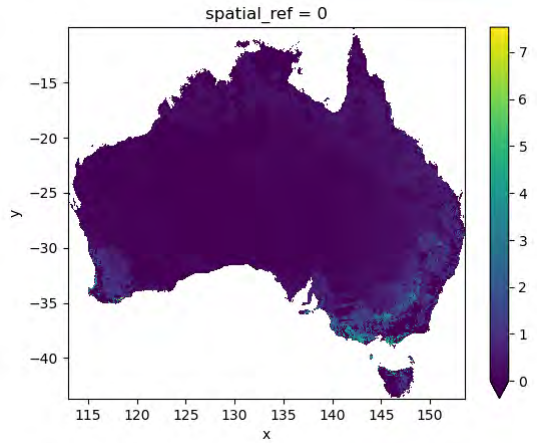

Figure 118 Yield potential of Beef -Natural Land under irrigation land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

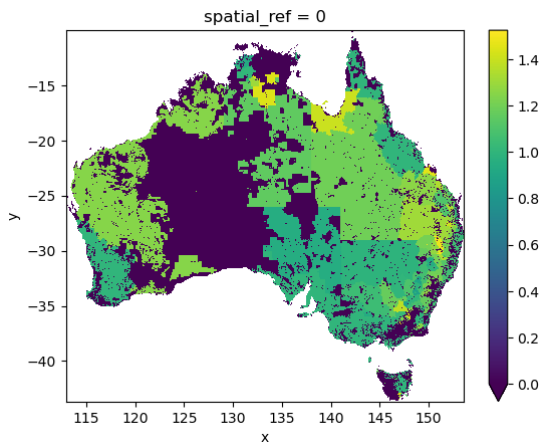

Figure 119 Yield potential of Beef -Modified Land under dry land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

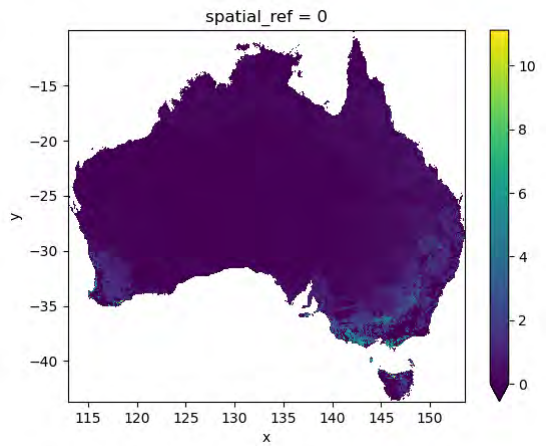

Figure 120 Yield potential of Beef -Modified Land under irrigation land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

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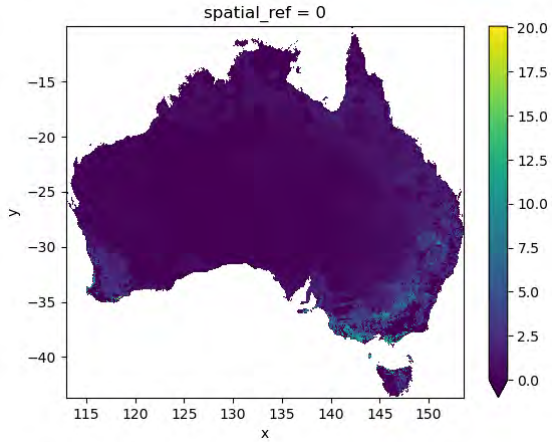

Figure 121 Yield potential of Sheep -Natural Land under dry land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

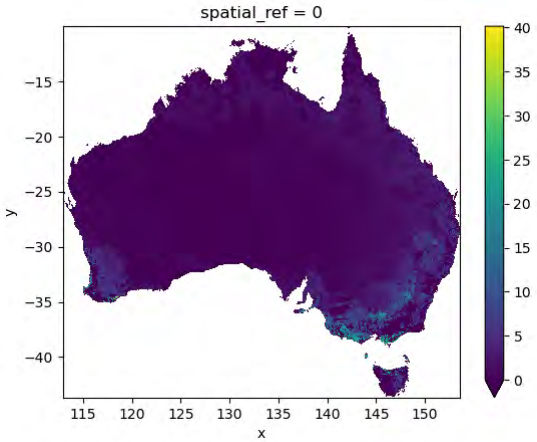

Figure 122 Yield potential of Sheep -Natural Land under irrigation land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

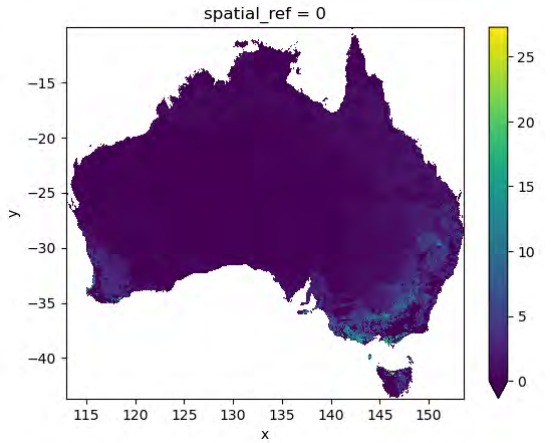

Figure 123 Yield potential of Sheep -Modified Land under dry land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

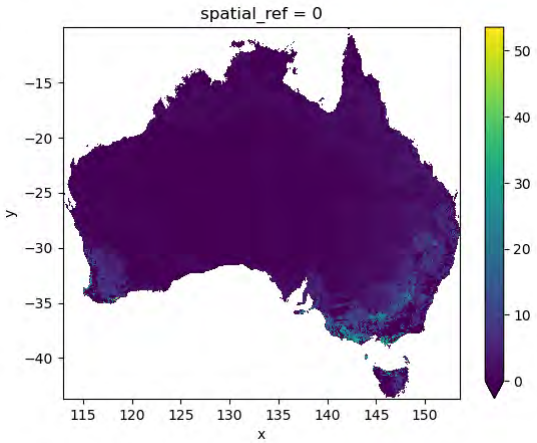

Figure 124 Yield potential of Sheep -Modified Land under irrigation land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

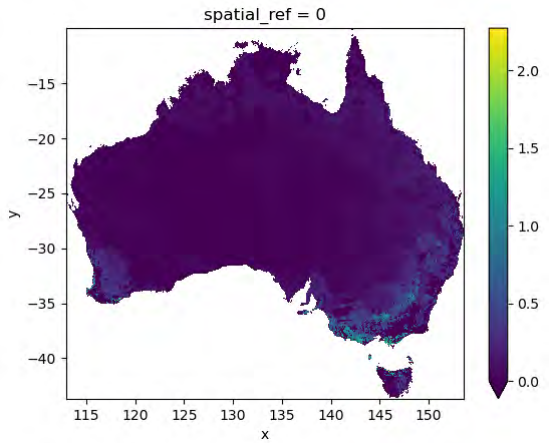

Figure 125 Yield potential of Dairy -Natural Land under dry land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

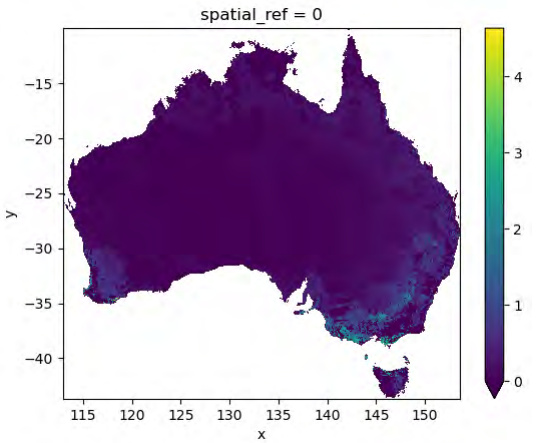

Figure 126 Yield potential of Dairy -Natural Land under irrigation land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

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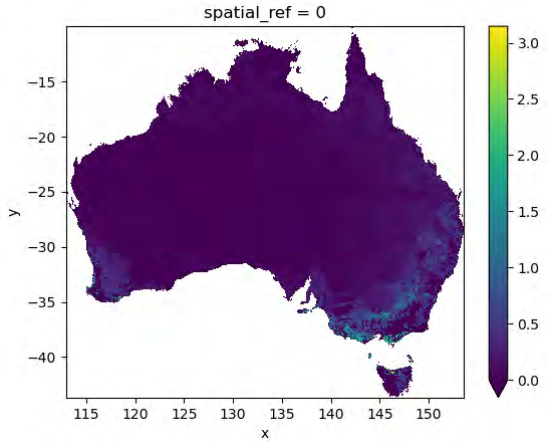	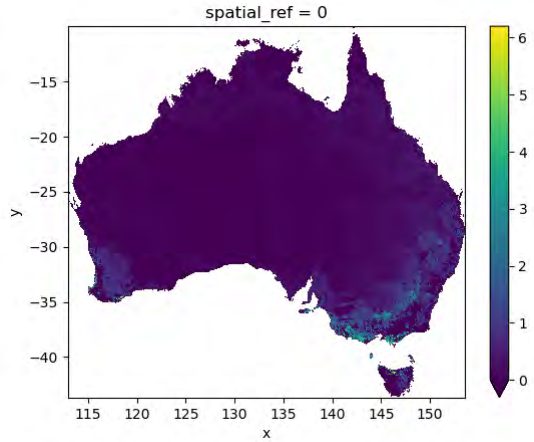
Figure 127 Yield potential of Dairy -Modified Land under dry land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$	Figure 128 Yield potential of Dairy -Modified Land under irrigation land management system $\mathbf{YPot}_{mr\ell}^{LS}(y)$

5.2. Livestock Quantity:

The livestock quantity is computed for the cells assigned to $\mathcal{L}_{\text{Livestock}}$ (Equation 16) as:

$\mathbf{LQY}_{mr\ell}^{LS}(y) = \mathbf{BQ}_{r}^{LS,Commedities} \times \mathbf{YPot}_{mr\ell}^{LS}(y) \times \mathbf{RA}_{r} \times PIF_{m\ell}^{LS}(y)$	Equation 114

where,

- $\mathbf{BQ}_{r}^{LS,Commedities}$ is the base quantity (see Equation 115-Equation 120 for each case). Here, $Commedities$ can be replaced by each member of $\mathcal{L}_{\text{Commodities}}^{\text{Livestock}}$.
- $\mathbf{YPot}_{mr\ell}^{LS}(y)$ represents the yield potential for livestock ℓ (Equation 113 and Figure 117-Figure 128).
- $\mathbf{RA}_{r}$ indicates the real area (Figure 5).
- $PIF_{m\ell}^{LS}(y)$ is the productivity increase factor for livestock ℓ under land management m in year y (Table 6).

The productivity increase factor for each livestock type ℓ, $\ell \in \mathcal{L}_{\text{Commodities}}^{\text{Livestock}}$, under different land management system m, is presented in Table 6. The value of $PIF_{m\ell}^{LS}(y)$ change each year y. However, within each year y, the value of $PIF_{m\ell}^{LS}(y)$ remain the same for Meat, Wool, LEXP and Diary for a given livestock type ℓ under the same land management system m.

Table 6 Productivity increase factor for livestock commodities

$PIF_{m\ell}^{LS}(y)$				Year					
				2010	**2020**	**2030**	**2040**	**2050**	**2100**
Beef	**Modified Land**	Dry	Meat	1	1.0984498	1.1968997	1.2953495	1.3937993	1.8860484
			LEXP	1	1.0984498	1.1968997	1.2953495	1.3937993	1.8860484
		Irrigation	Meat	1	1.1968997	1.3937993	1.590699	1.7875986	2.7720969
			LEXP	1	1.1968997	1.3937993	1.590699	1.7875986	2.7720969
	Natural Land	Dry	Meat	1	1.0984498	1.1968997	1.2953495	1.3937993	1.8860484
			LEXP	1	1.0984498	1.1968997	1.2953495	1.3937993	1.8860484
		Irrigation	Meat	1	1.1968997	1.3937993	1.590699	1.7875986	2.7720969
			LEXP	1	1.1968997	1.3937993	1.590699	1.7875986	2.7720969
Sheep	**Modified Land**	Dry	Meat	1	1.0670615	1.1341231	1.2011846	1.2682462	1.6035539
			Wool	1	0.925738	0.8569908	0.7933489	0.73443323	0.4993358
			LEXP	1	1.0670615	1.1341231	1.2011846	1.2682462	1.6035539
		Irrigation	Meat	1	1.1341231	1.2682462	1.4023693	1.5364923	2.2071078
			Wool	1	0.8569908	0.73443323	0.6294025	0.5393922	0.24933624
			LEXP	1	1.1341231	1.2682462	1.4023693	1.5364923	2.2071078
	Natural Land	Dry	Meat	1	1.0670615	1.1341231	1.2011846	1.2682462	1.6035539
			Wool	1	0.925738	0.8569908	0.7933489	0.73443323	0.4993358
			LEXP	1	1.0670615	1.1341231	1.2011846	1.2682462	1.6035539
		Irrigation	Meat	1	1.1341231	1.2682462	1.4023693	1.5364923	2.2071078
			Wool	1	0.8569908	0.73443323	0.6294025	0.5393922	0.24933624
			LEXP	1	1.1341231	1.2682462	1.4023693	1.5364923	2.2071078
Dairy	**Modified Land**	Dry	Dairy	1	1.1238153	1.2476307	1.371446	1.4952614	2.1143382
		Irrigation	Dairy	1	1.2476307	1.4952614	1.7428921	1.9905227	3.2286763
	Natural Land	Dry	Dairy	1	1.1238153	1.2476307	1.371446	1.4952614	2.1143382
		Irrigation	Dairy	1	1.2476307	1.4952614	1.7428921	1.9905227	3.2286763

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As mentioned in Equation 114, $\mathbf{BQ}_r^{LS,Commedities}$ is the base quantity, which must be determined case-by-case (Equation 115-Equation 120). Regarding the available livestock commodities $\mathcal{L}_{\text{Commodities}}^{\text{Livestock}}$ in Equation 38, the base quantity of each commodity $\mathbf{BQ}_r^{LS,Commedities}$ is computed as follows:

- ✓ **Beef**

$\forall r \in \{1, \dots, N_r\}\ \exists \ell, \ell \subset \mathcal{L}_{\text{Commodities}}^{\text{Beef}}$	
$\mathbf{BQ}_r^{BeefMeat} = \mathbf{AGEC}_r^{\text{Beef,F1}} \times \mathbf{AGEC}_r^{\text{Beef,Q1}}$	Equation 115
$\mathbf{BQ}_r^{BeefLEXP} = \mathbf{AGEC}_r^{\text{Beef,F3}} \times \mathbf{AGEC}_r^{\text{Beef,Q3}}$	Equation 116

where,

- $\mathcal{L}_{\text{Commodities}}^{\text{Beef}}$ is the list of commodities produced by beef (Equation 41).

The parameters $\mathbf{AGEC}_r^{\text{Beef,F1}}$, $\mathbf{AGEC}_r^{\text{Beef,Q1}}$, $\mathbf{AGEC}_r^{\text{Beef,F3}}$, and $\mathbf{AGEC}_r^{\text{Beef,Q3}}$ are listed in Table 7 and illustrated in Figure 129 - Figure 132, respectively. Moreover $\mathbf{BQ}_r^{BeefMeat}$ and $\mathbf{BQ}_r^{BeefLEXP}$ are illustrated in Figure 141 and Figure 142, respectively.

- ✓ **Sheep**

$\forall r \in \{1, \dots, N_r\}\ \exists \ell, \ell \subset \mathcal{L}_{\text{Commodities}}^{\text{Sheep}}$	
$\mathbf{BQ}_r^{SheepMeat} = \mathbf{AGEC}_r^{\text{Sheep,F1}} \times \mathbf{AGEC}_r^{\text{Sheep,Q1}}$	Equation 117
$\mathbf{BQ}_r^{SheepWool} = \mathbf{AGEC}_r^{\text{Sheep,Q1}} \times \mathbf{AGEC}_r^{\text{Sheep,Q2}}$	Equation 118
$\mathbf{BQ}_r^{SheepLEXP} = \mathbf{AGEC}_r^{\text{Sheep,F3}} \times \mathbf{AGEC}_r^{\text{Sheep,Q3}}$	Equation 119

where,

- $\mathcal{L}_{\text{Commodities}}^{\text{Sheep}}$ is the list of commodities produced by sheep (Equation 40).

The parameters $\mathbf{AGEC}_r^{\text{Sheep,F1}}$, $\mathbf{AGEC}_r^{\text{Sheep,Q1}}$, $\mathbf{AGEC}_r^{\text{Sheep,Q1}}$, $\mathbf{AGEC}_r^{\text{Sheep,Q2}}$, $\mathbf{AGEC}_r^{\text{Sheep,F3}}$ and $\mathbf{AGEC}_r^{\text{Sheep,Q3}}$ are listed in Table 7 and illustrated in Figure 133 - Figure 138, respectively. Moreover $\mathbf{BQ}_r^{SheepMeat}$, $\mathbf{BQ}_r^{SheepWool}$, and $\mathbf{BQ}_r^{SheepLEXP}$ illustrated in Figure 143 - Figure 145, respectively.

- ✓ **Dairy**

$\forall r \in \{1, \dots, N_r\}\ \exists \ell, \ell \subset \mathcal{L}_{\text{Commodities}}^{\text{Dairy}}$	
$\mathbf{BQ}_r^{Dairy} = \dfrac{\mathbf{AGEC}_r^{\text{DairyF1}} \times \mathbf{AGEC}_r^{\text{DairyQ1}}}{1000}$	Equation 120

where,

- $\mathcal{L}_{\text{Commodities}}^{\text{Dairy}}$ is the list of commodities produced by dairy (Equation 42).

The parameters $\mathbf{AGEC}_r^{\text{DairyF1}}$, and $\mathbf{AGEC}_r^{\text{DairyQ1}}$ are introduced in Table 7, and their corresponding maps are illustrated in Figure 139-Figure 140. Additionally, the base quantity for dairy, $\mathbf{BQ}_r^{Dairy}$, is illustrated in Figure 146.

It should be noted that in Equation 115-Equation 120 , the following relationships hold:

$$\mathcal{L}_{\text{Commodities}}^{\text{Beef}} \subset \mathcal{L}_{\text{Commodities}}^{\text{Livestock}}, \ \mathcal{L}_{\text{Commodities}}^{\text{Sheep}} \subset \mathcal{L}_{\text{Commodities}}^{\text{Livestock}}, \text{ and } \mathcal{L}_{\text{Commodities}}^{\text{Dairy}} \subset \mathcal{L}_{\text{Commodities}}^{\text{Livestock}}$$

The required parameters for Equation 117-Equation 120 are presented in Table 7.

Table 7 Required parameters for computing $\mathbf{BQ}_r^{LSCommedities}$ (Equation 117-Equation 120)

Livestock Type	Product Name	Fraction of herd producing (0 -1)	Quantity produced per head	Unit of the Quantity produced per head
Beef	Meat	$\mathbf{AGEC}_r^{\text{Beef,F1}}$	$\mathbf{AGEC}_r^{\text{Beef,Q1}}$	Meat tonnes/head
	LEXP	$\mathbf{AGEC}_r^{\text{Beef,F3}}$	$\mathbf{AGEC}_r^{\text{Beef,Q3}}$	Animal weight tonnes/head
Sheep	Meat	$\mathbf{AGEC}_r^{\text{Sheep,F1}}$	$\mathbf{AGEC}_r^{\text{Sheep,Q1}}$	Meat tonnes/head
	Wool	$\mathbf{AGEC}_r^{\text{Sheep,F2}}$	$\mathbf{AGEC}_r^{\text{Sheep,Q2}}$	Wool tonnes/head
	LEXP	$\mathbf{AGEC}_r^{\text{Sheep,F3}}$	$\mathbf{AGEC}_r^{\text{Sheep,Q3}}$	Animal weight tonnes/head
Dairy	Dairy	$\mathbf{AGEC}_r^{\text{DairyF1}}$	$\mathbf{AGEC}_r^{\text{DairyQ1}}$	Milk litter/head

All the parameters in Table 7 are mapped in Figure 129-Figure 140.

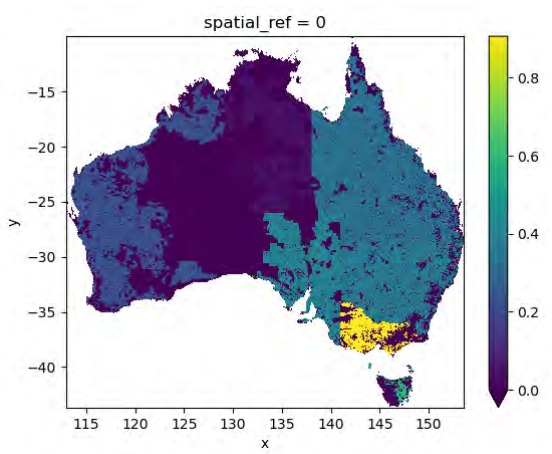

Figure 129 Parameter $\mathbf{AGEC}_r^{\text{Beef,F1}}$ required for $\mathbf{BQ}_r^{BeefMeat}$

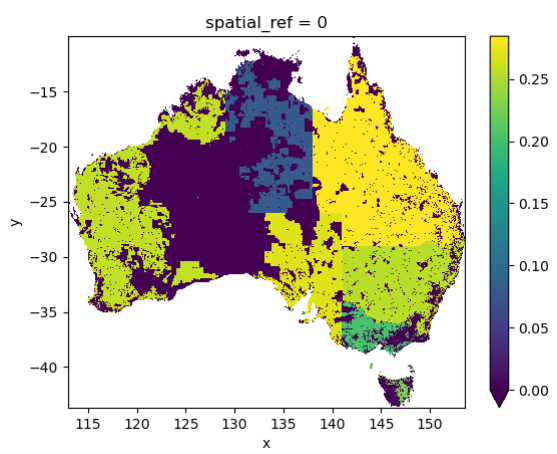

Figure 130 Parameter $\mathbf{AGEC}_r^{\text{Beef,Q1}}$ required for $\mathbf{BQ}_r^{BeefMeat}$

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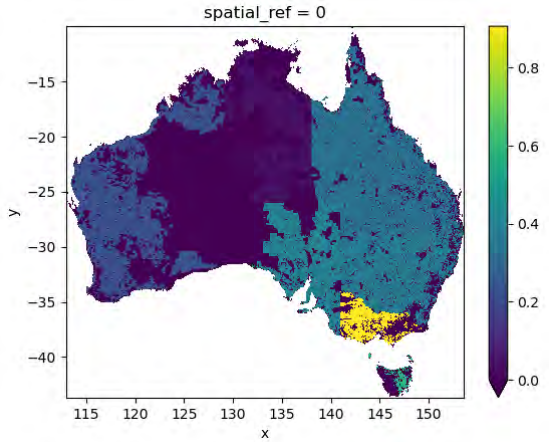

Figure 131 Parameter $\mathbf{AGEC}_r^{\text{Beef,F3}}$ required for $\mathbf{BQ}_r^{BeefLEXP}$

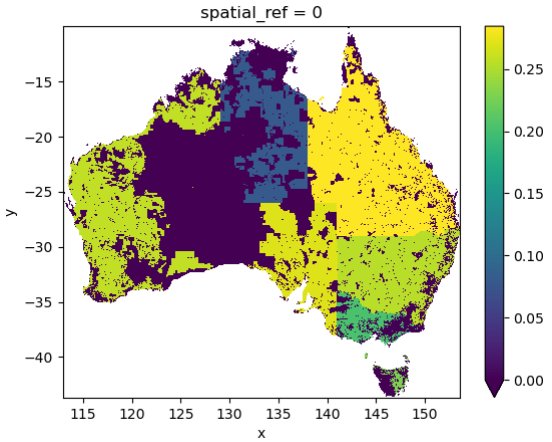

Figure 132 Parameter $\mathbf{AGEC}_r^{\text{Beef,Q3}}$ required for $\mathbf{BQ}_r^{BeefLEXP}$

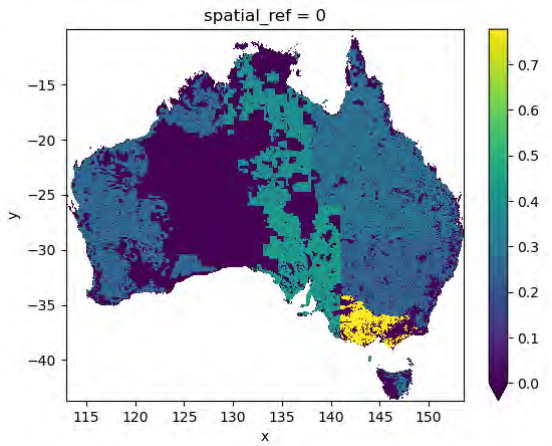

Figure 133 Parameter $\mathbf{AGEC}_r^{\text{Sheep,F1}}$ required for $\mathbf{BQ}_r^{SheepMeat}$

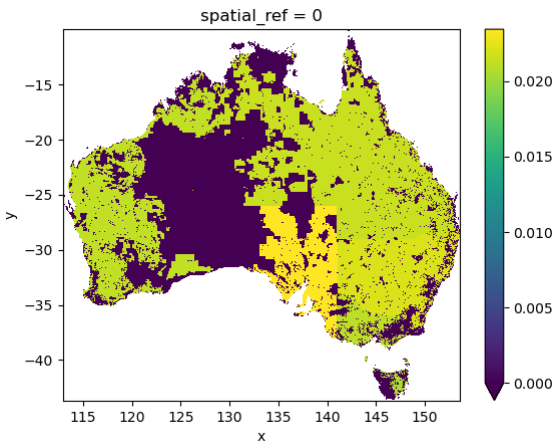

Figure 134 Parameter $\mathbf{AGEC}_r^{\text{Sheep,Q1}}$ required for $\mathbf{BQ}_r^{SheepMeat}$

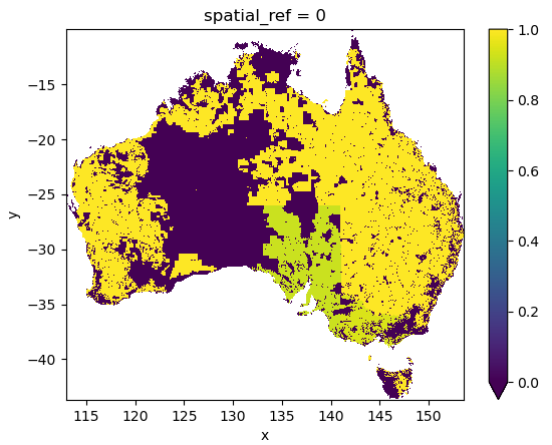

Figure 135 Parameter $\mathbf{AGEC}_r^{\text{Sheep,F2}}$ required for $\mathbf{BQ}_r^{SheepWool}$

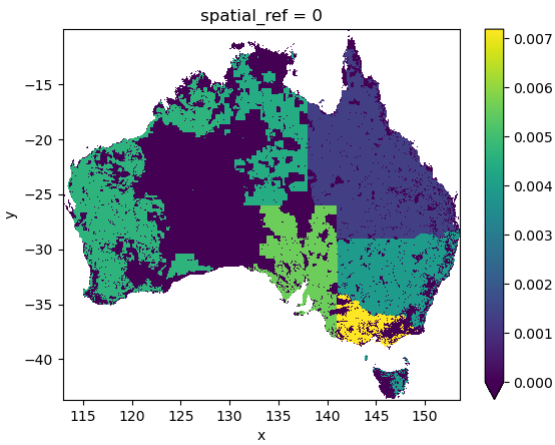

Figure 136 Parameter $\mathbf{AGEC}_r^{\text{Sheep,Q2}}$ required for $\mathbf{BQ}_r^{SheepWool}$

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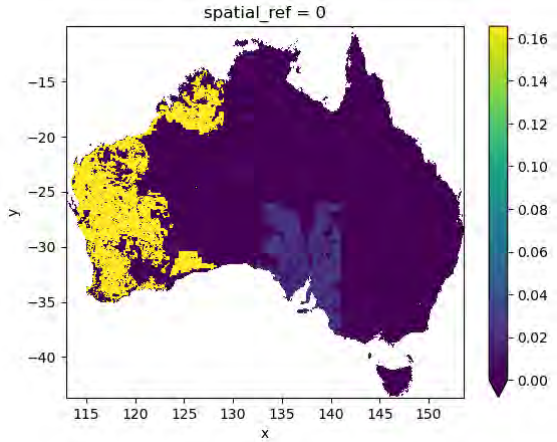

Figure 137 Parameter $\mathbf{AGEC}_r^{\text{Sheep,F3}}$ required for $\mathbf{BQ}_r^{SheepLEXP}$

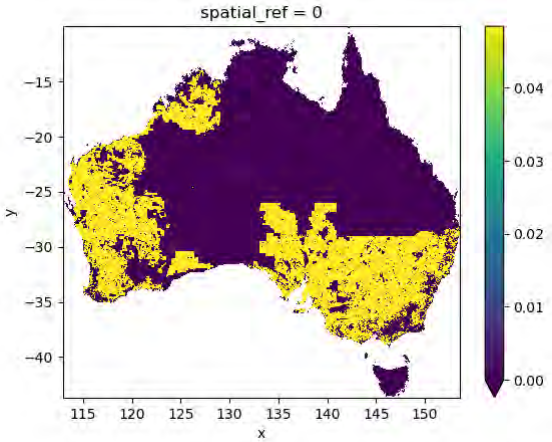

Figure 138 Parameter $\mathbf{AGEC}_r^{\text{Sheep,Q3}}$ required for $\mathbf{BQ}_r^{SheepLEXP}$

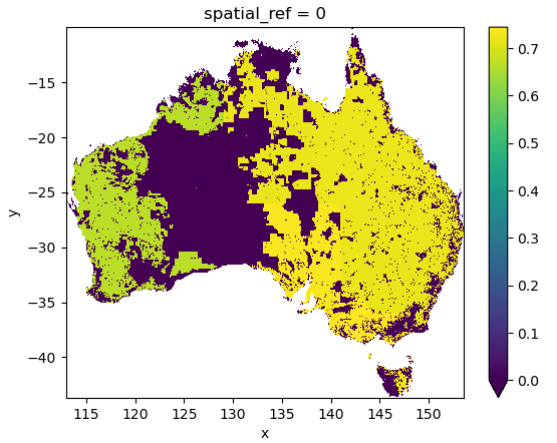

Figure 139 Parameter $\mathbf{AGEC}_r^{\text{DairyF1}}$ required for $\mathbf{BQ}_r^{Dairy}$

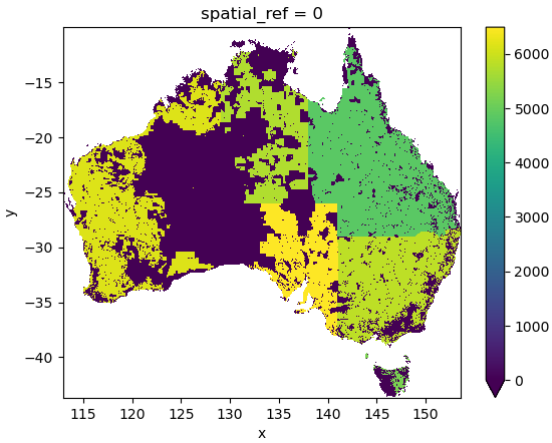

Figure 140 Parameter $\mathbf{AGEC}_r^{\text{DairyQ1}}$ required for $\mathbf{BQ}_r^{Dairy}$

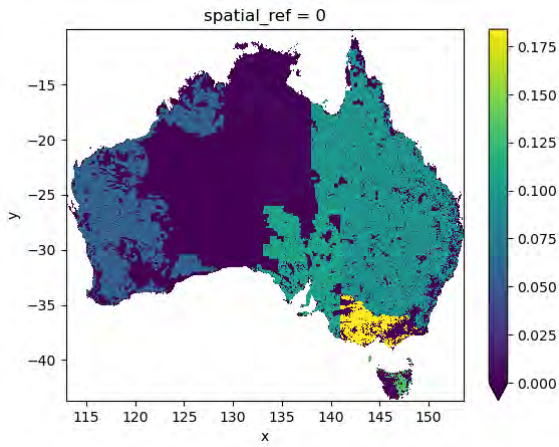

Figure 141 The base quantity of commodity $\mathbf{BQ}_r^{\text{BeefMeat}}$

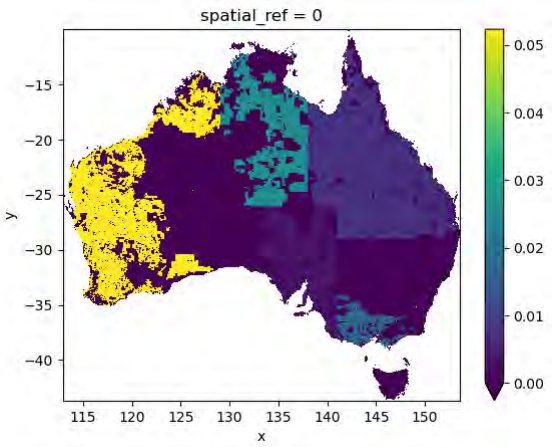

Figure 142 The base quantity of commodity $\mathbf{BQ}_r^{\text{BeefLEXP}}$

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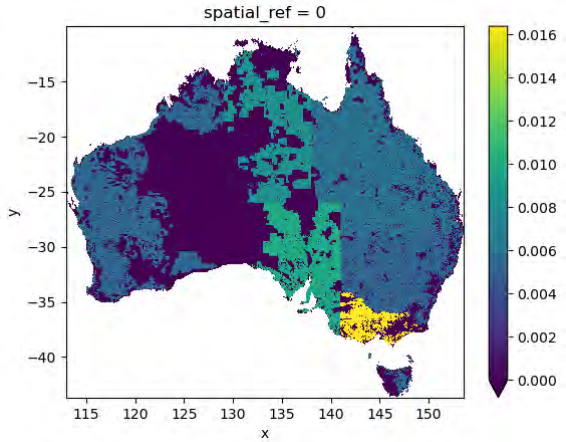

Figure 143 The base quantity of commodity $\mathbf{BQ}_r^{SheepMeat}$

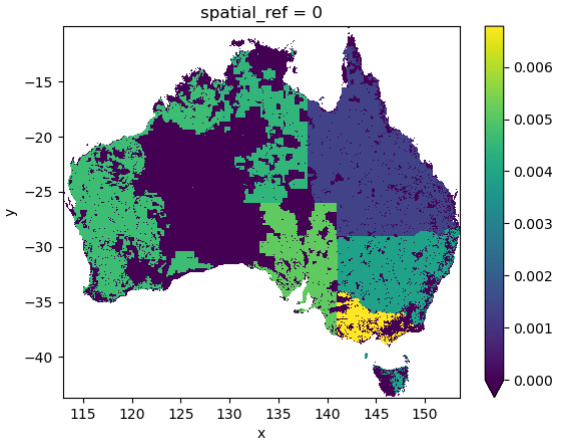

Figure 144 The base quantity of commodity $\mathbf{BQ}_r^{SheepWool}$

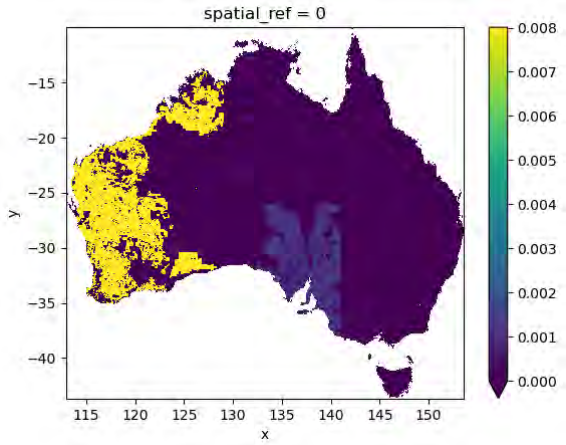

Figure 145 The base quantity of commodity $\mathbf{BQ}_r^{SheepLEXP}$

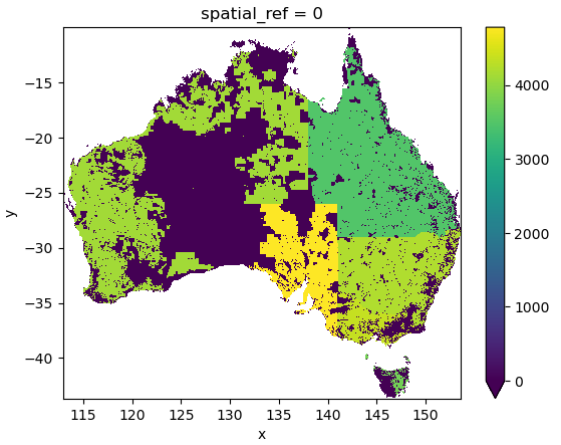

Figure 146 The base quantity of commodity $\mathbf{BQ}_r^{Dairy}$

After utilizing all the above-mentioned data by Equation 114, the livestock quantity $\mathbf{LQY}_{mr\ell}^{LS}(y)$ for all livestock type under all land management system will be produced. For example, Figure 147-Figure 158 illustrate the computed $\mathbf{LQY}_{mr\ell}^{LS}(y)$ for year 2050.

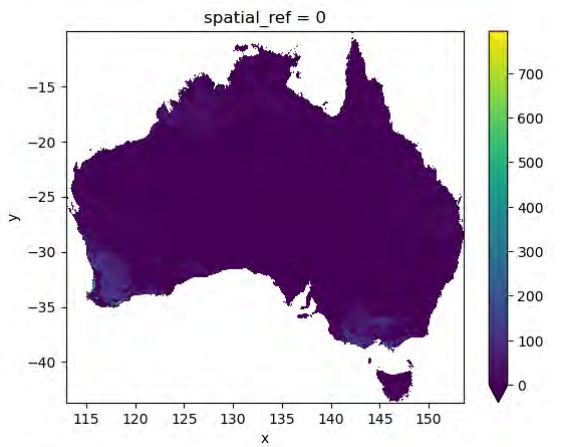

Figure 147 The livestock quantity for the beef - modified land LEXP

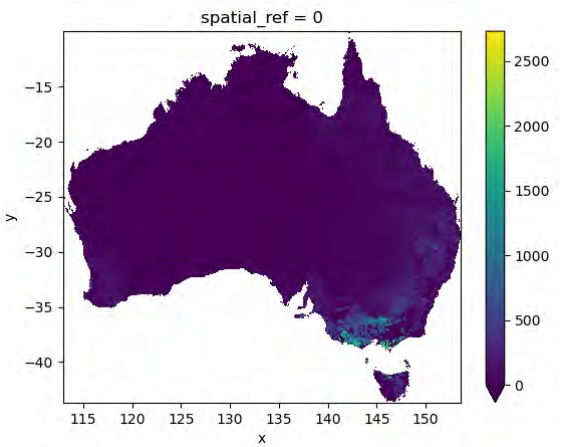

Figure 148 The livestock quantity for the beef - modified land meat

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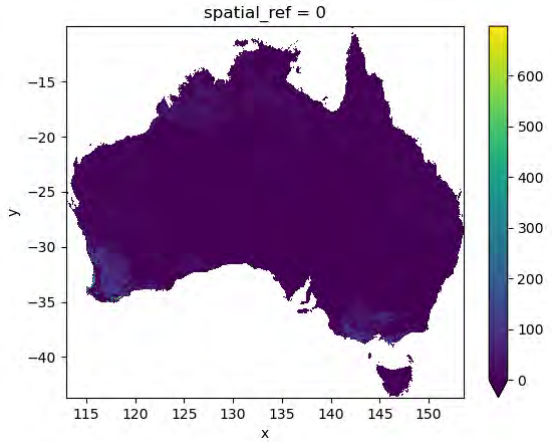

Figure 149 The livestock quantity for the beef - natural land LEXP

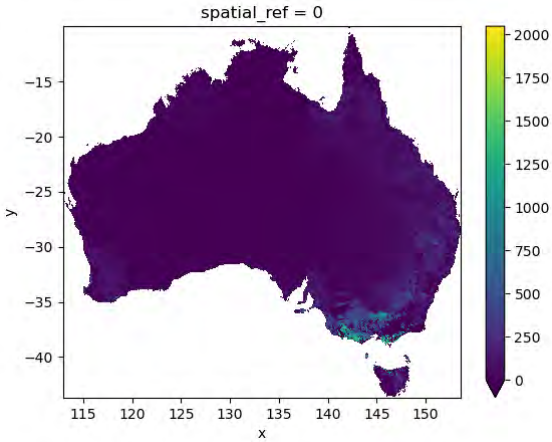

Figure 150 The livestock quantity for the beef - natural land meat

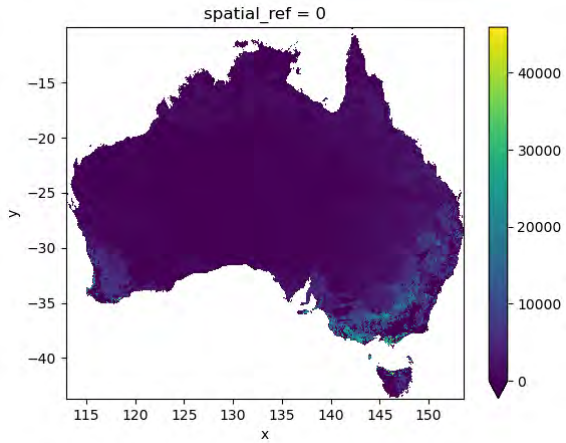

Figure 151 The livestock quantity for the dairy - modified land

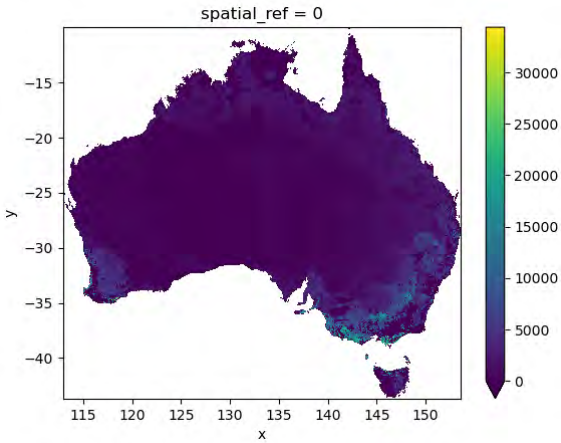

Figure 152 The livestock quantity for the dairy - natural land

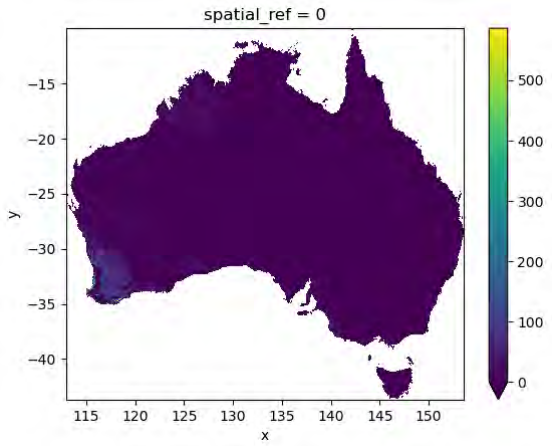

Figure 153 The livestock quantity for the sheep - modified land LEXP

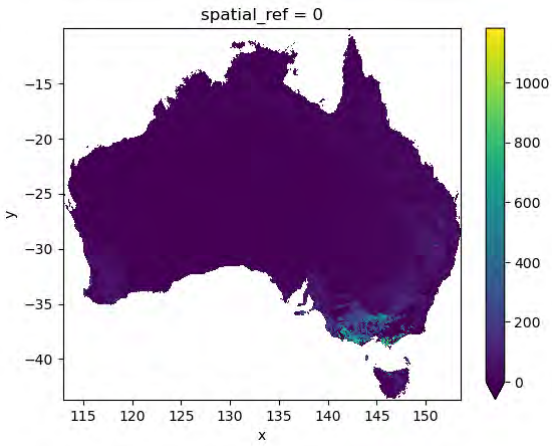

Figure 154 The livestock quantity for the sheep - modified land meat

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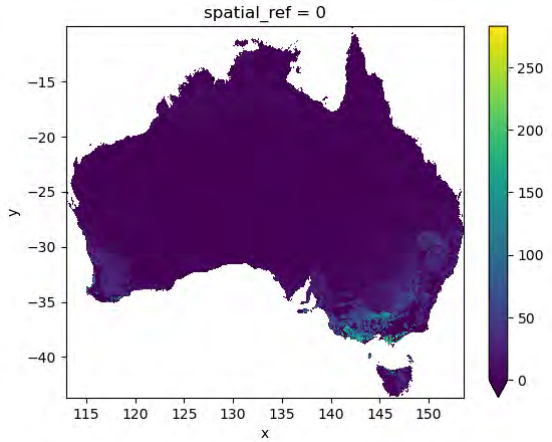

Figure 155 The livestock quantity for the sheep - modified land wool

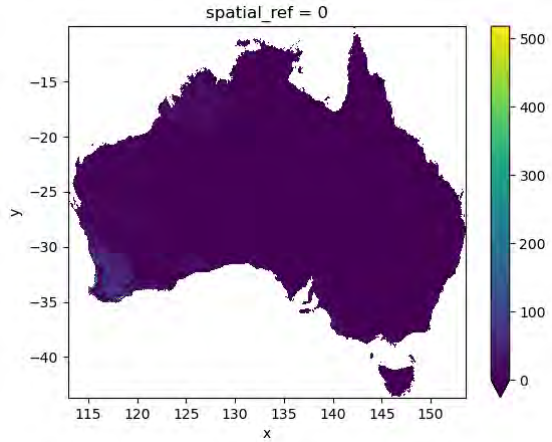

Figure 156 The livestock quantity for the sheep - natural land LEXP

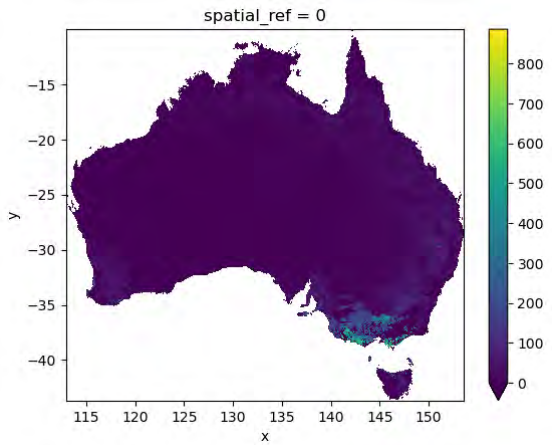

Figure 157 The livestock quantity for the sheep - natural land meat

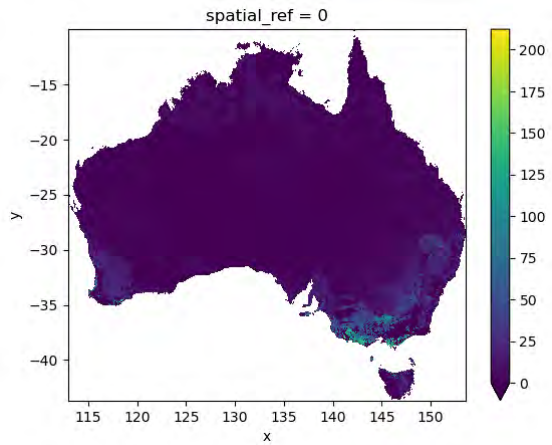

Figure 158 The livestock quantity for the sheep - natural land wool

5.3. Crop Yield Quantity

The crop yield quantity is computed for cells assigned to $\mathcal{L}_{\text{Crops}}$ (Equation 15), as:

$\mathbf{CQY}^{AG}_{mr\ell}(y) = \mathbf{RYQ}^{AG}_{mr\ell}(y) \times \mathbf{CCIM}^{AG}_{mr\ell}(y) \times \mathbf{RA}_r \times PIF^{AG}_{m\ell}(y)$	Equation 121

where:

- $\mathbf{RYQ}^{AG}_{mr\ell}(y)$ represents raw yield quantities in tonnes per hectare (see Figure 159-Figure 162)
- $\mathbf{CCIM}^{AG}_{mr\ell}(y)$ is the climate change impact multiplier (see Figure 163-Figure 166)
- $\mathbf{RA}_r$ is the real area multiplier (Figure 5)
- $PIF^{AG}_{m\ell}(y)$ is the productivity increase factor for land management type m and crop ℓ in year y.

The productivity increase factor for each crop ℓ, $\ell \in \mathcal{L}_{\text{Crops}}$, under different land management system m is presented in Table 8. As shown, the value of $PIF^{AG}_{m\ell}(y)$ changes for each crop ℓ under different land management system m for each given year y.

Table 8 Productivity increase factor ($PIF_{m\ell}^{AG}(y)$) for crops under dry and irrigated land management systems

$PIF_{m\ell}^{AG}(y)$		Year					
		2010	**2020**	**2030**	**2040**	**2050**	**2100**
Irrigation Land Management System	**Apples**	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Citrus	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Cotton	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Grapes	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Hay	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Nuts	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Other non-cereal crops	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Pears	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Plantation fruit	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Rice	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Stone fruit	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Sugar	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Summer cereals	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Summer legumes	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Summer oilseeds	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Tropical stone fruit	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Unallocated - modified land	1	1	1	1	1	1
	Unallocated - natural land	1	1	1	1	1	1
	Vegetables	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Winter cereals	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Winter legumes	1	1.0745	1.148999	1.223499	1.297998	1.737545
	Winter oilseeds	1	1.0745	1.148999	1.223499	1.297998	1.737545
Dry Land Management System	**Apples**	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Citrus	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Cotton	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Grapes	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Hay	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Nuts	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Other non-cereal crops	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Pears	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Plantation fruit	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Rice	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Stone fruit	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Sugar	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Summer cereals	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Summer legumes	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Summer oilseeds	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Tropical stone fruit	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Unallocated - modified land	1	1	1	1	1	1
	Unallocated - natural land	1	1	1	1	1	1
	Vegetables	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Winter cereals	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Winter legumes	1	1.03725	1.0745	1.111749	1.148999	1.368773
	Apples	1	1.03725	1.0745	1.111749	1.148999	1.368773

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After applying Equation 121 to the above data, the final crop yield quantity $\mathbf{CQY}_{mr\ell}^{AG}(y)$ is obtained for all crop types under all land management systems.

For example, Figure 167-Figure 172 illustrate the computed crop yield quantity for the year 2050.

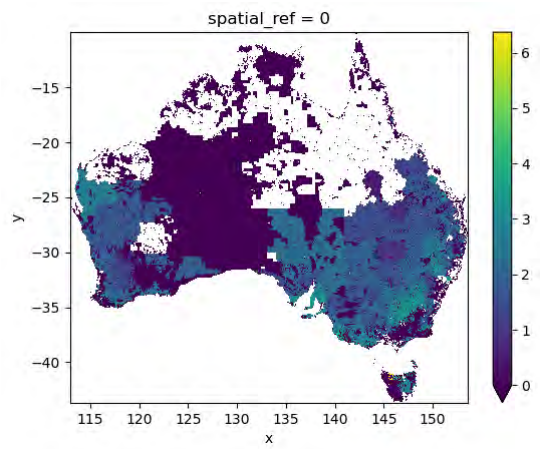

Figure 159 The raw yield quantities for winter cereals under dry land management system $\mathbf{RYQ}_{mr\ell}^{AG}(y)$

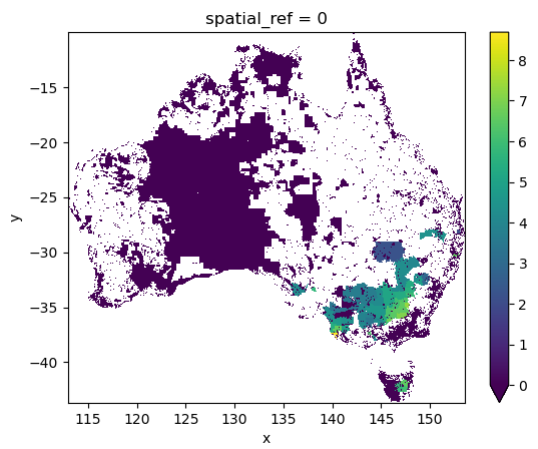

Figure 160 The raw yield quantities for winter cereals under irrigation land management system $\mathbf{RYQ}_{mr\ell}^{AG}(y)$

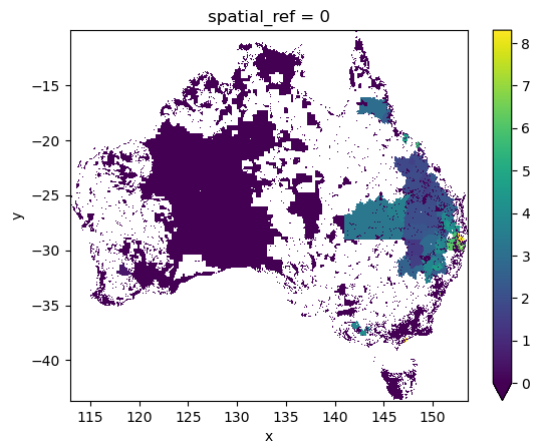

Figure 161 The raw yield quantities for summer cereals under dry land management system $\mathbf{RYQ}_{mr\ell}^{AG}(y)$

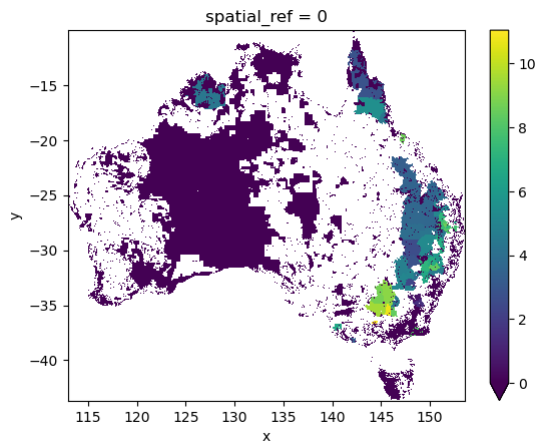

Figure 162 The raw yield quantities for summer cereals under irrigation land management system $\mathbf{RYQ}_{mr\ell}^{AG}(y)$

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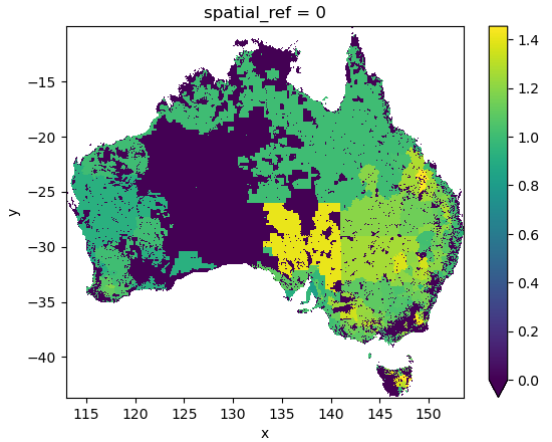

Figure 163 Climate change yield impact multiplier on winter cereals under dry land management system $\mathbf{CCIM}_{mr\ell}^{AG}(y)$

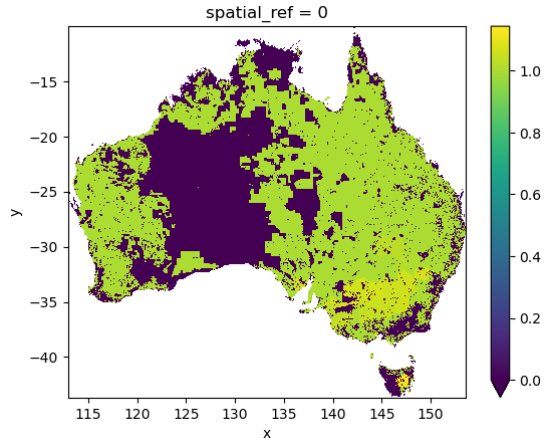

Figure 164 Climate change yield impact multiplier on winter cereals under irrigation land management system $\mathbf{CCIM}_{mr\ell}^{AG}(y)$

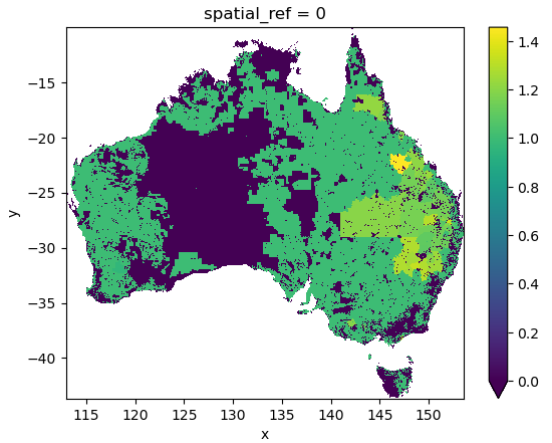

Figure 165 Climate change yield impact multiplier on summer cereals under dry land management system $\mathbf{CCIM}_{mr\ell}^{AG}(y)$

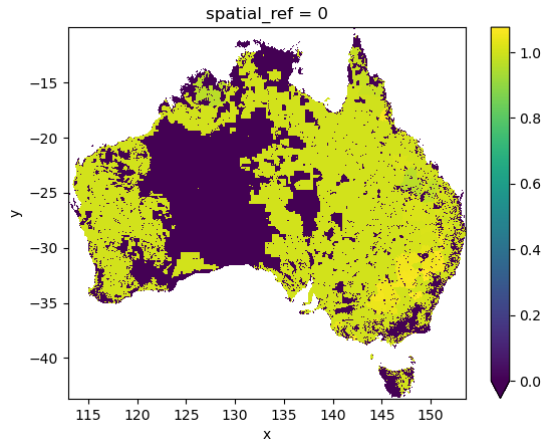

Figure 166 Climate change yield impact multiplier on summer cereals under irrigation land management system $\mathbf{CCIM}_{mr\ell}^{AG}(y)$

After utilizing all the above-mentioned data by Equation 121, the crop quantity $\mathbf{CQY}_{mr\ell}^{AG}(y)$ for all crop type under all land management system will be produced. For example, Figure 147-Figure 158 illustrate the computed $\mathbf{CQY}_{mr\ell}^{AG}(y)$ for year 2050.

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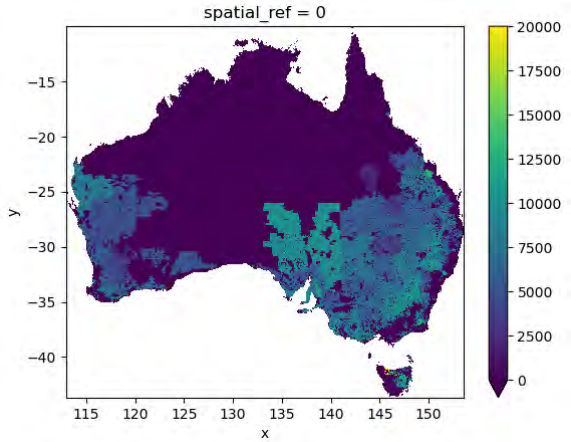

Figure 167 The crop quantity for winter cereals under dry land management system $\mathbf{CQY}_{mr\ell}^{AG}(y)$

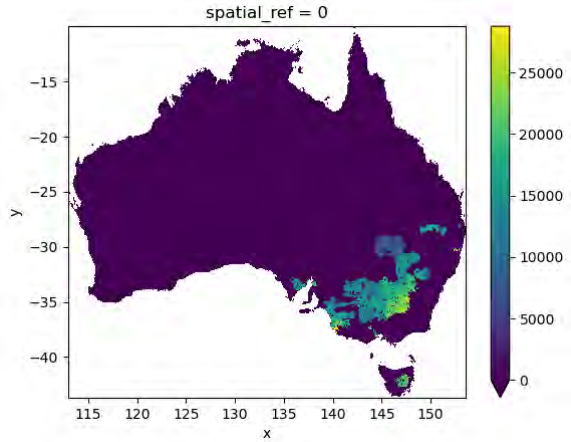

Figure 168 The crop quantity for winter cereals under irrigation land management system $\mathbf{CQY}_{mr\ell}^{AG}(y)$

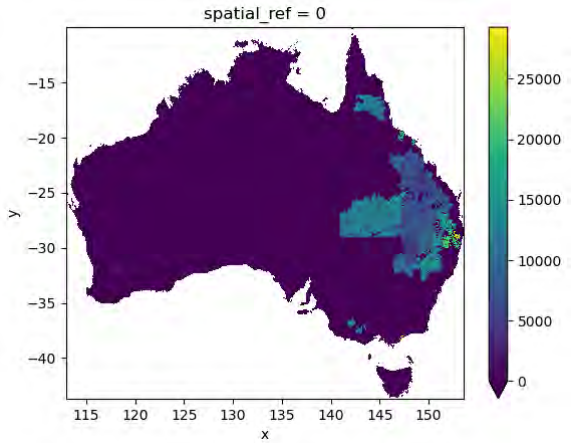

Figure 169 The crop quantity for summer cereals under dry land management system $\mathbf{CQY}_{mr\ell}^{AG}(y)$

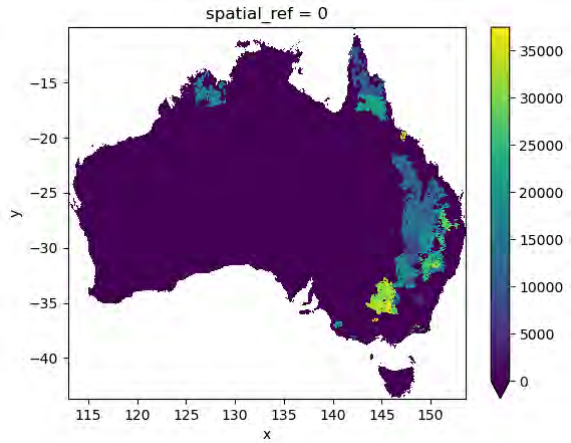

Figure 170 The crop quantity for summer cereals under irrigation land management system $\mathbf{CQY}_{mr\ell}^{AG}(y)$

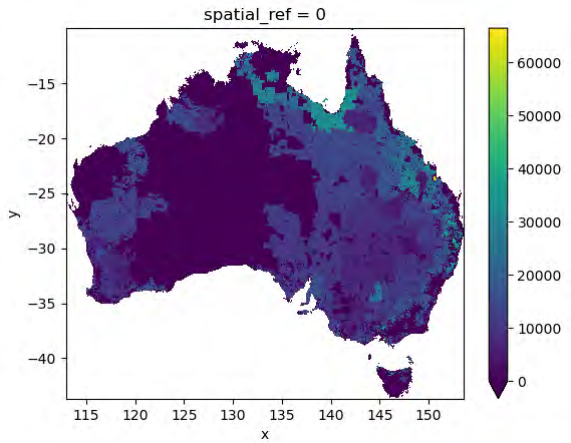

Figure 171 The crop quantity for Hay under dry land management system $\mathbf{CQY}_{mr\ell}^{AG}(y)$

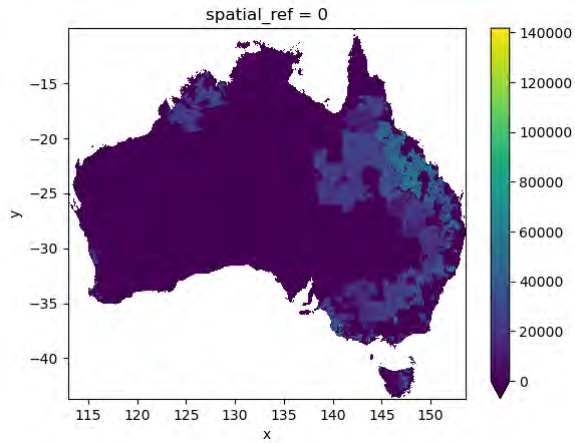

Figure 172 The crop quantity for Hay under irrigation land management system $\mathbf{CQY}_{mr\ell}^{AG}(y)$

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5.4. Crop and Livestock Yield Quantity:

Let $\mathbf{CLYQ}_{mr\ell}^{AG,LS}$ be a tensor representing the yield quantity for both crop and livestock products ($\ell \in \mathcal{L}_{\text{Products}}$) under dry and irrigation land management systems. The tensor $\mathbf{CLYQ}_{mr\ell}^{AG,LS}$ is initialized as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\text{Products}}$	Equation 122
$\mathbf{CLYQ}_{mr\ell}^{AG,LS} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{Products}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k represents the number of agricultural management practices, where $m \in \mathcal{M}$ (Equation 21), and hence $N_k = 2$ (for dry and irrigated management).
- $N_{lu}^{\text{Products}} = 32$, as the set $\mathcal{L}_{\text{Products}}$, consists of 32 products (Equation 37).

The tensor $\mathbf{CLYQ}_{mr\ell}^{AG,LS}(y)$ is updated using crop yield quantity $\mathbf{CQY}_{mr\ell}^{AG}(y)$ and livestock yield quantity $\mathbf{LQY}_{mr\ell}^{LS}(y)$, as computed in Equation 121 and Equation 114 respectively.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}_{\text{Products}}$	Equation 123
$\mathbf{CLYQ}_{mr\ell}^{AG,LS}(y) = \begin{cases} \mathbf{CQY}_{mr\ell}^{AG}(y) & \text{if } \ell \in \mathcal{L}_{\text{Crops}} \\ \mathbf{LQY}_{mr\ell}^{LS}(y) & \text{if } \ell \in \mathcal{L}_{\text{Livestock Commodities}} \end{cases}$	

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6. Impacts of Agricultural Management Practices on Yield Quantity of all relevant land use classes

6.1. Effects of Asparagopsis taxiformis on yield quantity

Let $\mathbf{YieldQ}_{mr\ell}^{\text{AspTaxifor}}$ be a tensor representing the yield quantity of agricultural products ($\mathcal{L}_{\text{Products}}$) in land management systems where *Asparagopsis taxiformis* can be integrated. This tensor is initialized as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\text{Products}}$	Equation 124
$\mathbf{YieldQ}_{mr\ell}^{\text{AspTaxifor}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{Products}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k represents the agricultural management practices $m \in \mathcal{M}$ (Equation 21), and thus $N_k = 2$.
- $N_{lu}^{\text{Products}} = 32$, as the set $\mathcal{L}_{\text{Products}}$ consists of 32 products (Equation 37).

To update $\mathbf{YieldQ}_{mr\ell}^{\text{AspTaxifor}}$ for the products where Asparagopsis taxiformis can be integrated into agricultural land management strategies, we use:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}_{\text{Products}}$	Equation 125
$\mathbf{YieldQ}_{mr\ell}^{\text{AspTaxifor}}(y) = \begin{cases} \mathbf{CLYQ}_{mr\ell}^{\text{AG,LS}}(y) \times \left(1 - YQM_{\ell}^{\text{AspTaxifor}}(y)\right) & \text{if } \ell \in \phi(\text{Asparagopsis taxiformis}) \wedge YQM_{\ell}^{\text{AspTaxifor}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Asparagopsis taxiformis}) \vee YQM_{\ell}^{\text{AspTaxifor}}(y) = 1 \end{cases}$	

where,

- $YQM_{\ell}^{\text{AspTaxifor}}(y)$ is the yield quantity multiplier
- $\mathbf{CLYQ}_{mr\ell}^{AG,LS}$ represents the yield quantity for all crop and livestock products ($\mathcal{L}_{\text{Products}}$) under dry and irrigated land management systems (Equation 123)
- $\phi(\text{Asparagopsis taxiformis})$ is the set of products where Asparagopsis taxiformis implemented (Equation 25)

However, in the current version of LUTO 2.0, we assume:

$$YQM_{\ell}^{\text{AspTaxifor}} = 1$$

which implies that the effect of *Asparagopsis taxiformis* on yield is not currently implemented, resulting in zero values for the affected matrices.

6.2. Effects of Precision Agriculture on Yield Quantity

Let $\mathbf{YieldQ}_{mr\ell}^{\text{PrecAgric}}$ be a tensor representing the yield quantity for agricultural products ($\mathcal{L}_{\text{Products}}$) in land management systems where Precision Agriculture is integrated. This tensor is initialized as:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\text{Products}}$	Equation 126
$\mathbf{YieldQ}_{mr\ell}^{\text{PrecAgric}} = \mathbf{0}_{\left(N_k \times N_c \times N_{lu}^{\text{Products}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k represents the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); and thus $N_k = 2$.
- $N_{lu}^{\text{Products}} = 32$, as the set $\mathcal{L}_{\text{Products}}$, consists of 32 products (Equation 37).

To update $\mathbf{YieldQ}_{mr\ell}^{\text{PrecAgric}}$ for products where Precision Agriculture is integrated, we use.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\} \exists\, \ell, \ell \in \mathcal{L}_{\text{Products}}$	Equation 127
$\mathbf{YieldQ}_{mr\ell}^{\text{PrecAgric}}(y) = \begin{cases} \mathbf{CLYQ}_{mr\ell}^{\text{AG,LS}}(y) \times \left(1 - YQM_{\ell}^{\text{PrecAgric}}(y)\right) & \text{if } \ell \in \phi(\text{Precision Agriculture}) \text{and} YQM_{\ell}^{\text{PrecAgric}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Precision Agriculture}) \text{or} YQM_{\ell}^{\text{PrecAgric}}(y) = 1 \end{cases}$	

where,

- $YQM_{\ell}^{\text{PrecAgric}}(y)$ is the yield quantity multiplier (Figure 173)
- $\mathbf{CLYQ}_{mr\ell}^{\text{AG,LS}}$ represents the yield quantity for all crop and livestock products ($\mathcal{L}_{\text{Products}}$) under dry and irrigated land management systems (Equation 123)
- $\phi(\text{Precision Agriculture})$ is the set of products where Precision Agriculture is implemented (Equation 27)

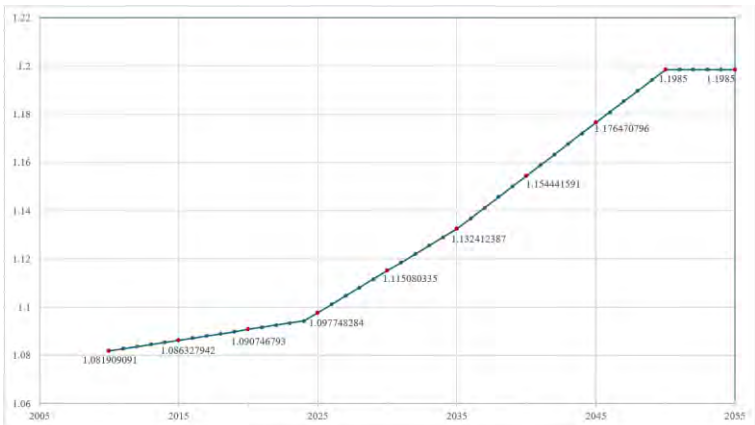

Figure 173 Yield quantity multiplier of Precision Agriculture Effects

The crop quantity for winter cereals , summer cereals, and hay under dry and irrigated land management systems, illustrated in Figure 174-Figure 179.

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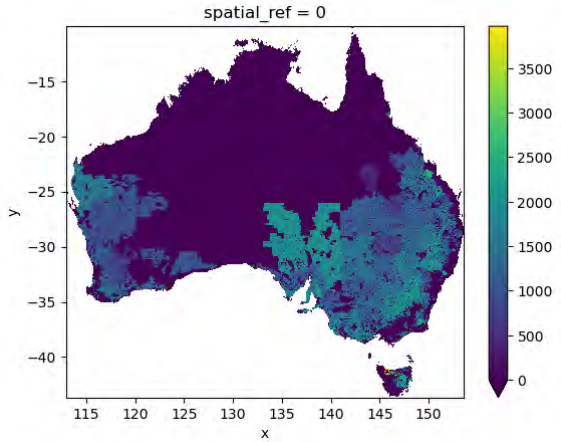

Figure 174 The crop quantity for winter cereals under dry land management system by considering the effects of precision agriculture

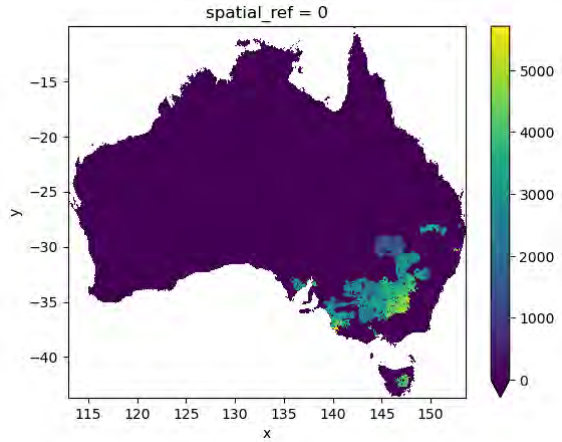

Figure 175 The crop quantity for winter cereals under irrigation land management system by considering the effects of precision agriculture

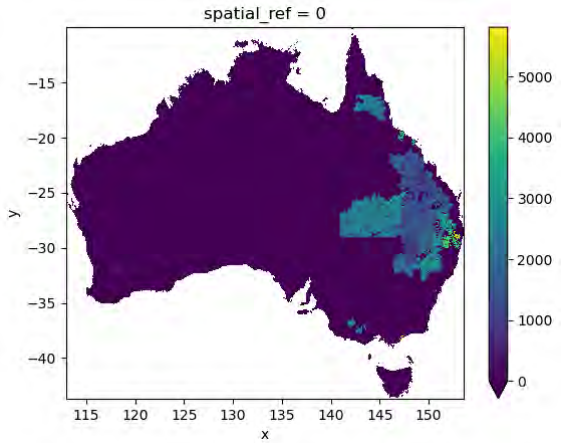

Figure 176 The crop quantity for summer cereals under dry land management system by considering the effects of precision agriculture

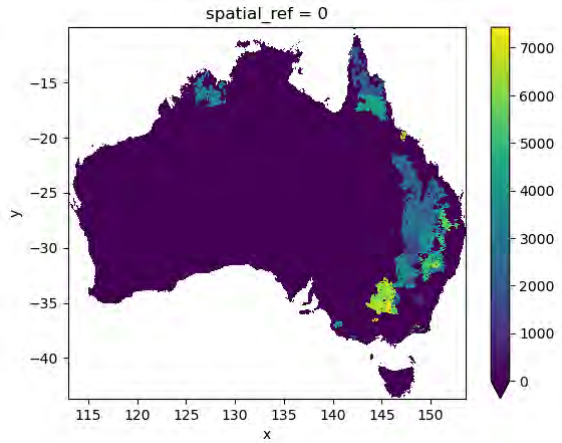

Figure 177 The crop quantity for summer cereals under irrigation land management system by considering the effects of precision agriculture

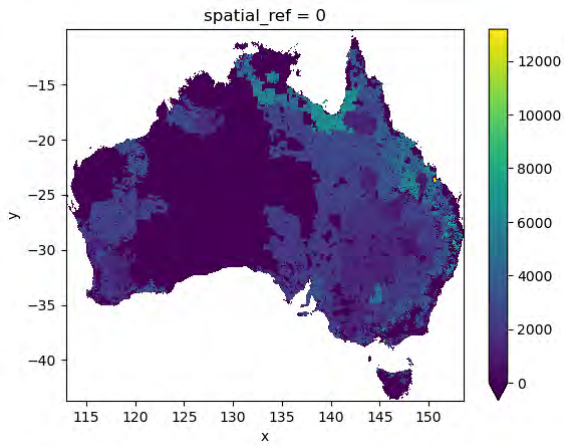

Figure 178 The crop quantity for hay under dry land management system by considering the effects of precision agriculture

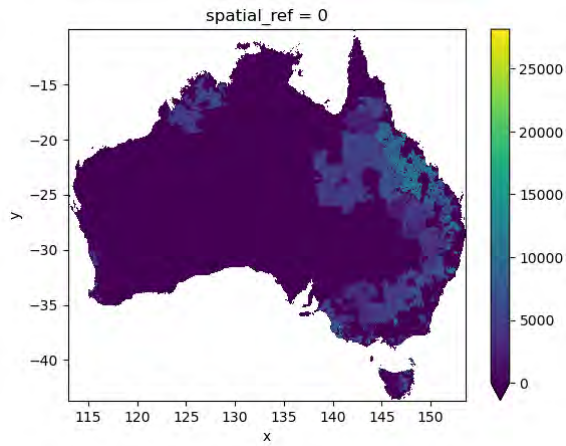

Figure 179 The crop quantity for hay under irrigation land management system by considering the effects of precision agriculture

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6.3. Effects of ecological grazing on yield quantity

Let $\mathbf{YieldQ}_{mr\ell}^{\text{EcolGrazing}}$ be a tensor representing the yield quantity for agricultural products ($\mathcal{L}_{\text{Products}}$) in land management systems where Ecological Grazing can be integrated. This tensor is initialized as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\text{Products}}$	Equation 128
$\mathbf{YieldQ}_{mr\ell}^{\text{EcolGrazing}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{Products}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k represents the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); and thus $N_k = 2$ (dry and irrigated management systems).
- $N_{lu}^{\text{Products}} = 32$, as the set $\mathcal{L}_{\text{Products}}$ consists of 32 products (Equation 37).

The tensor $\mathbf{YieldQ}_{mr\ell}^{\text{EcolGrazing}}$ is updated for products where Ecological Grazing is applied, using:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}_{\text{Products}}$	Equation 129
$\mathbf{YieldQ}_{mr\ell}^{\text{EcolGrazing}} = \begin{cases} \mathbf{CLYQ}_{mr\ell}^{AG,LS}(y) \times \left(1 - YQM_{\ell}^{\text{EcolGrazing}}(y)\right) & \text{if } \ell \in \phi(\text{Ecological Grazing}) \text{and} YQM_{\ell}^{\text{EcolGrazing}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Ecological Grazing}) \text{or} YQM_{\ell}^{\text{EcolGrazing}}(y) = 1 \end{cases}$	

where,

- $YQM_{\ell}^{\text{EcolGrazing}}(y)$ is the yield quantity multiplier
- $\mathbf{CLYQ}_{mr\ell}^{AG,LS}$ represents the yield quantity for all crop and livestock products ($\mathcal{L}_{\text{Products}}$) under dry and irrigated land management systems (Equation 123)
- $\phi(\text{Ecological Grazing})$ is the set of products where Ecological Grazing implemented (Equation 29)

In the current version of LUTO 2.0, the yield quantity multiplier is

$$YQM_{\ell}^{\text{EcolGrazing}} = 1.055$$

for all years and livestock products.

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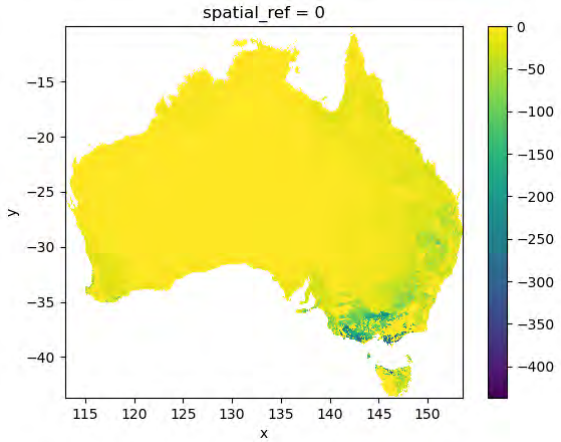

Figure 180 The livestock quantity for Beef - modified land meat under dry land management system by considering the effects of precision agriculture

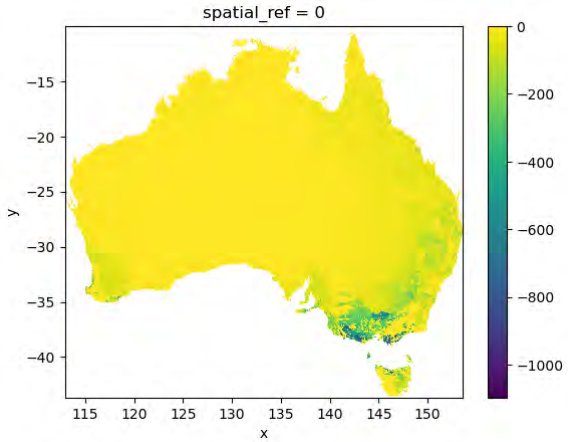

Figure 181 The livestock quantity for Beef - modified land meat under irrigation land management system by considering the effects of precision agriculture

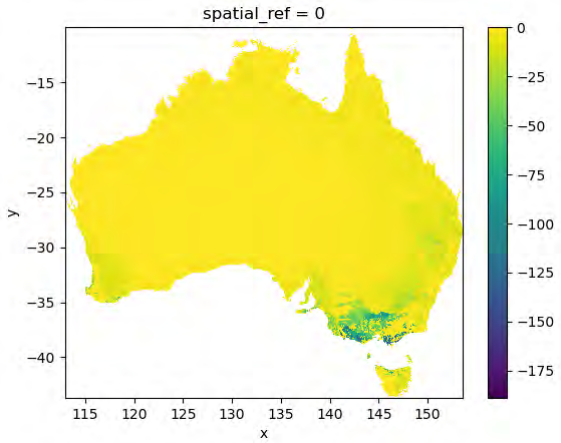

Figure 182 The livestock quantity for Sheep - modified land meat under dry land management system by considering the effects of precision agriculture

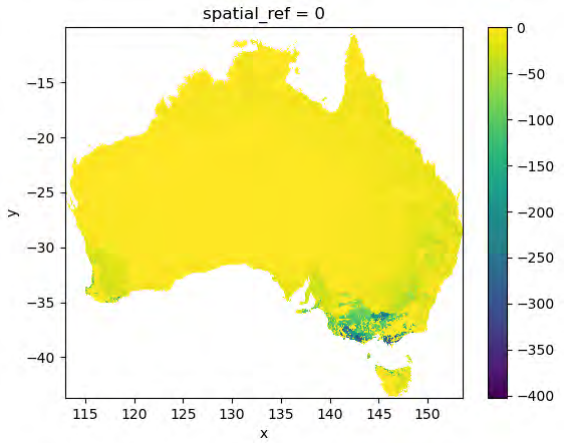

Figure 183 The livestock quantity for Sheep - modified land meat under irrigation land management system by considering the effects of precision agriculture

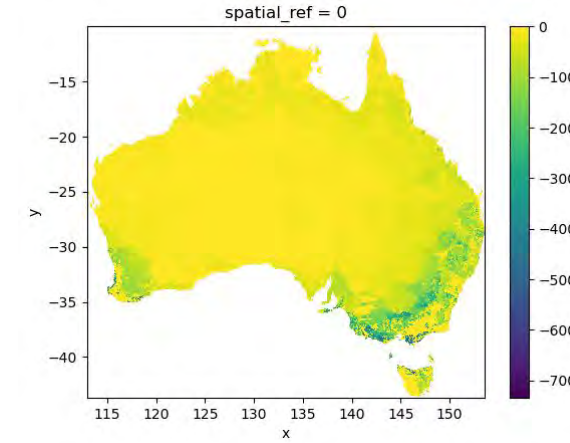

Figure 184 The livestock quantity for Dairy - modified land under dry land management system by considering the effects of precision agriculture

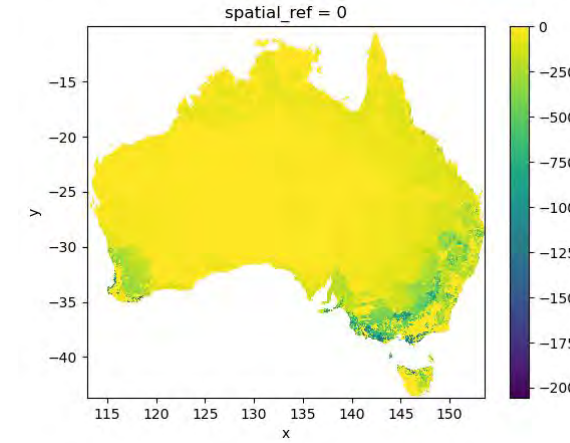

Figure 185 The livestock quantity for Dairy - modified land under dry land management system by considering the effects of precision agriculture

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6.4. Effects of Savanna Burning on Yield Quantity

Let $\mathbf{YieldQ}_{mr\ell}^{\text{SavBurn}}$ be a tensor representing the yield quantity for agricultural products ($\mathcal{L}_{\text{Products}}$) in land management systems where Savanna burning can be integrated. This tensor is initialized as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\text{Products}}$	Equation 130
$\mathbf{YieldQ}_{mr\ell}^{\text{SavBurn}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{Products}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k represents the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); and thus $N_k = 2$ (dry and irrigated management systems).
- $N_{lu}^{\text{Products}} = 32$, as the set $\mathcal{L}_{\text{Products}}$ consists of 32 products (Equation 37).

The tensor $\mathbf{YieldQ}_{mr\ell}^{\text{SavBurn}}$ is updated for products where Savanna burning is applied, using:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\} \exists\, \ell, \ell \in \mathcal{L}_{\text{Products}}$	Equation 131
$\mathbf{YieldQ}_{mr\ell}^{\text{SavBurn}}(y) = \begin{cases} \mathbf{CLYQ}_{mr\ell}^{AG,LS}(y) \times \left(1 - YQM_{\ell}^{\text{SavBurn}}(y)\right) & \text{if } \ell \in \phi(\text{Savanna Burning}) \text{ and } YQM_{\ell}^{\text{SavBurn}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Savanna Burning}) \text{ or } YQM_{\ell}^{\text{SavBurn}}(y) = 1 \end{cases}$	

where,

- $YQM_{\ell}^{\text{SavBurn}}(y)$ is the yield quantity multiplier
- $\mathbf{CLYQ}_{mr\ell}^{AG,LS}$ represents the yield quantity for all crop and livestock products ($\mathcal{L}_{\text{Products}}$) under dry and irrigated land management systems (Equation 123)
- $\phi(\text{Savanna Burning})$ is the set of products where Savana burning is implemented (Equation 31)

However, since Savana burning does no impact the quantity produced, LUTO 2.0 assumes:

$$YQM_{\ell}^{\text{SavBurn}}(y) = 1$$

Which results in zero effect on yield quantity for those affected cells.

6.5. Effects of AgTech EI on yield quantity

Let $\mathbf{YieldQ}_{mr\ell}^{\text{AgTech EI}}$ be a tensor representing the yield quantity for agricultural products ($\mathcal{L}_{\text{Products}}$) in land management systems where AgTech EI can be integrated. This tensor is initialized as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\text{Products}}$	Equation 132

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$\mathbf{YieldQ}_{mr\ell}^{\text{AgTech EI}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{Products}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k represents the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); and thus $N_k = 2$ (dry and irrigated management systems).
- $N_{lu}^{\text{Products}} = 32$, as the set $\mathcal{L}_{\text{Products}}$ consists of 32 products (Equation 37).

The tensor $\mathbf{YieldQ}_{mr\ell}^{\text{AgTech EI}}$ is updated for products where AgTech EI is applied, using:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}_{\text{Products}}$	Equation 133
$\mathbf{YieldQ}_{mr\ell}^{\text{AgTech EI}}(y) = \begin{cases} \mathbf{CLYQ}_{mr\ell}^{AG,LS}(y) \times \left(1 - YQM_{\ell}^{\text{AgTech EI}}(y)\right) & \text{if } \ell \in \phi(\text{AgTech EI}) \text{ and } YQM_{\ell}^{\text{AgTech EI}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{AgTech EI}) \text{ or } YQM_{\ell}^{\text{AgTech EI}}(y) = 1 \end{cases}$	

where,

- $YQM_{\ell}^{\text{AgTech EI}}(y)$ is the yield quantity multiplier
- $\mathbf{CLYQ}_{mr\ell}^{AG,LS}$ represents the yield quantity for all crop and livestock products ($\mathcal{L}_{\text{Products}}$) under dry and irrigated land management systems (Equation 123)
- $\phi(\text{AgTech EI})$ is the set of products where AgTech EI is implemented (Equation 33)

In the current version of LUTO 2.0, the yield quantity multiplier is set to:

$$YQM_{\ell}^{\text{AgTech EI}} = 1.055$$

for all years.

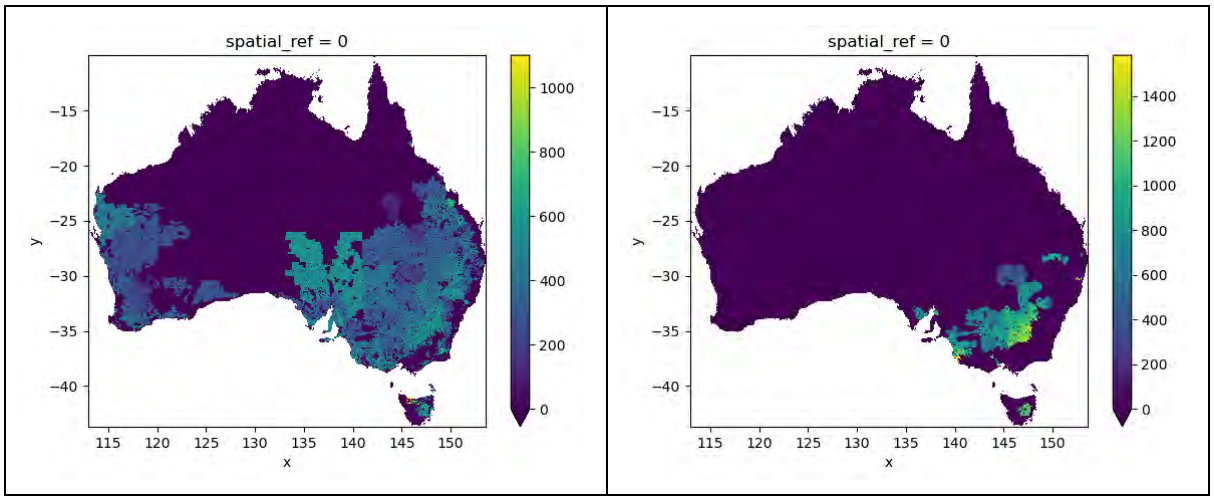

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Figure 186 The crop quantity for summer cereals under dry land management system by considering the effects of AgTech EI	Figure 187 The crop quantity for summer cereals under irrigation land management system by considering the effects of AgTech EI
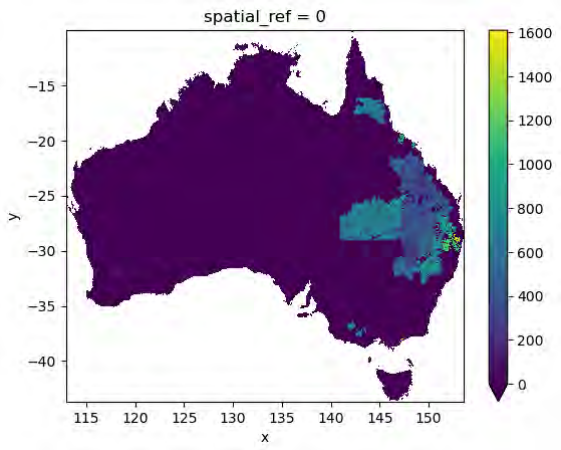	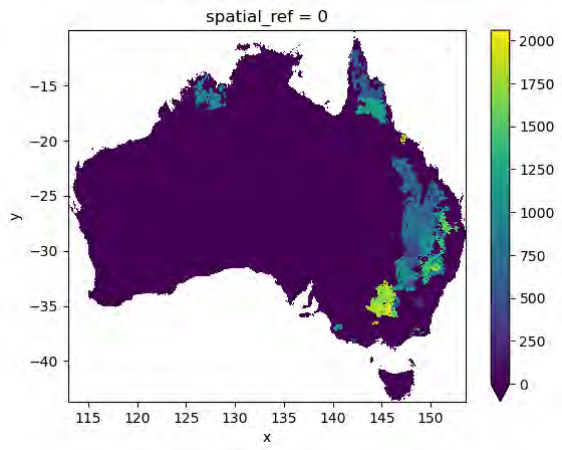
Figure 188 The crop quantity for summer cereals under dry land management system by considering the effects of AgTech EI	Figure 189 The crop quantity for summer cereals under irrigation land management system by considering the effects of AgTech EI
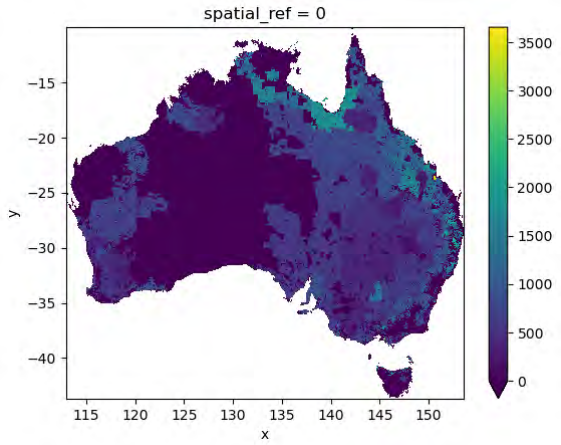	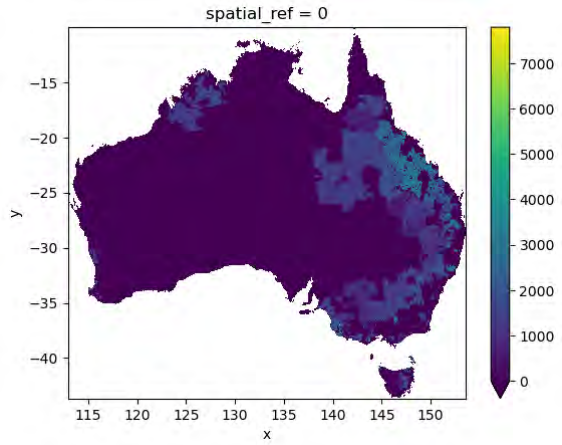
Figure 190 The crop quantity for hay under dry land management system by considering the effects of AgTech EI	Figure 191 The crop quantity for hay under irrigation land management system by considering the effects of AgTech EI

6.6. Effects of Agricultural Management Practices on Yield Quantity of All Relevant Land Use Classes

Define the variable $\mathbf{TranMatC}^{\mathrm{AGMP}}$, which represents a dictionary mapping agricultural management practice to their transition cost variable. This dictionary assigns a key k to the corresponding yield quantity matrix $\mathbf{TranMatC}^{k}_{mr\ell}$, defined as:

$\mathbf{YieldQ}^{\mathrm{AGMP}} = \left\{k \rightarrowtail \mathbf{YieldQ}^{k}_{mr\ell}(y) \middle| r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}, \mathbf{YieldQ}^{k}_{mr\ell}(y) \in \mathbb{R}^{N_k \times N_c \times N^{k}_{lu}}\right\}$	Equation 134

where,

- $\mathcal{K}$ is the set of agricultural management practices that can be applied to different land use types (Equation 22)
- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k represents the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); an thus $N_k = 2$ (dry and irrigated management systems).
- N_{lu}^{k} represents the number of land-use types for each agricultural management practice $\mathcal{K}$ (Equation 24-Equation 32)
- $\mathbb{R}$ represents the set of real number
- $\mathbf{YieldQ}_{mr\ell}^{k}(y)$ is the yield quantity Matrix integrating the k-th agricultural management practice.

The set $\mathcal{K}$ consists of agricultural management practices applicable to different land-use types (Equation 22). As defined in Equation 23, there exists a mapping function ϕ that associates elements from the set of agricultural management practices k to land-use types $\mathcal{L}$ (Equation 1) that are relevant to each practice.

The practices related to each agricultural management practice are detailed in Equation 24-Equation 32.

The initialized $\mathbf{YieldQ}^{\mathrm{AGMP}}$ (Equation 134) is updated, as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists k\ , k \in \mathcal{K}$	Equation 135
$\mathbf{YieldQ}^{\mathrm{AGMP}}(y) = \left\{ \begin{array}{lll} k \rightarrowtail \mathbf{YieldQ}_{mr\ell}^{\mathrm{AspTaxifor}}(y) & if & k \in \phi(\text{Asparagopsis taxiformis}) \\ k \rightarrowtail \mathbf{YieldQ}_{mr\ell}^{\mathrm{PrecAgric}}(y) & if & k \in \phi(\text{Precision Agriculture}) \\ k \rightarrowtail \mathbf{YieldQ}_{mr\ell}^{\mathrm{EcolGrazing}}(y) & if & k \in \phi(\text{Ecological Grazing}) \\ k \rightarrowtail \mathbf{YieldQ}_{mr\ell}^{\mathrm{SavBurn}}(y) & if & k \in \phi(\text{Savanna Burning}) \\ k \rightarrowtail \mathbf{YieldQ}_{mr\ell}^{\mathrm{AgTech\ EI}}(y) & if & k \in \phi(\text{AgTech EI}) \end{array} \right\}$	

where,

- $\mathcal{K}$ is the set of agricultural management practices applicable to different land use types (Equation 22)
- k represents a specific agricultural management practice type.
- $\mathbf{YieldQ}_{mr\ell}^{\mathrm{AspTaxifor}}(y)$ is the Yield Quantity Matrix integrating Asparagopsis taxiformis into agricultural land management strategies (Equation 125)
- $\mathbf{YieldQ}_{mr\ell}^{\mathrm{PrecAgric}}(y)$ is the Yield Quantity Matrix integrating Precision Agriculture into agricultural land management strategies (Equation 127)
- $\mathbf{YieldQ}_{mr\ell}^{\mathrm{EcolGrazing}}(y)$ is the Yield Quantity Matrix integrating Ecological Grazing into agricultural land management strategies (Equation 129)
- $\mathbf{YieldQ}_{mr\ell}^{\mathrm{SavBurn}}(y)$ is the Yield Quantity Matrix integrating Savanna Burning into agricultural land management strategies (Equation 131)
- $\mathbf{YieldQ}_{mr\ell}^{\mathrm{AgTech\ EI}}(y)$ is the Yield Quantity Matrix integrating AgTech EI into agricultural land management strategies (Equation 133)
- $\phi(\text{Asparagopsis taxiformis})$ is the Yield Quantity Matrix integrating Asparagopsis taxiformis into agricultural land management strategies (Equation 25)
- $\phi(\text{Precision Agriculture})$ is the Yield Quantity Matrix integrating Precision Agriculture into agricultural land management strategies (Equation 27)

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- $\phi(\text{Ecological Grazing})$ is the Yield Quantity Matrix integrating Ecological Grazing into agricultural land management strategies (Equation 29)
- $\phi(\text{Savanna Burning})$ is the Yield Quantity Matrix integrating Savanna Burning into agricultural land management strategies (Equation 31)
- $\phi(\text{AgTech EI})$ is the Yield Quantity Matrix integrating AgTech EI into agricultural land management strategies (Equation 33)

Each agricultural management practice affects specific land-use categories:

Practice	Relevant Land Use	Equation
$\phi(\text{Asparagopsis taxiformis})$	Primarily affects livestock on natural and modified land	Equation 25
$\phi(\text{Precision Agriculture})$	Primarily applied to cropping, intensive cropping, and horticulture	Equation 27
$\phi(\text{Ecological Grazing})$	Primarily applied to livestock on modified land	Equation 29
$\phi(\text{Savanna Burning})$	Primarily related to livestock on natural land and unallocated natural land	Equation 31
$\phi(\text{AgTech EI})$	Primarily affects cropping, intensive cropping, and horticulture	Equation 33

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7. The Water Requirements

7.1. Water requirements matrix for all land use classes under different land management system

Define $\mathbf{WReqM}_{mr\ell}^{AG,LS}(y)$, the water requirement matrix representing water requirements for land under dry and irrigation land management systems:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 136
$\mathbf{WReqM}_{mr\ell}^{AG,LS} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- N_{lu}: Number of land-use classes $\mathcal{L}$, which includes crop, livestock, and unallocated land purposes (Equation 1), $N_{lu} = 28$

This matrix $\mathbf{WReqM}_{mr\ell}^{AG,LS}$ is updated using the initial water requirements, adjusting for yield potential based on land use type, and converting units to megalitres (ML) per cell:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 137
$\mathbf{WReqM}_{mr\ell}^{AG,LS}(y) = \begin{cases} \mathbf{WReq}_{mr\ell}^{LS,Drink}(y) & \text{if } m = 0 \\ \mathbf{WReq}_{mr\ell}^{AG,LS}(y) & \text{if } m = 1 \end{cases}$	

where,

- $\mathbf{WReq}_{mr\ell}^{AG,LS}(y)$: Water requirements for both irrigation of crop lands and livestock drinking (Equation 141).
- $\mathbf{WReq}_{mr\ell}^{LS,Drink}(y)$: Water requirements for livestock drinking under dry land management (Equation 138).

7.2. Water requirements for drinking of Livestock under dry land management

For dry land management $m = 0$, livestock drinking water requirements $\mathbf{WReq}_{mr\ell}^{LS,Drink}$ are calculated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}\ \exists \ell, \ell \in \mathcal{L}_{\mathrm{Livestock}}$	Equation 138
$\mathbf{WReq}_{mr\ell}^{LS,Drink}(y) = \mathbf{FWR}_{mr\ell}^{LS,Drink} \times LDW_l^{LS} \times \mathbf{RA}_r \times \mathbf{YPot}_{mr\ell}^{LS}(y)$	

where,

- $\mathbf{FWR}_{mr\ell}^{LS,Drink}$: Fixed area-based drinking water requirements per head for all livestock available in $\mathcal{L}_{\mathrm{Crops}}$ (Figure 192-Figure 194)
- LDW_l^{LS}: Livestock drinking water factor (0 or 1)

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- $\mathbf{YPot}_{mr\ell}^{LS}(y)$: Yield potential for livestock ℓ under dry land management (Figure 117,Figure 119,Figure 121,Figure 123,Figure 125,Figure 127). This parameter is computed using Equation 113.
- $\mathbf{RA}_r$: Real area multiplier (Figure 5)

7.3. Water requirements for irrigation of Livestock fields under irrigation land management

For irrigation land management $m = 1$:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}\ \exists \ell, \ell \in \mathcal{L}_{\text{Livestock}}$	
$\mathbf{WReq}_{mr\ell}^{LS,Irrigat} = \mathbf{FWR}_{mr\ell}^{LS,Irr} \times \mathbf{RA}_r$	Equation 139

where,

- $\mathbf{FWR}_{mr\ell}^{LS,Irr}$: Fixed area-based water requirements for irrigation (Figure 195-Figure 197)
- $\mathbf{RA}_r$: Real area multiplier (Figure 5)

7.4. Combined water requirements for drinking of Livestock under irrigation land management

Water requirements for irrigation and drinking of livestock under irrigation land management ($m = 1$):

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, y = 2010\ \exists \ell, \ell \in \mathcal{L}_{\text{Livestock}}$	Equation 140
$\mathbf{WReq}_{mr\ell}^{LS,Drink}(y) = \mathbf{FWR}_{mr\ell}^{LS,Drink} \times LDW_{\ell}^{LS} \times \mathbf{RA}_r \times \mathbf{YPot}_{mr\ell}^{LS}(y)$	

where,

- $\mathbf{FWR}_{mr\ell}^{LS,Drink}$: Fixed area-based drinking water requirements per head for all livestock available in $\mathcal{L}_{\text{Crops}}$ (Figure 192-Figure 194)
- LDW_{l}^{LS}: Livestock drinking water factor (0 or 1)
- $\mathbf{YPot}_{mr\ell}^{LS}(y)$: Yield potential for livestock ℓ under irrigated land managment system for the base year $y = 2010$ (Figure 118,Figure 120,Figure 122,Figure 124,Figure 126,Figure 128). This parameter is computed using Equation 113.
- $\mathbf{RA}_r$: Real area multiplier (Figure 5)

7.5. Combined water requirements for irrigation and drinking of Livestock under irrigation land management

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}\ \exists \ell, \ell \in \mathcal{L}_{\text{Livestock}}$	

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$$\mathbf{WReq}_{mr\ell}^{AG,LS}(y) = \mathbf{WReq}_{mr\ell}^{LS,Irrigat}(y) + \mathbf{WReq}_{mr\ell}^{LS,Drink}(y)$$	Equation 141

where,

- $\mathbf{WReq}_{mr\ell}^{LS,Irrigat}$ is the water requirements for irrigation of livestock fields (Equation 139, Figure 195-Figure 197)
- $\mathbf{WReq}_{mr\ell}^{LS,Drink}$ is the water requirements for livestock drinking (Equation 140, Figure 192-Figure 194)
- $\mathbf{WReq}_{mr\ell}^{AG,LS}(y)$ is the water requirements for drinking and irrigation of livestock under irrigation land management (Figure 198-Figure 200)

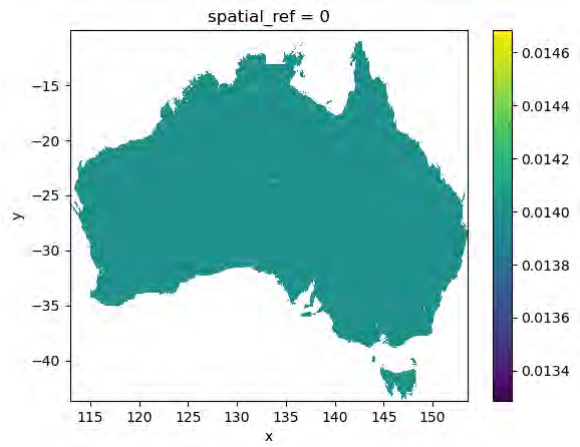

Figure 192 The fixed area-based drinking water requirements per head for Beef

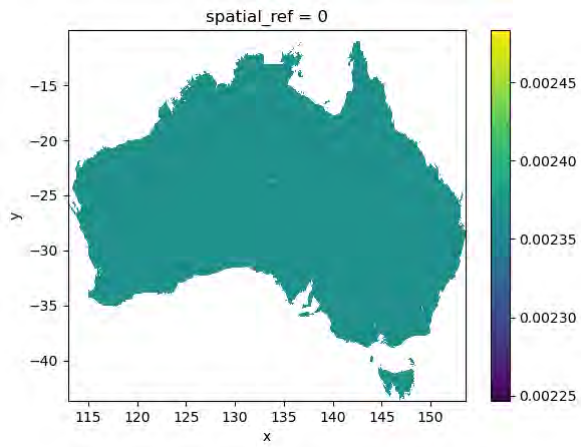

Figure 193 The fixed area-based drinking water requirements per head for Sheep

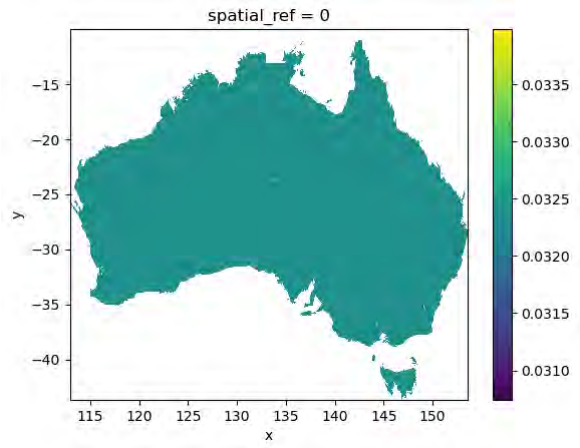

Figure 194 The fixed area-based drinking water requirements per head for Dairy

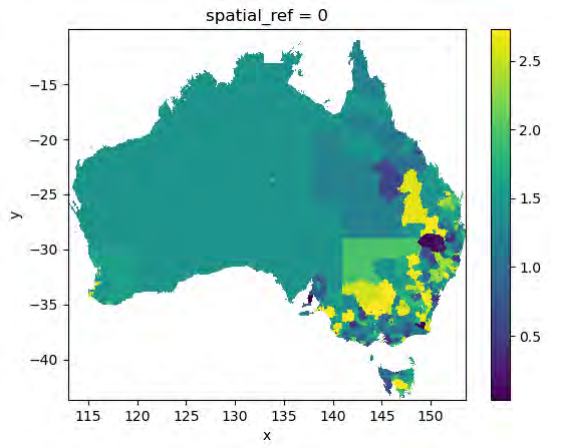

Figure 195 The fixed area-based irrigation water requirements per head for Beef

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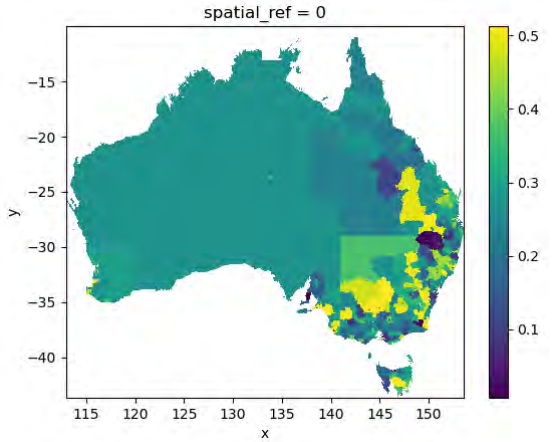

Figure 196 The fixed area-based irrigation water requirements per head for Sheep

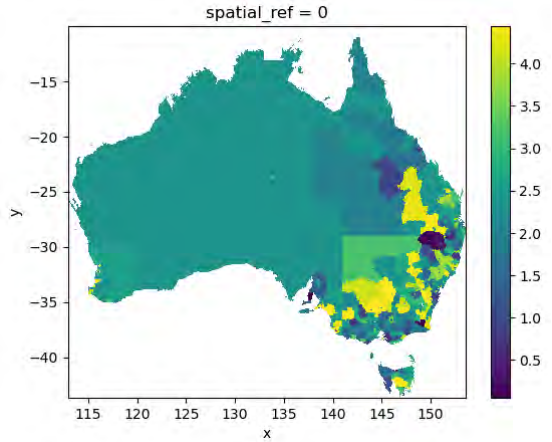

Figure 197 The fixed area-based irrigation water requirements per head for Dairy

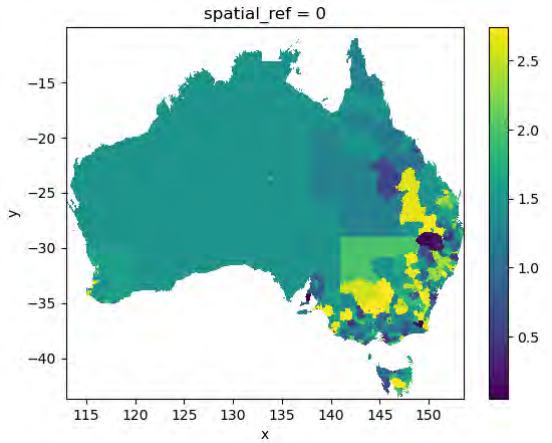

Figure 198 Water requirements for irrigation and drinking of Beef under irrigation land management system

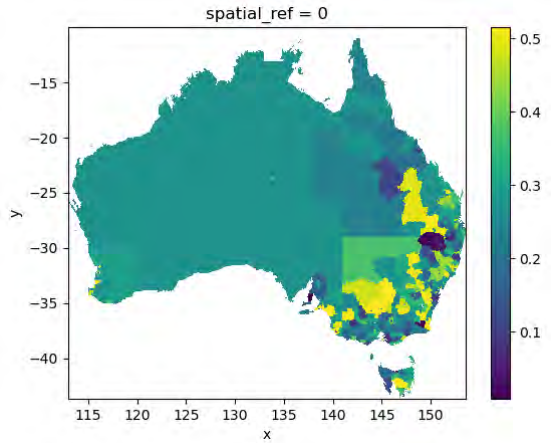

Figure 199 Water requirements for irrigation and drinking of Sheep under irrigation land management system

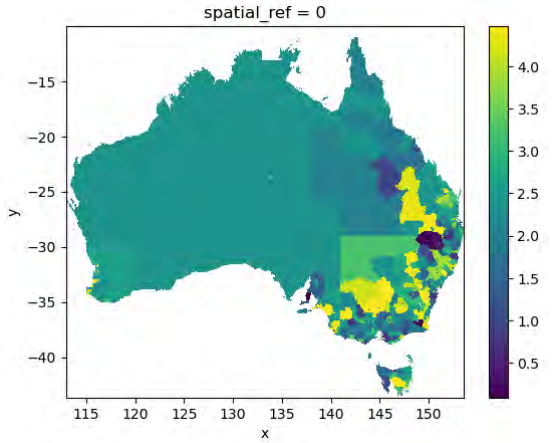

Figure 200 Water requirements for irrigation and drinking of Dairy under irrigation land management system

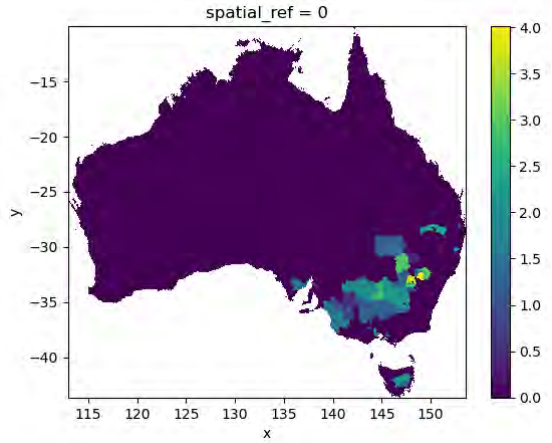

Figure 201 The fixed area-based irrigation water requirements for winter cereals

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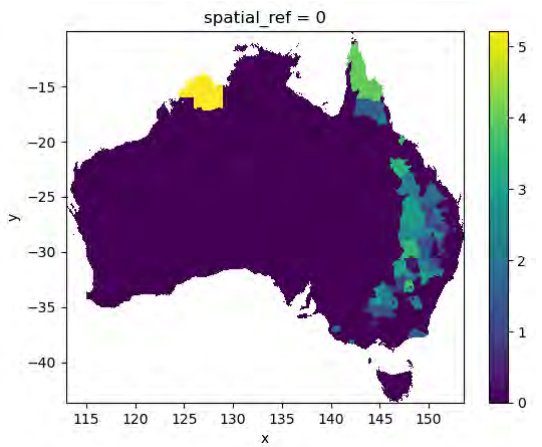	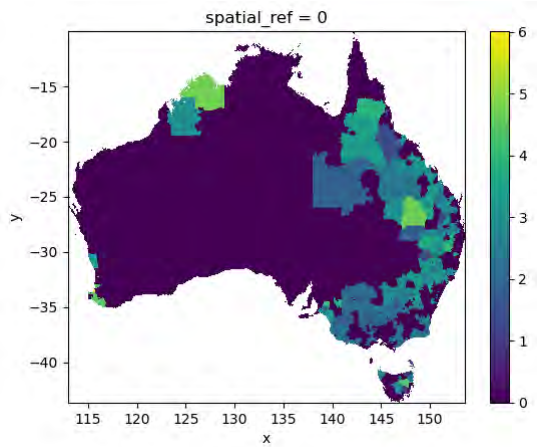
Figure 202 The fixed area-based irrigation water requirements for summer cereals	Figure 203 The fixed area-based irrigation water requirements for Hay

7.6. Water Yield Matrix

To compute the water yield matrix $\mathbf{WYield}_{mr\ell}$, we define:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 142
$\mathbf{WYield}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k represents the number of agricultural management practices ($m \in \mathcal{M}$ as defined in Equation 21); and thus $N_k = 2$ (dry and irrigated management systems).
- $N_{lu} = 28$, as the set $\mathcal{L}$ includes all land use classes assigned to crop, livestock, and unallocated land purposes (Equation 1).

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 143
$\mathbf{WYield}_{mr\ell}(y) = \begin{cases} \mathbf{WYield}_r^{SR}(y) \times \mathbf{RA}_r & \text{if } \ell \in \mathcal{L}_{\mathrm{SR}} \\ \mathbf{WYield}_r^{DR}(y) \times \mathbf{RA}_r & \text{if } \ell \in \mathcal{L}_{\mathrm{DR}} \\ \mathbf{WYield}_r^{NL}(y) \times \mathbf{RA}_r & \text{if } \ell \in \mathcal{L}_{\mathrm{NatAgLu}} \end{cases}$	

where,

- $\mathbf{WYield}_{mr\ell}(y)$ is the water yield matrix for Cell r in year y.
- $\mathbf{WYield}_r^{SR}(y)$ is the water yield for Cell r covered by Shallow-rooted plants in year y.
- $\mathbf{WYield}_r^{DR}(y)$ is the water yield for Cell r covered by Deep-rooted plants in year y.
- $\mathbf{WYield}_r^{NL}(y)$ is the water yield for Cell r in the Natural Area Class, computed by Equation 144.
- $\mathbf{RA}_r$ is the real area multiplier (Figure 5)
- $\mathcal{L}_{\mathrm{NatAgLu}}$ is the set of natural land-use classes (Equation 18)
- $\mathcal{L}_{\mathrm{DR}}$ is the set of deep-rooted plants (Equation 43)
- $\mathcal{L}_{\mathrm{SR}}$ is the set of Shallow-rooted plants (Equation 44)

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For each cell r under an agricultural management practice m in year y, the water yield matrix $\mathbf{WYield}_{mr\ell}(y)$ is identical for all land-use classes within $\mathcal{L}_{\mathrm{DR}}$, $\mathcal{L}_{\mathrm{SR}}$ and $\mathcal{L}_{\mathrm{NatAgLu}}$. Since agricultural management practices m do not influence $\mathbf{WYield}_{mr\ell}(y)$, a single representative land-use class is selected from each of $\mathcal{L}_{\mathrm{DR}}$, $\mathcal{L}_{\mathrm{SR}}$ and $\mathcal{L}_{\mathrm{NatAgLu}}$ to illustrate water yield distributions. Example maps (year 2050): Figure 207, Figure 208, and Figure 209 visualize $\mathbf{WYield}_{mr\ell}$ for land-use classes assigned to $\mathcal{L}_{\mathrm{DR}}$, $\mathcal{L}_{\mathrm{SR}}$ and $\mathcal{L}_{\mathrm{NatAgLu}}$, respectively. A display threshold of 1000 was chosen for visualization; actual values may exceed this threshold.

In LUTO 2.0, the water yield in natural land areas $\mathbf{WYield}_r^{NL}(y)$ is computed, as:

$\mathbf{WYield}_r^{NL}(y) = (\mathbf{DRProp}_r \times \mathbf{WYield}_r^{DR}(y)) + [(1 - \mathbf{DRProp}_r) \times \mathbf{WYield}_r^{SR}(y)]$	Equation 144

where,

- $\mathbf{DRProp}_r(y)$ is the proportion of available deep-rooted plants (Figure 210)
- $\mathbf{WYield}_r^{SR}(y)$ is the water yield for shallow-rooted plants in cell r in year y.
- $\mathbf{WYield}_r^{DR}(y)$ is the water yield for deep-rooted plants in cell r in year y.

7.7. Water net yield matrices

The water net yield matrices are computed based on land management type, cell, and land-use category. The net yield is calculated as:

$\mathbf{WYield}_{mr\ell}^{Net}(y) = \mathbf{WYield}_{mr\ell}(y) - \mathbf{WReqM}_{mr\ell}^{AG,LS}(y)$	Equation 145

where,

- $\mathbf{WYield}_{mr\ell}^{Net}(y)$ is the water net yield matrices
- $\mathbf{WYield}_{mr\ell}(y)$ is the water yield matrix, computed by Equation 143.
- $\mathbf{WReqM}_{mr\ell}^{AG,LS}(y)$ represents water requirements for all land uses in year y (Equation 137).

Similar to Equation 143, for each given cell r under an agricultural management practice m in year y, the net water yield matrix $\mathbf{WYield}_{mr\ell}^{Net}(y)$ is identical for all land-use classes within $\mathcal{L}_{\mathrm{DR}}$, $\mathcal{L}_{\mathrm{SR}}$ and $\mathcal{L}_{\mathrm{NatAgLu}}$.

Example maps (year 2050):

- Figure 211, Figure 213, and Figure 215 illustrate net water yield under dry land management for $\mathcal{L}_{\mathrm{SR}}$, $\mathcal{L}_{\mathrm{DR}}$ and $\mathcal{L}_{\mathrm{NatAgLu}}$, respectively.
- Figure 212, Figure 214, and Figure 216 illustrate net water yield under irrigation land management for $\mathcal{L}_{\mathrm{SR}}$, $\mathcal{L}_{\mathrm{DR}}$ and $\mathcal{L}_{\mathrm{NatAgLu}}$, respectively.

A display threshold of 2000 was chosen for visualization; actual values may exceed this threshold.

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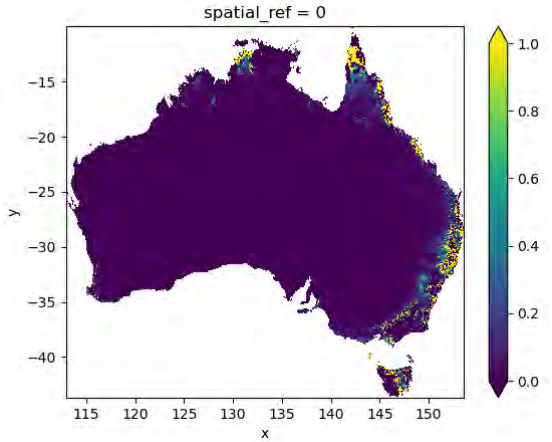

Figure 204 Water yield value for the cells that are covered by Deep-rooted plants $\mathbf{WYield}_r^{DR}$

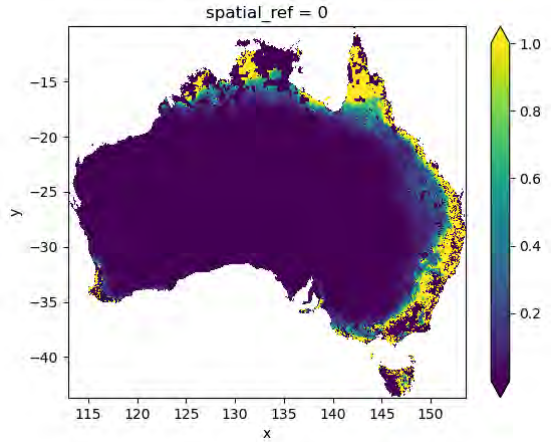

Figure 205 Water yield value for the cells that are covered by Shallow-rooted plants $\mathbf{WYield}_r^{SR}$

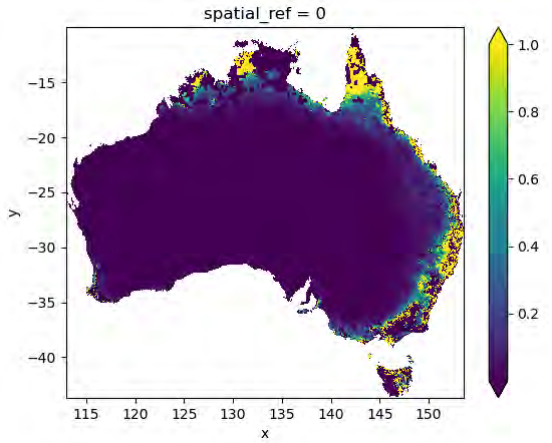

Figure 206 Water yield value for the cells that are covered by natural land plants $\mathbf{WYield}_r^{NL}$

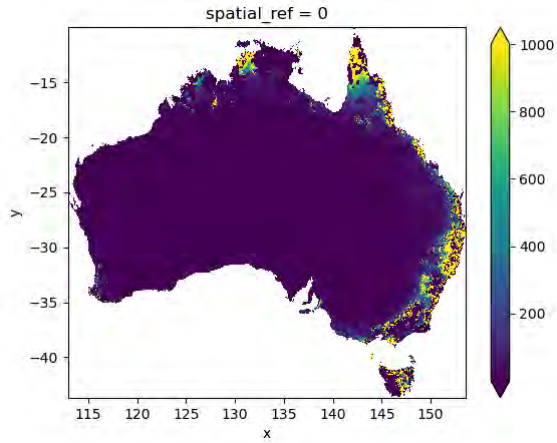

Figure 207 Water yield matrix $\mathbf{WYield}_{mr\ell}$ of grapes as a sample of classes that are available in $\mathcal{L}_{\mathrm{DR}}$ in year 2050.

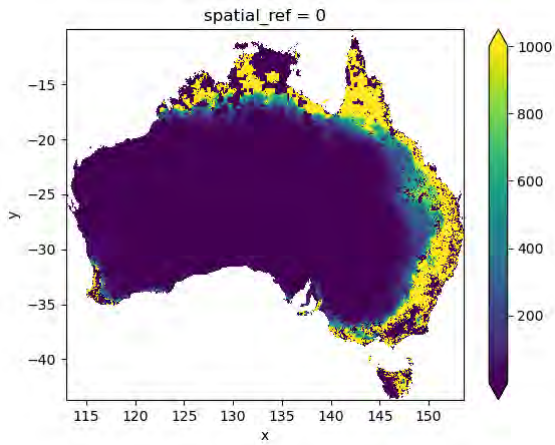

Figure 208 Water yield matrix $\mathbf{WYield}_{mr\ell}$ of winter cereals as a sample of classes that are available in $\mathcal{L}_{\mathrm{SR}}$ in year 2050.

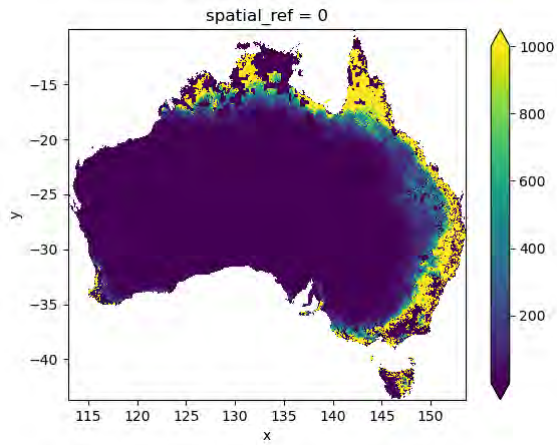

Figure 209 Water yield matrix $\mathbf{WYield}_{mr\ell}$ of Beef-Natural land as a sample of classes that are available in $\mathcal{L}_{\mathrm{NatAgLu}}$ in year 2050.

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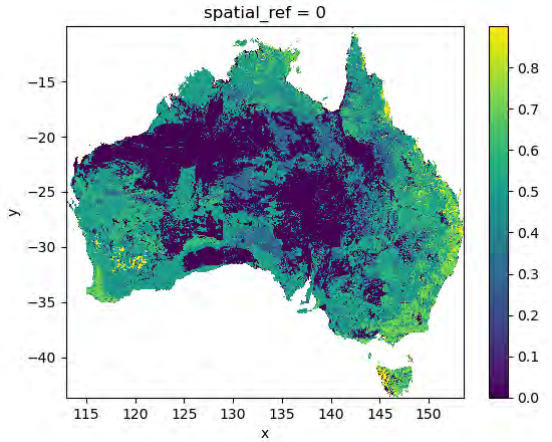

Figure 210 The proportion of available Deep-rooted plants $\mathbf{DRProp}_r$

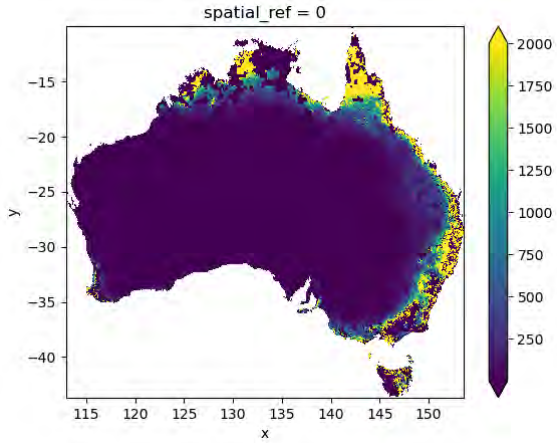

Figure 211 Water net yield of winter cereals under dry land management system as a sample of classes that are available in $\mathcal{L}_{\mathrm{SR}}$ in year 2050.

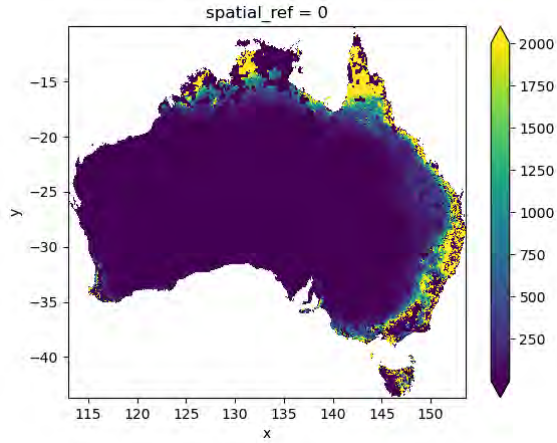

Figure 212 Water net yield of winter cereals under irrigation land management system as a sample of classes that are available in $\mathcal{L}_{\mathrm{SR}}$ in year 2050.

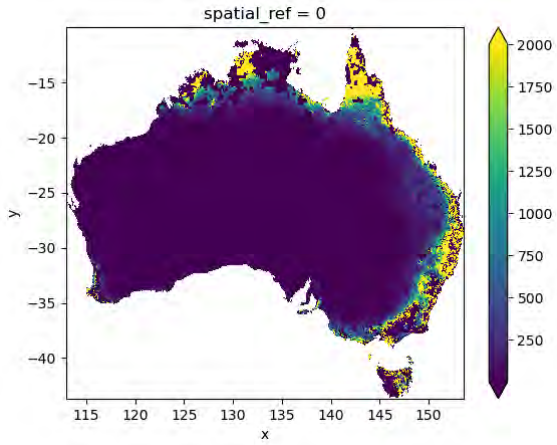

Figure 213 Water bet yield of grapes under dry land management system as a sample of classes that are available in $\mathcal{L}_{\mathrm{DR}}$ in year 2050.

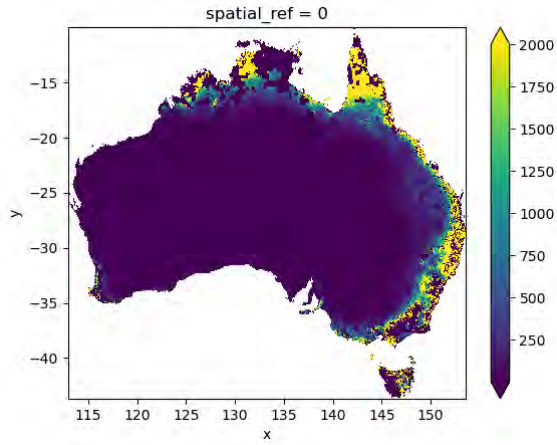

Figure 214 Water net yield of grapes under irrigation land management system as a sample of classes that are available in $\mathcal{L}_{\mathrm{DR}}$ in year 2050.

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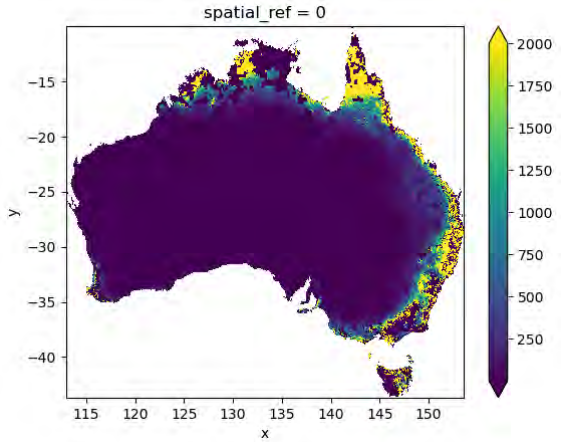

Figure 215 Water net yield of Beef-Natural land under dry land management system as a sample of classes that are available in $\mathcal{L}_{\mathrm{NatAgLu}}$ in year 2050.

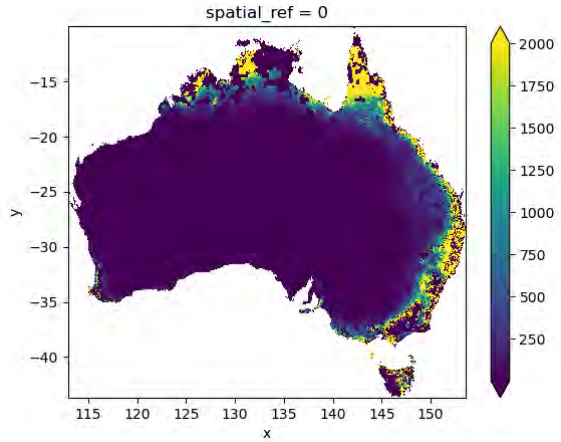

Figure 216 Water net yield of Beef-Natural land under irrigation land management system as a sample of classes that are available in $\mathcal{L}_{\mathrm{NatAgLu}}$ in year 2050.

7.8. Climate Change Impacts on water yield

This section quantifies the impact of climate change (CC) on water yield based on land management, spatial units (cells), and land-use types. The analysis extends beyond the typical LUTO assessment, incorporating urban and public service areas.

7.8.1. Climate Change Scenario Selection

To evaluate climate change impacts, LUTO 2.0 assumes that climate protection measures are implemented. Among the available Shared Socioeconomic Pathways (SSPs):

- SSP126 (low emissions)
- SSP245 (moderate emissions)
- SSP370 (high emissions)
- SSP585 (very high emissions)

LUTO selects SSP245, which represents a medium emissions trajectory with an additional radiative forcing of 4.5 W/m² by 2100. This scenario is an updated version of RCP4.5, commonly used for moderate future climate projections.

7.8.2. Defining Spatial Boundaries for Water Yield Analysis

To assess climate change impacts on water yield, LUTO 2.0 considers two possible spatial boundary definitions:

1- River Regions (RR)

- Defined by watersheds that capture water flowing into individual river systems.
- Used for local hydrological assessments.

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2- Drainage Divisions (DD)

- Larger hydrological regions encompassing multiple river basins.
- Define how water drains into larger systems, such as basins or oceans.

Both River Region and Drainage Division boundaries are illustrated in Figure 234.

7.8.3. Climate Change Impact Calculations on Water Yield

The climate change impact on water yield is computed at two levels, depending on the selected spatial boundary:

1. If the water region is set as 'River Region':
   - The output is stored in $\mathbf{WYield}_{\mathrm{RR}}^{\mathrm{CCI}}$, a dictionary containing water yield climate change impact data.
   - Each key y (year) maps to a vector with N_{RR} records, corresponding to river regions under SSP245.
2. If the water region is set as 'Drainage Division':
   - The output is stored in $\mathbf{WYield}_{\mathrm{DD}}^{\mathrm{CCI}}$, a dictionary containing water yield climate change impact data.
   - Each key y (year) maps to a vector with N_{DD} records, corresponding to drainage divisions under SSP245.

$\forall y \in \{2010, \cdots, 2100\}$	Equation 146
$\mathbf{WYield}_{\mathrm{DD}}^{\mathrm{CCI}} = \{y \rightarrowtail \mathbf{CCI}_{SSP}^{DD}(y) \mid \mathbf{CCI}_{SSP}^{DD} \in \mathbb{R}^{91 \times N_{DD}}\}$	
$\mathbf{WYield}_{\mathrm{RR}}^{\mathrm{CCI}} = \{y \rightarrowtail \mathbf{CCI}_{SSP}^{RR}(y) \mid \mathbf{CCI}_{SSP}^{RR} \in \mathbb{R}^{91 \times N_{RR}}\}$	

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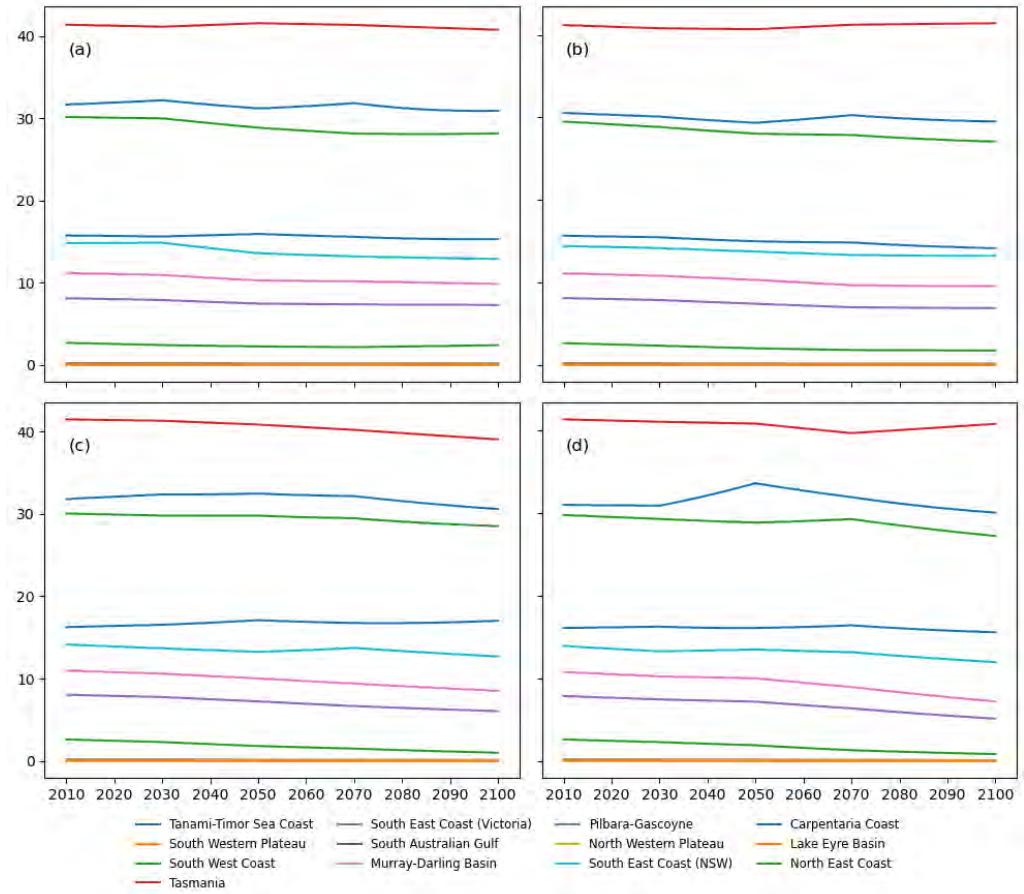

Figure 217 The climate change (CC) impact on Drainage Divisions under different Scenarios; (a) SSp126, (b) SSP245, (c) SSP370, (d)SSP585

The results highlight spatial variations in climate change-induced water yield changes. These variations depend on the chosen SSP scenario, with SSP126 (low emissions) showing minimal impact and SSP585 (high emissions) indicating significant changes.

8. Impacts of Agricultural Management Practices on Water Requirements

This section evaluates how various agricultural management practices impact water requirements for different land-use classes under dry and irrigation land management systems.

8.1. Effects of Asparagopsis Taxiformis on Water Requirements

To assess the impact of integrating Asparagopsis taxiformis into agricultural land management strategies, we define the updated water requirements matrix $\mathbf{WReqM}_{mr\ell}^{\text{AspTaxifor}}$:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Asparagopsis taxiformis})$	Equation 147
$\mathbf{WReqM}_{mr\ell}^{\text{AspTaxifor}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AspTaxifor}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.

- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{AspTaxifor}}$ is 6, as Asparagopsis taxiformis affects beef, sheep, and dairy production on both natural and modified land, $N_{lu} = 6$ (Equation 25).

Let update $\mathbf{WReqM}_{mr\ell}^{\text{AspTaxifor}}$, we apply:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}_{\text{Livestock}}$	Equation 148
$\mathbf{WReqM}_{mr\ell}^{\text{AspTaxifor}}(y) = \begin{cases} \mathbf{WReqM}_{mr\ell}^{AG,LS}(y) \times \left(1 - WIM_{\ell}^{\text{AspTaxifor}}(y)\right) & \text{if } \ell \in \phi(\text{Asparagopsis taxiformis}) \text{ and } WIM_{\ell}^{\text{AspTaxifor}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Asparagopsis taxiformis}) \text{ or } WIM_{\ell}^{\text{AspTaxifor}}(y) = 1 \end{cases}$	

where,

- $WIM_{\ell}^{\text{AspTaxifor}}(y)$ is the water impact multiplier
- $\mathbf{WReqM}_{mr\ell}^{AG,LS}(y)$ represents water requirements for all livestock land-use classes $\mathcal{L}_{\text{Livestock}}$ (Equation 16) under dry and irrigated system, computed in Equation 137.
- $\phi(\text{Asparagopsis taxiformis})$ is the set of livestock products influenced by Asparagopsis taxiformis (Equation 25)

LUTO 2.0 Assumption: Currently, $WIM_{\ell}^{\text{AspTaxifor}} = 1$, meaning no impact on water requirements.

8.2. Effects of Precision Agriculture on Water Requirements

To integrate Precision Agriculture into agricultural land management strategies, the updated water requirements matrix is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 149
$\mathbf{WReqM}_{mr\ell}^{\text{PrecAgric}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{PrecAgric}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{PrecAgric}} = 20$, as precision agriculture affects 20 land use classes (Equation 27).

The matrix is updated as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 150
$\mathbf{WReqM}_{mr\ell}^{\text{PrecAgric}}(y) = = \begin{cases} \mathbf{WReqM}_{mr\ell}^{AG,LS}(y) \times \left(1 - WIM_{\ell}^{\text{PrecAgric}}(y)\right) & \text{if } \ell \in \phi(\text{Precision Agriculture}) \text{ and } WIM_{\ell}^{\text{PrecAgric}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Precision Agriculture}) \text{ or } WIM_{\ell}^{\text{PrecAgric}}(y) = 1 \end{cases}$	

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where,

- $WIM_{\ell}^{\text{PrecAgric}}(y)$ is the water impact multiplier (Figure 218)
- $\mathbf{WReqM}_{mr\ell}^{AG,LS}(y)$ represents the water requirements data in year y for all land uses available in $\phi(\text{Precision Agriculture})$ under dry and irrigation land management systems, computed by Equation 137.
- $\phi(\text{Precision Agriculture})$ refers to land-use types impacted by precision agriculture (Equation 27).

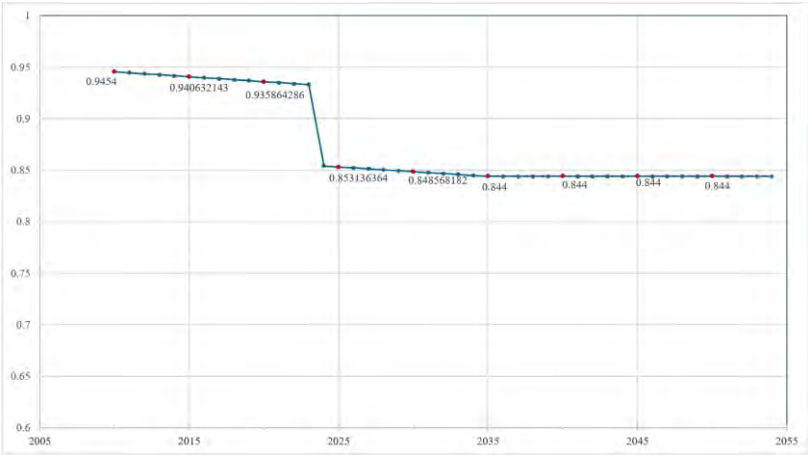

Figure 218 The water impact multiplier of precision agriculture effects

The updated water requirements $\mathbf{WReqM}_{mr\ell}^{\text{PrecAgric}}$ for winter cereals , summer cereals, hay, and grapes under irrigation systems are illustrated in Figure 219-Figure 222.

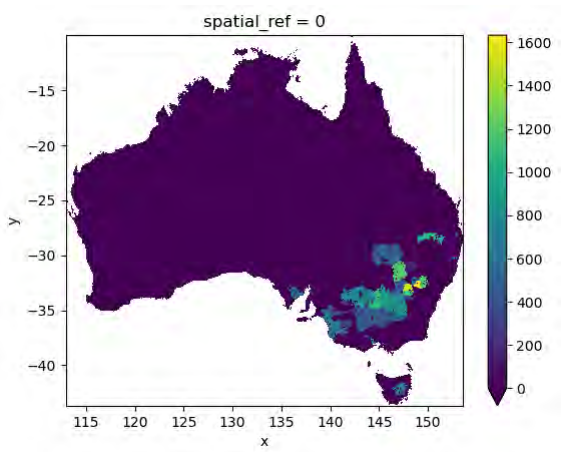

Figure 219 The water requirements for winter cereals under irrigation land management system by considering the effects of precision agriculture

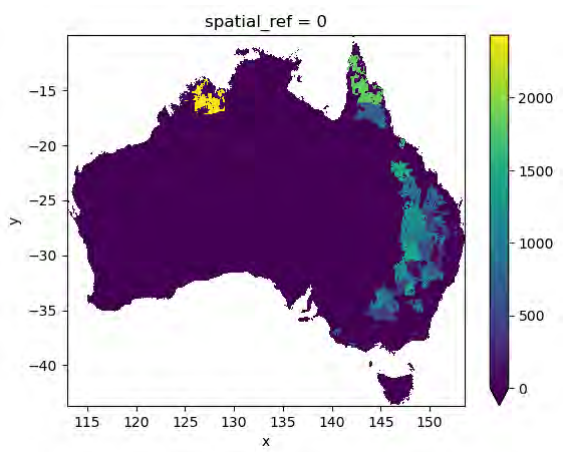

Figure 220 The crop quantity for summer cereals under irrigation land management system by considering the effects of precision agriculture

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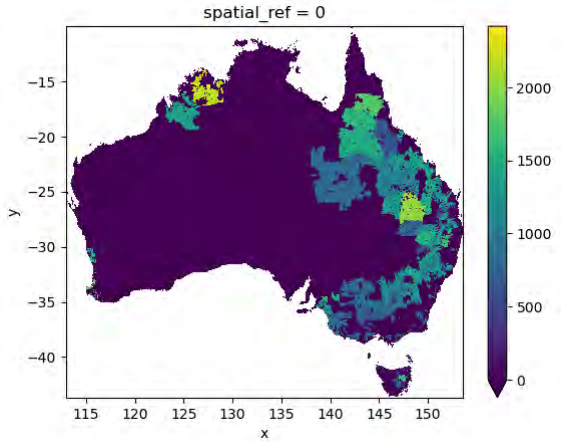	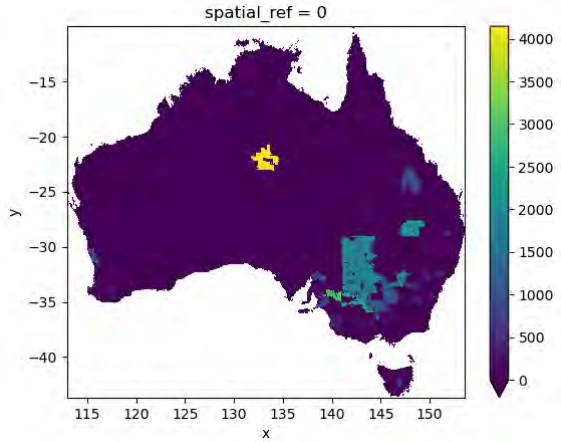
Figure 221 The crop quantity for hay under irrigation land management system by considering the effects of precision agriculture	Figure 222 The crop quantity for grapes under irrigation land management system by considering the effects of precision agriculture

8.3. Effects of ecological grazing on Water Requirements

To assess the water impact of ecological grazing, the updated matrix is:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Ecological Grazing})$	Equation 151
$\mathbf{WReqM}_{mr\ell}^{\text{EcolGrazing}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{EcolGrazing}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{EcolGrazing}} = 3$, as ecological grazing affects beef, sheep, and dairy production on modified land (Equation 29).

The updated values are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Ecological Grazing})$	Equation 152
$\mathbf{WReqM}_{mr\ell}^{\text{EcolGrazing}}(y) = = \begin{cases} \mathbf{WReqM}_{mr\ell}^{AG,LS}(y) \times \left(1 - WIM_{\ell}^{\text{EcolGrazing}}(y)\right) & \text{if } \ell \in \phi(\text{Ecological Grazing}) \text{ and } WIM_{\ell}^{\text{EcolGrazing}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Ecological Grazing}) \text{ or } WIM_{\ell}^{\text{EcolGrazing}}(y) = 1 \end{cases}$	

where,

- $WIM_{\ell}^{\text{EcolGrazing}}(y)$ is the water impact multiplier (Figure 218)
- $\mathbf{WReqM}_{mr\ell}^{AG,LS}(y)$ represents the water requirements data in year y for all land uses available in $\phi(\text{Ecological Grazing})$ (Equation 29) under dry and irrigation land management systems, computed by Equation 137.

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- $\phi(\text{Precision Agriculture})$ refers to land-use types impacted by precision agriculture (Equation 27).

In the current version of LUTO 2.0, the water impact multiplier is $WIM_{\ell}^{\text{EcolGrazing}}(y) = 0.8$ for all years and all livestock products. Figure 223-Figure 228 illustrate the computed water requirements for all classes under ecological grazing in dry and irrigated systems.

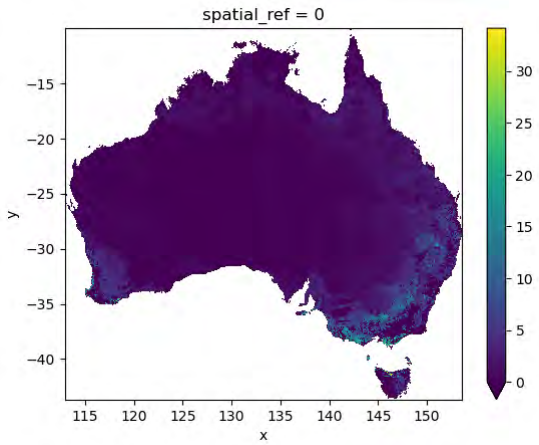

Figure 223 The water requirements for Beef - modified land meat under dry land management system by considering the effects of precision agriculture

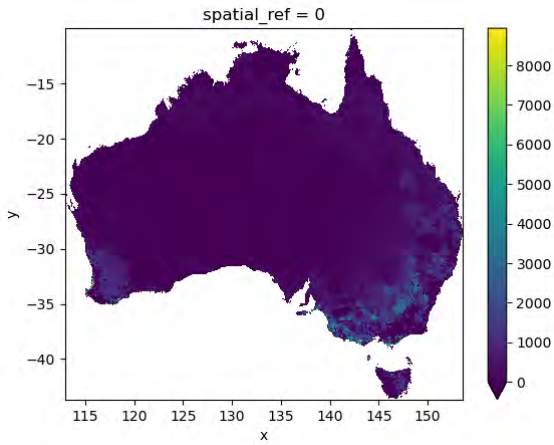

Figure 224 The water requirements for Beef - modified land meat under irrigation land management system by considering the effects of precision agriculture

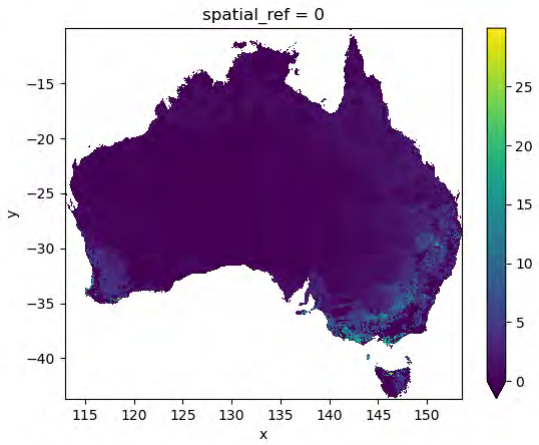

Figure 225 The water requirements for Sheep - modified land Meat under dry land management system by considering the effects of precision agriculture

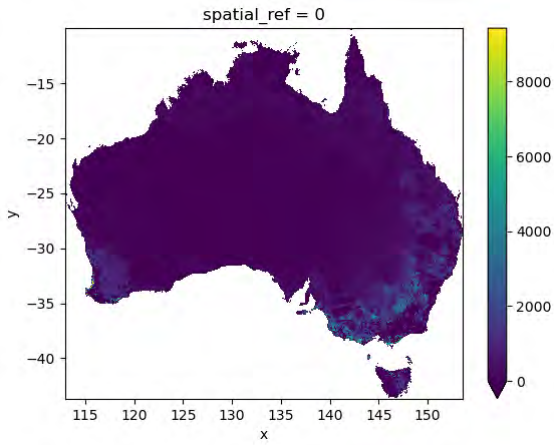

Figure 226 The water requirements for Sheep - modified land Meat under irrigation land management system by considering the effects of precision agriculture

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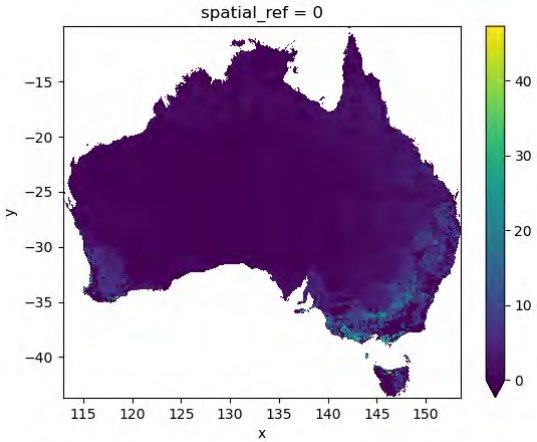	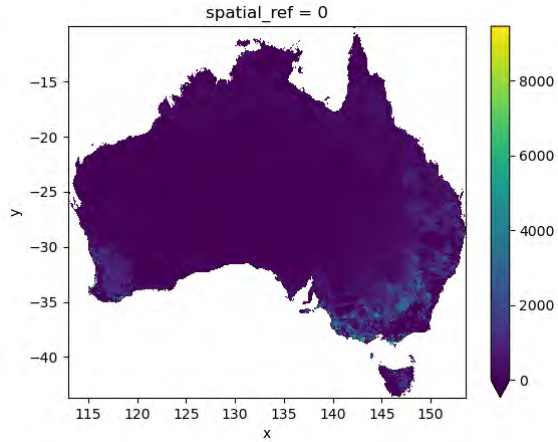
Figure 227 The water requirements for Dairy - modified land under dry land management system by considering the effects of precision agriculture	Figure 228 The water requirements for Dairy - modified land under dry land management system by considering the effects of precision agriculture

8.4. Effects of Savana burning on the Water Requirements

To integrate Savanna burning into agricultural land management strategies, we define the updated water requirements matrix:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 153
$\mathbf{WReqM}_{mr\ell}^{\text{SavBurn}} = 0_{(N_k \times N_c \times N_{lu}^{\text{SavBurn}})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{SavBurn}} = 4$, as Savana burning affects beef, sheep, and dairy production on natural and unallocated natural land (Equation 31).

To update $\mathbf{WReqM}_{mr\ell}^{\text{SavBurn}}$, we apply:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 154
$\mathbf{WReqM}_{mr\ell}^{\text{SavBurn}}(y) = = \begin{cases} \mathbf{WReqM}_{mr\ell}^{AG,LS}(y) \times \left(1 - WIM_{\ell}^{\text{SavBurn}}(y)\right) & \text{if } \ell \in \phi(\text{Savanna Burning}) \text{ and } WIM_{\ell}^{\text{SavBurn}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Savanna Burning}) \text{ or } WIM_{\ell}^{\text{SavBurn}}(y) = 1 \end{cases}$	

where,

- $WIM_{\ell}^{\text{SavBurn}}(y)$ is the water impact multiplier.
- $\mathbf{WReqM}_{mr\ell}^{AG,LS}(y)$ represents water requirements for all land uses under Savanna burning $\phi(\text{Savanna Burning})$ (Equation 31) computed in Equation 137.

Savana burning has no effect on water requirements; hence LUTO 2.0 considered $WIM_{\ell}^{\text{SavBurn}}(y) = 1$; meaning no impact on water requirements.

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8.5. Effects of AgTech EI on Water Requirements

To assess the water impact of AgTech EI, the updated matrix is:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 155
$\mathbf{WReqM}_{mr\ell}^{\text{AgTech EI}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AgTech EI}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{AgTech EI}} = 20$, as AgTech EI practice affects 20 land use classes (Equation 33).

The updated values are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 156
$\mathbf{WReqM}_{mr\ell}^{\text{AgTech EI}}(y) = \begin{cases} \mathbf{WReqM}_{mr\ell}^{AG,LS}(y) \times \left(1 - WIM_{\ell}^{\text{AgTech EI}}(y)\right) & \text{if } \ell \in \phi(\text{AgTech EI}) \text{ and } WIM_{\ell}^{\text{AgTech E}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{AgTech EI}) \text{ or } WIM_{\ell}^{\text{AgTech E}}(y) = 1 \end{cases}$	

where,

- $WIM_{\ell}^{\text{AgTech EI}}(y)$ is the water impact multiplier (Figure 229)
- $\mathbf{WReqM}_{mr\ell}^{AG,LS}(y)$ represents water requirements for all land uses under AgTech EI $\phi(\text{AgTech EI})$ (Equation 33), computed in Equation 137.

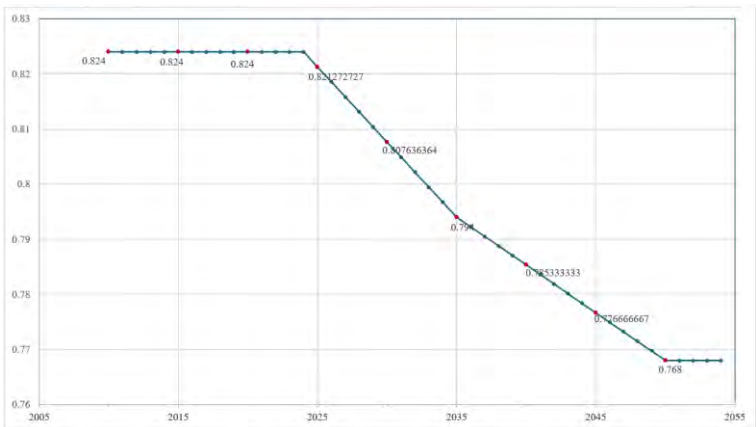

Figure 229 The water impact multiplier of Precision agriculture Effects

Updated water requirements $\mathbf{WReqM}_{mr\ell}^{\text{PrecAgric}}$ for winter cereals , summer cereals, hay, and grapes under irrigation systems are illustrated in Figure 219-Figure 222.

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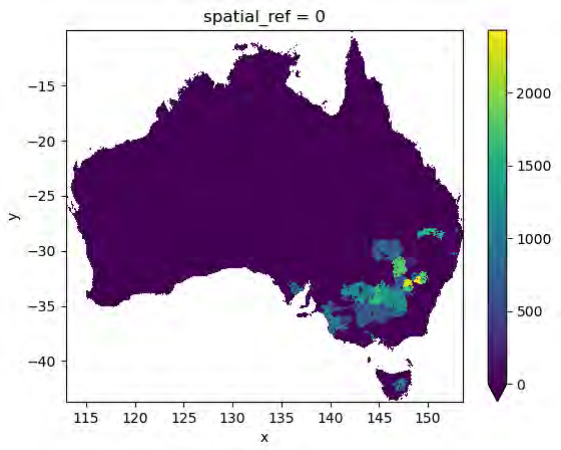

Figure 230 The water requirements for winter cereals under irrigation land management system by considering the effects of AgTech EI

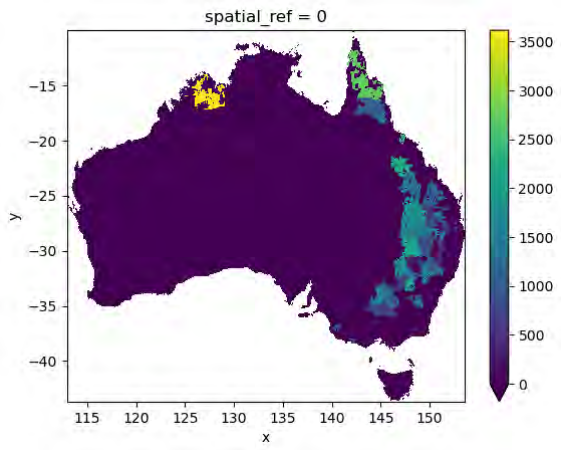

Figure 231 The crop quantity for summer cereals under irrigation land management system by considering the effects of AgTech EI

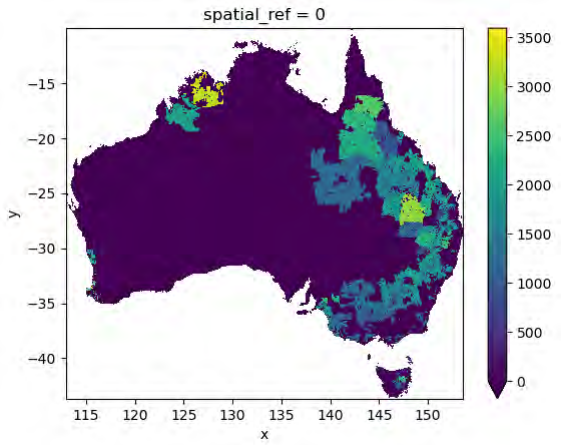

Figure 232 The crop quantity for hay under irrigation land management system by considering the effects of AgTech EI

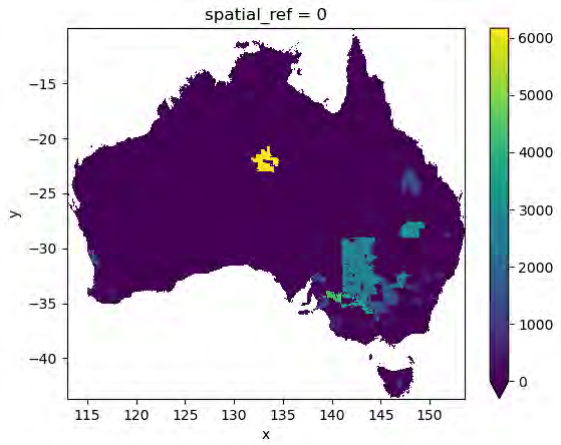

Figure 233 The crop quantity for grapes under irrigation land management system by considering the effects of AgTech EI

8.6. Water Requirements of Agricultural Management Practices on agricultural land uses

Define $\mathbf{WReqM}^{\mathrm{AGMP}}$, which represents a dictionary mapping each agricultural management practice (key k) to its respective water requirement matrix:

$$\mathbf{WReqM}_k^{\mathrm{AGMP}} = \left\{k \rightarrowtail \mathbf{WReqM}_{mr\ell}^k(y) | r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}, \mathbf{WReqM}_{mr\ell}^k(y) \in \mathbb{R}^{N_k \times N_c \times N_{lu}^k}\right\} \quad \text{Equation 157}$$

where,

- $\mathcal{K}$ is the set lists agricultural management practices applied to different land-use types (Equation 22)
- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- N_{lu}^k represents the number of land-use classes for each practices $\mathcal{K}$ (Equation 24-Equation 32)

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- $\mathbb{R}$ denotes real number
- $\mathbf{WReqM}_{mr\ell}^{k}(y)$ is the water requirement matrix for each agricultural management practice k.

Regarding agricultural management practices, $\mathcal{K}$ represents the set of agricultural management practices that can be applied to different land-use types (Equation 22). As stated in Equation 23, a rule or mapping ϕ defines the relationship between elements in the set of agricultural management practices ($\mathcal{K}$, the domain) and the corresponding land-use types ($\mathcal{L}$, Equation 1) to which these practices are applicable. The specific agricultural management practices and their corresponding land-use applications are detailed in Equation 24-Equation 32.

Accordingly, the initialized water requirements matrix $\mathbf{WReqM}_{k}^{\mathrm{AGMP}}(y)$ (Equation 157) is updated as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists k\,, k \in \mathcal{K}$	Equation 158
$\mathbf{WReqM}_{k}^{\mathrm{AGMP}}(\boldsymbol{y}) = \begin{cases} k \rightarrowtail \mathbf{WReqM}_{mr\ell}^{\mathrm{AspTaxifor}}(y) & if \quad k \in \phi(\text{Asparagopsis taxiformis}) \\ k \rightarrowtail \mathbf{WReqM}_{mr\ell}^{\mathrm{PrecAgric}}(y) & if \quad k \in \phi(\text{Precision Agriculture}) \\ k \rightarrowtail \mathbf{WReqM}_{mr\ell}^{\mathrm{EcolGrazing}}(y) & if \quad k \in \phi(\text{Ecological Grazing}) \\ k \rightarrowtail \mathbf{WReqM}_{mr\ell}^{\mathrm{SavBurn}}(y) & if \quad k \in \phi(\text{Savanna Burning}) \\ k \rightarrowtail \mathbf{WReqM}_{mr\ell}^{\mathrm{AgTech\ EI}}(y) & if \quad k \in \phi(\text{AgTech EI}) \end{cases}$	

where,

- $\mathcal{K}$ is the set lists agricultural management practices that can be applied to different land use types (Equation 22)
- $k\ is$ the agricultural management practice type
- $\mathbf{WReqM}_{mr\ell}^{\mathrm{AspTaxifor}}(y)$ is Water Requirement Matrix by integrating Asparagopsis taxiformis into agricultural land management strategies (Equation 148)
- $\mathbf{WReqM}_{mr\ell}^{\mathrm{PrecAgric}}(y)$ is Water Requirement Matrix by integrating Precision Agriculture into agricultural land management strategies (Equation 150)
- $\mathbf{WReqM}_{mr\ell}^{\mathrm{EcolGrazing}}(y)$ is Water Requirement Matrix by integrating Ecological Grazing into agricultural land management strategies (Equation 152)
- $\mathbf{WReqM}_{mr\ell}^{\mathrm{SavBurn}}(y)$ is Water Requirement Matrix by integrating Savanna Burning into agricultural land management strategies (Equation 154)
- $\mathbf{WReqM}_{mr\ell}^{\mathrm{AgTech\ EI}}(y)$ is Water Requirement Matrix by integrating AgTech EI into agricultural land management strategies (Equation 156)
- $\phi(\text{Asparagopsis taxiformis})$ is the Asparagopsis taxiformis practice that primarily affecting livestock on natural and modified land (Equation 25)
- $\phi(\text{Precision Agriculture})$ is the Precision Agriculture practice that primarily applied to cropping, intensive cropping, and horticulture (Equation 27)
- $\phi(\text{Ecological Grazing})$ is the Ecological Grazing practice that primarily applied to livestock on modified land (Equation 29)
- $\phi(\text{Savanna Burning})$ is the Savanna Burning practice that primarily related to livestock on natural land, as well as unallocated natural land (Equation 31)
- $\phi(\text{AgTech EI})$ is the AgTech EI practice that primarily affecting cropping, intensive cropping, and horticulture (Equation 33)
- $\mathrm{Revenue}_{k}^{\mathrm{AGMP}}$ represents a dictionary where each key $k \in \mathcal{K}$ maps to a 3D matrix of revenue matrix of agricultural management practice variables

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8.7. River Regions or Drainage Divisions boundaries

LUTO 2.0 model uses two maps, namely River Regions and Drainage Divisions to compute some parameters such as the water net yield in each River Regions or Drainage Divisions boundaries. For example, Figure 234 illustrates the Topographic Drainage Divisions and River Regions map that was produced by the Bureau of Meteorology using the Australian Hydrological Geospatial Fabric (the Geofabric). This data is used as a reliable source to identify the cells are in each River Regions or Drainage Divisions. This procedure can be modelled using set theory and spatial partitioning.

8.7.1. Define the Spatial Grid

Let the region of interest be represented as a grid of spatial cells $C = \{c_1, c_2, \cdots, c_{N_r}\}$, where each c_r represents a specific cell on the grid. Each cell corresponds to a geographic coordinate or a pixel in a raster dataset.

8.7.2. Define River Regions and Drainage Divisions

Let $R = \{R_1, R_2, \cdots, R_{N_{RR}}\}$ be the set of River Regions, where $N_{RR} = 218$ is the total number of River Regions; and $D = \{D_1, D_2, \cdots, D_{N_{DD}}\}$ be the set of Drainage Divisions, where $N_{DD} = 13$ is the total number of Drainage Divisions. Each River Region and Drainage Division is defined as a collection of spatial cells:

- $R_i \subseteq C$ for each River Region i,
- $D_j \subseteq C$ for each Drainage Division j.

8.7.3. Cell Assignment

To determine whether a given cell c_r belongs to a specific River Region R_i or Drainage Division D_j, we define an indicator function f_R and f_D for River Regions and Drainage Divisions, respectively:

$\forall r \in \{1, \dots, N_r\}, i \in \{1, \cdots, N_{RR}\}, j \in \{1, \cdots, N_{DD}\}$	Equation 159
$f_R(c_r) = \begin{cases} 1 & \text{if } c_r \in R_i \\ 0 & \text{otherwise} \end{cases}$	
$f_D(c_r) = \begin{cases} 1 & \text{if } c_r \in D_j \\ 0 & \text{otherwise} \end{cases}$	

Thus, $f_R(c_r) = 1$ means cell c_r is in River Region R_i , and $f_D(c_r) = 1$ means it is in Drainage Division D_j.

8.7.4. Geospatial Mapping

The boundaries of River Regions or Drainage Divisions (Figure 234) are provided in LUTO 2.0 by geospatial data layers that assign each cell c_r to one of these regions $R_i, R_i \in R$ or divisions $D_j, D_j \in D$. This is essentially a spatial partitioning, where the grid C is divided into non-overlapping subsets based on geospatial criteria.

Thus, for each cell c_r, its assignment to a region is determined by the geospatial data layer, which maps the geographic coordinates of c_r to its corresponding River Region or Drainage Division.

8.7.5. Intersection with Other Geospatial Layers

If working with additional geospatial datasets (e.g., topography, land use) are required, the intersection of a cell's location with multiple layers can be computed. For instance, to identify the water requirements data

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$\mathbf{WReqM}_{mr\ell}^{AG,LS}$ in each River Region, we would analyse which cells c_r belong to both the region and specific hydrological criteria.

$\forall r \in \{1, \dots, N_r\}, i \in \{1, \cdots, N_{RR}\}, k \in \{1, \cdots, N_H\}$	Equation 160
$c_r \in (R_i \cap H_k)$	

Where H represents another layer, and the intersection $R_i \cap H_k$ identifies cells that are within both the River Region R_i and have the relevant hydrological properties H_k.

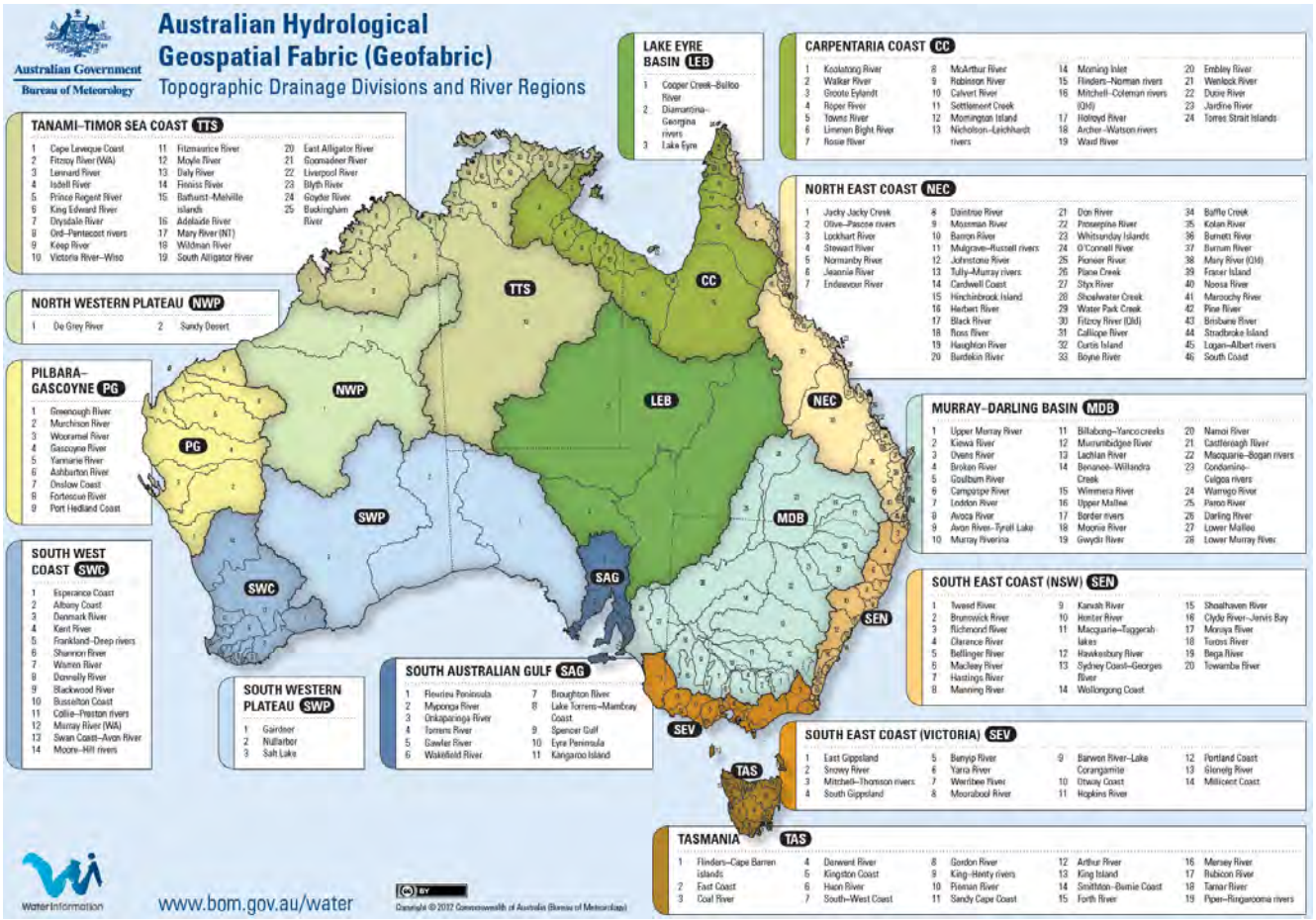

Figure 234 Topographic Drainage Divisions and River Regions map (Bureau of Meteorology)

Therefore, regarding Equation 159 and Equation 160, using the boundaries of River Regions or Drainage Divisions; it is possible to find the cells that are in each of the River Region (Figure 236) or Drainage Division (Figure 235).

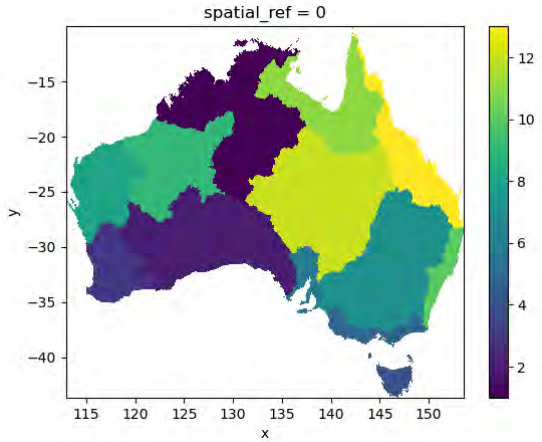

Figure 235 The cells that are located in each Drainage Divisions

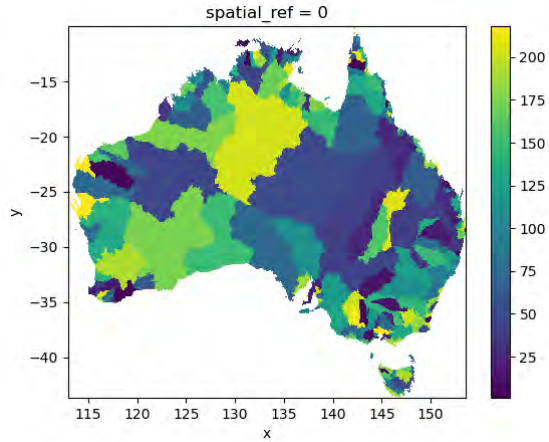

Figure 236 The cells that are located in each River Regions

8.8. Water Net Yield for River Regions and Drainage Divisions

LUTO 2.0 model utilizes the historical water yield for each river regions ($\mathbf{HWYield}_i^{Net,RR}$) or Drainage Division ($\mathbf{HWYield}_j^{Net,DD}$) dataset (Table 9 and Table 10). These tables represent the net water yield before European colonization (Figure 237-Figure 240).

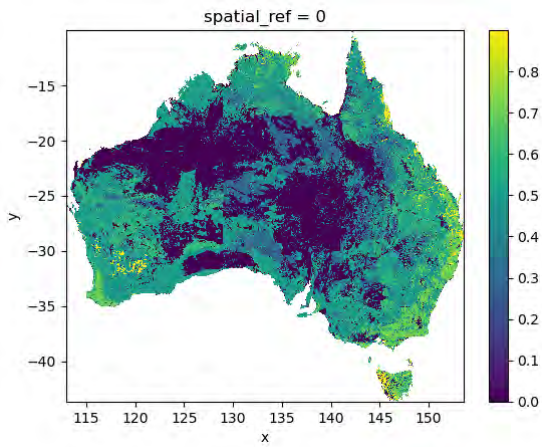

Figure 237 The proportion of historical deep-rooted plants

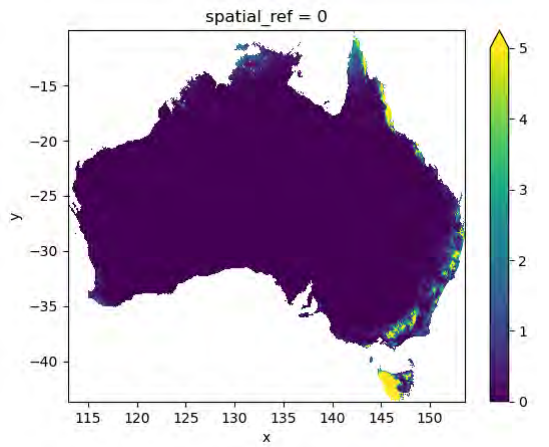

Figure 238 The historical Water yields (run off) from a cell into catchment by deep-rooted Cells

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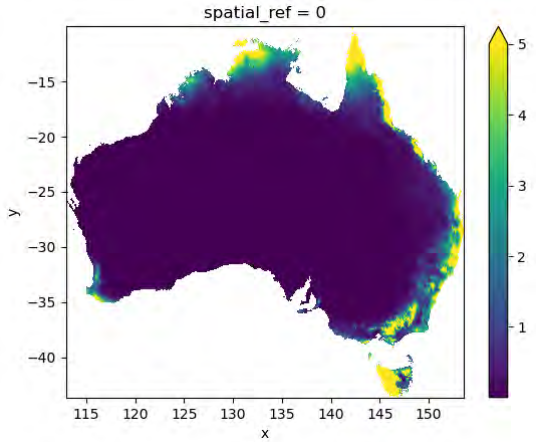

Figure 239 The historical Water yields (run off) from a cell into catchment by shallow-rooted Cells

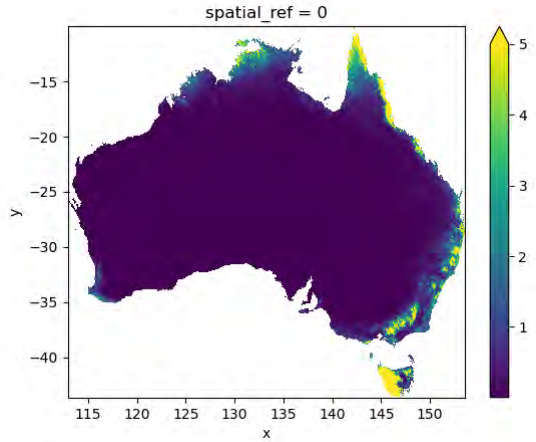

Figure 240 The historical Water yields (run off) from a cell into catchment by natural land Cells

Table 9 The historical water yield for river regions (ML)

No	River Regions Name	Water Yield (ML)
1	Adelaide River	1848572.2500
2	Albany Coast	181853.1719
3	Archer-Watson Rivers	5137273.5000
4	Arthur River	2354801.5000
5	Ashburton River	1420.4240
...	...	...
214	Wimmera River	142197.8125
215	Wollongong Coast	285492.0938
216	Wooramel River	405.2775
217	Yannarie River	167.8913
218	Yarra River	1035678.2500

Table 10 The historical water yield baseline (ML)

No	Drainage Division Name	Water Yield (ML)
1	Tanami-Timor Sea Coast	43985164
2	South Western Plateau	118963.0312
3	South West Coast	4550247
4	Tasmania	46493460
5	South East Coast (Victoria)	12331523
6	South Australian Gulf	481037.5938
7	Murray-Darling Basin	23661100
8	Pilbara-Gascoyne	23543.4785
9	North Western Plateau	77247.5781
10	South East Coast (NSW)	27616702
11	Carpentaria Coast	39672932
12	Lake Eyre Basin	162335.8906
13	North East Coast	56828424

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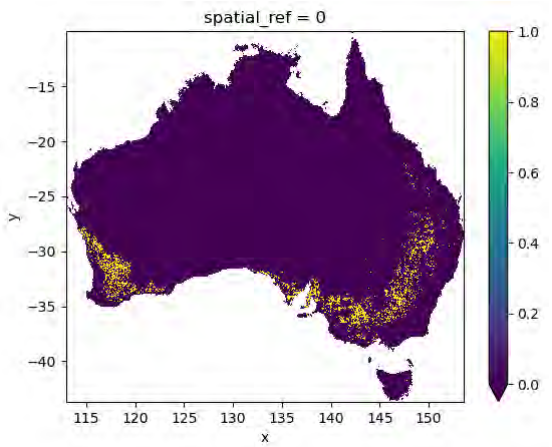


Figure 241 Agricultural Decision Variable for winter cereals under dry land management system in Year 2010

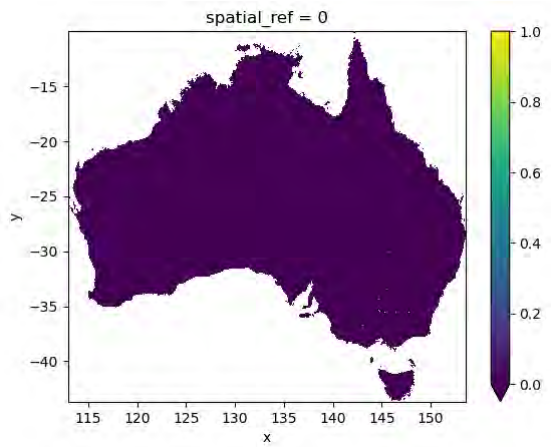


Figure 242 Agricultural Decision Variable for winter cereals under irrigation land management system in Year 2010

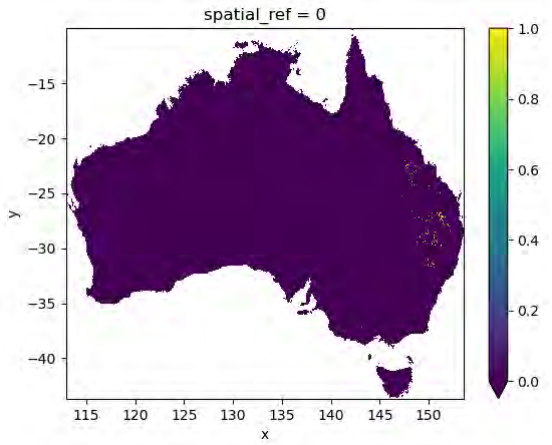


Figure 243 Agricultural Decision Variable for summer cereals under dry land management system in Year 2010

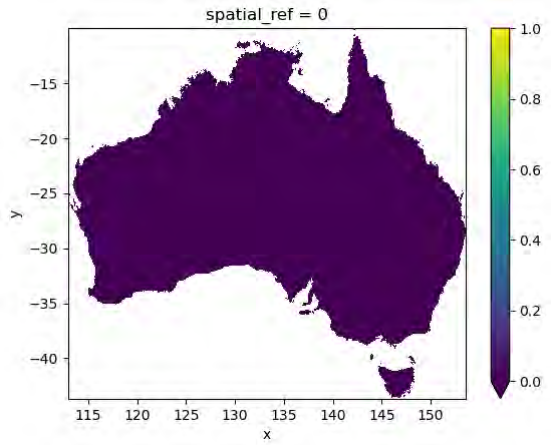
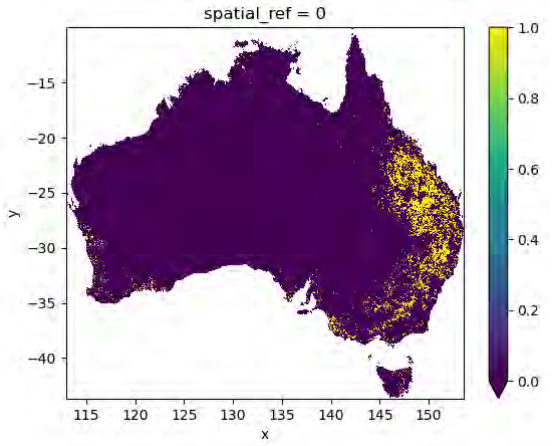


Figure 244 Agricultural Decision Variable for winter summer under irrigation land management system in Year 2010



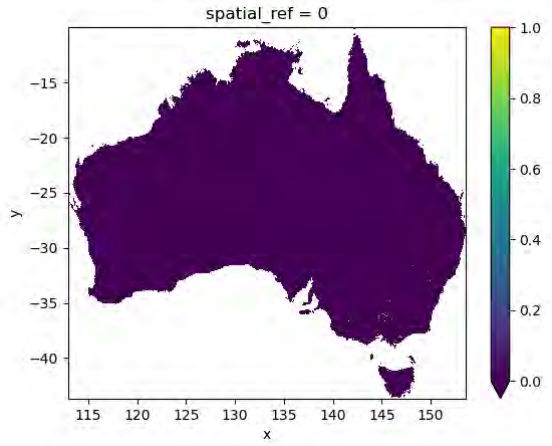


Figure 245 Agricultural Decision Variable for Beef-modified land under dry land management system in Year 2010	Figure 246 Agricultural Decision Variable for Beef-modified land under irrigation land management system in Year 2010

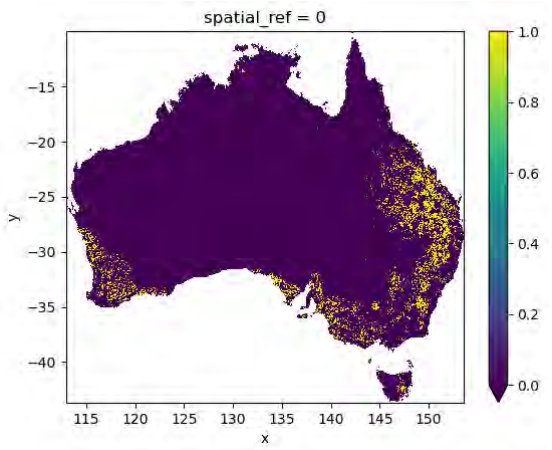
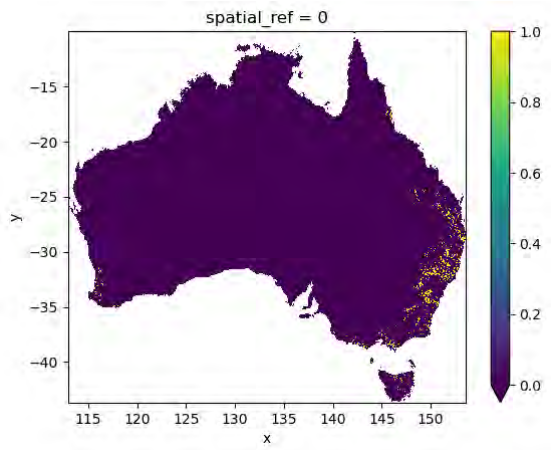

	

Figure 247 Agricultural Decision Variable for Environmental Plantings in Year 2010	Figure 248 Agricultural Decision Variable for Carbon Plantings (Block) in Year 2010

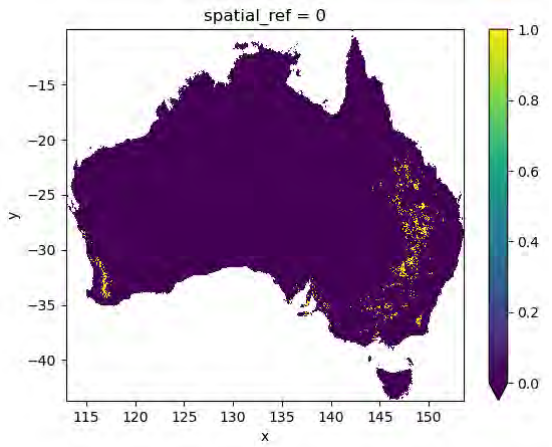



Figure 249 Agricultural Decision Variable for BECCS in Year 2010	

To compute the net water yield for a specific river region or drainage division, considering contributions from agricultural activities, non-agricultural activities, agricultural management practices, and climate change impact, the following terms are defined:

- Let $\mathbf{D}_{mr\ell}^{AG}(y)$, $\ell \in \mathcal{L}$ (Equation 1) represents agricultural decision variables
- $\mathbf{D}_{mr\ell}^{NonAgLU}(y)$, $\ell \in \mathcal{L}_{\text{NonAgrLand}}$ (Equation 13) represents non-agricultural decision variables
- $\mathbf{D}_{mr\ell}^{AgManag}(y)$, $\ell \in \mathcal{K}$ Equation 22 represents agricultural management decision variable
- $\mathbf{WReqM}_{mr\ell}^{AG}(y)$, $\ell \in \mathcal{K}$ Equation 22 represents water usage matrix for agricultural land uses
- $\mathbf{WReqM}_{mr\ell}^{AgManag}(y)$, $\ell \in \mathcal{K}$ Equation 22 represents water usage matrix for agricultural management practices
- $\mathbf{WReqM}_{mr\ell}^{NonAgLU}(y)$ represents water usage matrix for non-agricultural management practices
- $CCI_{SSP}^{RV}(y)$ represents climate change impact data on water yield for river regions
- $CCI_{SSP}^{DD}(y)$ represents climate change impact data on water yield for drainage devision

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- $\mathcal{L}$ is the set of land use classes assigned to crop, livestock, and unallocated land purposes Equation 1
- $\mathcal{L}_{\text{NonAgrLand}}$ is the set of a non-agricultural land use Equation 13
- $\mathcal{K}$ is the set of agricultural management practices Equation 22

8.8.1. Agricultural Contribution

For the case where LUTO is implemented based on river region assumptions:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}, m \in \mathcal{M}, i \in \{1, \cdots, N_{RR}\}$	Equation 161
$\mathbf{WNetY}_{mr\ell}^{AgContr,RR}(y) = \begin{cases} \sum_{m\in\mathcal{M}} \sum_{\ell\in\mathcal{L}} f_R(c_r) \times \left(\mathbf{WReqM}_{mr\ell}^{AG}(y) \times \mathbf{D}_{mr\ell}^{AG}(y)\right) & \text{if} \quad f_R(c_r) = 1 \\ 0 & \text{otherwise} \end{cases}$	

Where,

- $f_R(c_r)$ represent a function that determines whether the cell $r \in \mathcal{J}_j$ is classified as river region (Equation 159)

For the case where LUTO is implemented based on drainage division assumptions:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}, m \in \mathcal{M}, j \in \{1, \cdots, N_{DD}\}$	Equation 162
$\mathbf{WNetY}_{mr\ell}^{AgContr,DD}(y) = \begin{cases} \sum_{m\in\mathcal{M}} \sum_{\ell\in\mathcal{L}} f_D(c_r) \times \left(\mathbf{WReqM}_{mr\ell}^{AG}(y) \times \mathbf{D}_{mr\ell}^{AG}(y)\right) & \text{if} \quad f_D(c_r) = 1 \\ 0 & \text{otherwise} \end{cases}$	

where,

- $f_D(c_r)$ represent a function that determines whether a specific cell $r \in \mathcal{J}_i$ is classified as part of a drainage division (Equation 159).

8.8.2. Non-Agricultural Contribution

For the case where LUTO is implemented based on river region assumptions

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}, m \in \mathcal{M}, i \in \{1, \cdots, N_{RR}\}$	Equation 163
$\mathbf{WNetY}_{mr\ell}^{NonAgContr,RR}(y) = \begin{cases} \sum_{m\in\mathcal{M}} \sum_{\ell\in\mathcal{L}_{\text{NonAgrLand}}} f_R(c_r) \times \left(\mathbf{WReqM}_{mr\ell}^{AgManag}(y) \times \mathbf{D}_{mr\ell}^{NonAgLU}(y)\right) & \text{if} \quad f_R(c_r) = 1 \\ 0 & \text{otherwise} \end{cases}$	

where,

- $f_R(c_r)$ represent a function that determines whether the cell $r \in \mathcal{J}_j$ is classified as river region (Equation 159)

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For the case where LUTO is implemented based on drainage division assumptions

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}, m \in \mathcal{M}, j \in \{1, \cdots, N_{DD}\}$	Equation 164
$\mathbf{WNetY}_{mr\ell}^{NonAgContr,DD}(y) = \begin{cases} \sum_{m \in \mathcal{M}} \sum_{\ell \in \mathcal{L}_{\text{NonAgrLand}}} f_D(c_r) \times \left(\mathbf{WReqM}_{mr\ell}^{AgManag}(y) \times \mathbf{D}_{mr\ell}^{NonAgLU}(y)\right) & \text{if} \quad f_D(c_r) = \\ 0 & \text{otherwise} \end{cases}$	

where,

- $f_D(c_r)$ represent a function that determines whether a specific cell $r \in \mathcal{J}_i$ is classified as part of a drainage division (Equation 159).

8.8.3. Agricultural Management Contribution

As mentioned in Equation 22, the agricultural management contribution is applied using the set $\mathcal{K}$ of agricultural management practices. For each $k \in \mathcal{K}$, the mapping $\varphi(k)$ assigns the relevant land uses for that practice (Equation 23). For each given river region i or drainage region j, the value of $f_R(c_r)$ or $f_D(c_r)$ for those cells located in that region (either i or j) is equal to 1 ($f_R(c_r) = 1$ or $f_D(c_r) = 1$). Therefore, where $f_R(c_r) = 0$ or $f_D(c_r) = 0$; those cells will not contribute to.

For the case where LUTO is implemented based on river region assumptions:

$\forall r \in \{1, \dots, N_r\}, \ell \in \varphi(k), m \in \mathcal{M}, i \in \{1, \cdots, N_{RR}\}$	Equation 165
$\mathbf{WNetY}_{mr\ell}^{AgManagContr,RR}(y) = \begin{cases} \sum_{k \in \mathcal{K}} \sum_{\ell \in \varphi(k)} f_D(c_r) \times \left(\mathbf{WReqM}_{mr\ell}^{AgManag}(y) \times \mathbf{D}_{mr\ell}^{NonAgLU}(y)\right) & \text{if} \quad f_D(c_r) = 1 \\ 0 & \text{otherwise} \end{cases}$	

where,

- $f_D(c_r)$ represent a function that determines whether a specific cell $r \in \mathcal{J}_i$ is classified as part of a drainage division (Equation 159).

For the case where LUTO is implemented based on drainage division assumptions

$\forall r \in \{1, \dots, N_r\}, \ell \in \varphi(k), m \in \mathcal{M}, j \in \{1, \cdots, N_{DD}\}$	Equation 166
$\mathbf{WNetY}_{mr\ell}^{AgManagContr,DD}(y) = \begin{cases} \sum_{k \in \mathcal{K}} \sum_{\ell \in \varphi(k)} f_R(c_r) \times \left(\mathbf{WReqM}_{mr\ell}^{AgManag}(y) \times \mathbf{D}_{mr\ell}^{NonAgLU}(y)\right) & \text{if} \quad f_R(c_r) = 1 \\ 0 & \text{otherwise} \end{cases}$	

where,

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- $f_R(c_r)$ represent a function that determines whether the cell $r \in \mathcal{I}_j$ is classified as a river region (Equation 159)

8.8.4. Water Net Yield for River Regions

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}, m \in \mathcal{M}$	Equation 167
$\mathbf{WNetY}_{mr\ell}^{RR}(y) = \mathbf{WNetY}_{mr\ell}^{AgContr,RR}(y) + \mathbf{WNetY}_{mr\ell}^{NonAgContr,RR}(y) + \mathbf{WNetY}_{mr\ell}^{AgManagContr,RR}(y) + CCI_{SSP}^{RV}(y)$	

where,

- $\mathbf{WNetY}_{mr\ell}^{AgContr,RR}(y)$ represents agricultural contribution based on river region assumptions (Equation 161)
- $\mathbf{WNetY}_{mr\ell}^{NonAgContr,RR}(y)$ represents non-agricultural contribution based on river region assumptions (Equation 163)
- $\mathbf{WNetY}_{mr\ell}^{AgManagContr,RR}(y)$ represents agricultural management practices contribution based on river region assumptions (Equation 165)
- $CCI_{SSP}^{RV}(y)$ represents climate change impact data on water yield for river regions

8.8.5. Water Net Yield for Drainage Division

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}, m \in \mathcal{M}$	Equation 168
$\mathbf{WNetY}_{mr\ell}^{DD}(y) = \mathbf{WNetY}_{mr\ell}^{AgContr,DD}(y) + \mathbf{WNetY}_{mr\ell}^{NonAgContr,DD}(y) + \mathbf{WNetY}_{mr\ell}^{AgManagContr,DD}(y) + CCI_{SSP}^{DD}(y)$	

where,

- $\mathbf{WNetY}_{mr\ell}^{AgContr,DD}(y)$ represents agricultural contribution based on drainage division assumptions (Equation 162)
- $\mathbf{WNetY}_{mr\ell}^{NonAgContr,DD}(y)$ represents non-agricultural contribution based on drainage division assumptions (Equation 164)
- $\mathbf{WNetY}_{mr\ell}^{AgManagContr,RR}(y)$ represents agricultural management practices contribution based on drainage division assumptions (Equation 166)
- $CCI_{SSP}^{DD}(y)$ represents climate change impact data on water yield for drainage division

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8.9. Water Net Yield Limit Values

This section computes the water net yield limits for each region (river regions or drainage divisions) over time. It interpolates between historical water yield and predefined targets, which decrease over time.

8.9.1. Historical Water Yield

As mentioned in Section 8.8, for each region, the historical water yield was defined as $\mathbf{HWYield}_i^{Net,RR}$ and $\mathbf{HWYield}_j^{Net,DD}$ for river regions i and drainage divisions j, respectively.

8.9.2. Base Year Net Water Yield

The net water yield was computed in Equation 167 and Equation 168. The base year yield is set to 2010, representing the initial state of the system before any reductions are applied. Considering $y_{Base} = 2010$, the computed $\mathbf{WNetY}_{mr\ell}^{RR}(y)$ and $\mathbf{WNetY}_{mr\ell}^{DD}(y)$ for the base net water yield for river regions and drainage divisions can be written as $\mathbf{WNetY}_{mr\ell}^{RR}(y_{Base})$ and $\mathbf{WNetY}_{mr\ell}^{DD}(y_{Base})$.

8.9.3. Water Yield Targets Over Time

Water yield targets are defined in the settings and gradually decrease over time. Hence, the target water yield which is specified for a future year, the model calculates a smooth reduction in water yield between 2010 and the target year. The year-specific yield targets for each region are interpolated linearly between the base year (2010) and the target year.

To compute the target water yield over the time, three parameters including hydrological stress coefficient (α_{hyd}), agricultural water allocation fraction (β_{ag}), and target agricultural water yield proportion (γ_{ag}) are required. In the current version of LUTO 2.0, $\alpha_{\text{hyd}} = 0.2$ and $\beta_{\text{ag}} = 1.0$. Using α_{hyd}, the target agricultural water yield proportion is computed as:

$\gamma_{\text{ag}} = (1 - \alpha_{\text{hyd}}) \times \beta_{\text{ag}}$	Equation 169
$\gamma_{\text{ag}} = (1 - 0.2) \times 1 = 0.8$	

therefore, $\gamma_{\text{ag}} = 0.8$.

Given the historical water yield, and the base water yield, the target water yield for a given river region i and drainage divisions j can be computed as:

$\forall\, i \in \{1, \cdots, N_{RR}\}$	Equation 170
$\mathbf{WNetY}_i^{RR}(y_{Target}) = \mathbf{HWYield}_i^{Net,RR} \times \gamma_{\text{ag}}$	
$\forall\, j \in \{1, \cdots, N_{DD}\}$	Equation 171
$\mathbf{WNetY}_j^{DD}(y_{Target}) = \mathbf{HWYield}_j^{Net,DD} \times \gamma_{\text{ag}}$	

where,

- $\mathbf{HWYield}_i^{Net,RR}$ represents the historical water yield for the river regions i
- $\mathbf{HWYield}_j^{Net,DD}$ represents the historical water yield for the drainage divisions j
- $\mathbf{WNetY}_i^{RR}(y_{Target})$ is the water net yield for a given river region in the target year
- $\mathbf{WNetY}_j^{DD}(y_{Target})$ is the water net yield for a given drainage divisions in the target year

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- y_{Target} is the target year which could be either 2030 or 2100.

Regarding γ_{ag} value, the water yield must reach 80% of its historical value by the target year y_{Target}.

The water yield for a given year (y_{Given}) between the base year y_{Base} and the target year $y_2 = y_{Target}$ is computed using linear interpolation. The interpolation ensures a gradual reduction in water yield over time:

$\forall\, i \in \{1, \cdots, N_{RR}\}, y_{Base} \leq y_{Given} \leq y_{Target}$	
$\mathbf{WNetY}_i^{RR}(y_{Given}) = \mathbf{WNetY}_i^{RR}(y_{Start}) + \frac{\mathbf{WNetY}_i^{RR}(y_{Target}) - \mathbf{WNetY}_i^{RR}(y_{Start})}{y_{Target} - y_{Start}} \times (y_{Target} - y_{Start})$	Equation 172
$\forall\, j \in \{1, \cdots, N_{DD}\}, y_{Start} \leq y_{Given} \leq y_{Target}$	
$\mathbf{WNetY}_j^{DD}(y_{Given}) = \mathbf{WNetY}_j^{DD}(y_{Start}) + \frac{\mathbf{WNetY}_j^{DD}(y_{Target}) - \mathbf{WNetY}_j^{DD}(y_{Start})}{y_{Target} - y_{Start}} \times (y_{Target} - y_{Start})$	Equation 173

For each year between the base year and the target year, the yield targets are interpolated. If the region's base year water yield (either $\mathbf{WNetY}_i^{RR}(y_{Base})$ or $\mathbf{WNetY}_j^{DD}(y_{Base})$) is higher than the (either $\mathbf{WNetY}_i^{RR}(y_{Target})$ or $\mathbf{WNetY}_j^{DD}(y_{Target})$), the starting point is adjusted to the minimum of these two values:

For the base year y_{Base}, the water yield is calculated as the minimum of the historical water yield and the base water yield:

$\forall\, i \in \{1, \cdots, N_{RR}\}$	
$\mathbf{WNetY}_i^{RR}(y_{Base}) = \begin{cases} \min\left(\mathbf{HWYield}_i^{Net,RR}, \mathbf{WNetY}_i^{RR}(y_{Target})\right) & if \quad y_{Start} = y_{Base} \\ \min\left(\mathbf{HWYield}_i^{Net,RR}, \mathbf{WNetY}_i^{RR}(y_{Start})\right) & \text{otherwise} \end{cases}$	Equation 174
$\forall\, j \in \{1, \cdots, N_{DD}\}, y_{Base} \leq y_{Given} \leq y_{Target}$	

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$\mathbf{WNetY}_i^{DD}(y_{Base}) = \begin{cases} \min\left(\mathbf{HWYield}_i^{Net,DD}, \mathbf{WNetY}_i^{DD}(y_{Target})\right) & if \quad y_{Start} = y_{Base} \\ \min\left(\mathbf{HWYield}_i^{Net,DD}, \mathbf{WNetY}_i^{DD}(y_{Start})\right) & \text{otherwise} \end{cases}$	Equation 175

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9. The Biodiversity

9.1. Non-Penalty Land-Use Indices

In biodiversity assessments, certain land-use types are considered "natural" and generally support biodiversity. However, when these land types are repurposed for livestock activities, their biodiversity value is penalized due to associated environmental degradation. This function takes a dataset of land-use indices and excludes livestock-associated uses from the natural set to identify land-use types that contribute to biodiversity without incurring penalties:

$\mathcal{L}_{\text{non-penalty}} = \mathcal{L}_{\text{natural}} \setminus \mathcal{L}_{\text{livestock}}$	Equation 176

where,

- $\mathcal{L}_{\text{natural}}$ represents the natural land-use types
- $\mathcal{L}_{\text{livestock}}$ represent the indices of land-use types associated with livestock
- $\mathcal{L}_{\text{natural}} \setminus \mathcal{L}_{\text{livestock}}$ represents the set of elements (land-use indices) that are in $\mathcal{L}_{\text{natural}}$ but not in $\mathcal{L}_{\text{livestock}}$
- $\mathcal{L}_{\text{non-penalty}}$ is the set of natural land-use indices that do not involve livestock, meaning these land-use types contribute to biodiversity without incurring a penalty

9.2. Livestock-Penalty Land-Use Indices

In biodiversity assessments, natural land-use types are typically considered beneficial. However, when these lands are used for livestock activities, their ecological value is reduced due to the associated environmental degradation. To accurately reflect this in biodiversity scoring models, it is necessary to distinguish between purely natural land uses and those natural lands that are also used for livestock.

This function extracts and returns a list of indices representing land-use types that are both natural and used for livestock. These indices are crucial for applying appropriate penalties to biodiversity scores, as specified by the BIODIV_LIVESTOCK_IMPACT setting within the model:

$\mathcal{L}_{\text{livestock-natural}} = \mathcal{L}_{\text{natural}} \cap \mathcal{L}_{\text{livestock}}$	Equation 177

where,

- $\mathcal{L}_{\text{natural}}$ represents the natural land-use types
- $\mathcal{L}_{\text{livestock}}$ represents the indices of land-use types associated with livestock
- $\mathcal{L}_{\text{natural}} \cap \mathcal{L}_{\text{livestock}}$ identifies the overlap between natural land-use types $\mathcal{L}_{\text{natural}}$ and those associated with livestock $\mathcal{L}_{\text{livestock}}$, effectively isolating the land uses that require penalty adjustments in biodiversity assessments.
- $\mathcal{L}_{\text{livestock-natural}}$ represents Land-use types with both natural features and livestock, penalized in biodiversity assessments.

9.3. Biodiversity Score Matrix by Land Management

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The Biodiversity Score Matrix (BSM) is a critical component of the ecological modelling framework. It quantifies the biodiversity contribution of different land-use types across various management practices and spatial cells. This matrix enables the model to evaluate the ecological impacts of land management decisions and supports land-use optimization for biodiversity conservation.

Let $\mathbf{BSM}_{mr\ell}$ represent the Biodiversity Score Matrix by Land management. First, initialize the $\mathbf{BSM}_{mr\ell}$ as follows: the biodiversity contribution of various land-use types under different land management practices and across spatial cells.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 178
$\mathbf{BSM}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$; hence $N_k = 2$.
- N_{lu} is the number of agricultural land-use categories; hence, $N_{lu} = 28$.

Now, let update the $\mathbf{BSM}_{mr\ell}$:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 179
$\mathbf{BSM}_{mr\ell} = \left[\mathbf{BSM}_r^{\mathrm{LDS}} - \left(\mathbf{WBSM}_r^{raw} \times \left(\mathbf{1} - \mathbf{BDC}_\ell^{HCB}\right)\right)\right] \times \mathbf{RA}_r$	

where

- $\mathbf{BDC}_\ell^{HCB}$ is the habitat condition-based biodiversity degradation Index (Equation 184)
- $\mathbf{WBSM}_r^{raw}$ is the weighted biodiversity score raw matrix (Equation 181, and Figure 253, Figure 255, Figure 257, Figure 259)
- $\mathbf{BSM}_r^{\mathrm{LDS}}$ is the weighted biodiversity score raw matrix under late-dry season (LDS) burning adjustment factor (Equation 180, and Figure 262)
- $\mathbf{RA}_r$ is Real area multiplier (Figure 5)

As m represents different land management practices ($m \in \{0,1\}$), and Equation 180 shows that none of the parameters depend on m; therfore, the Biodiversity Score Matrix $\mathbf{BSM}_{mr\ell}$ will be the same for both dry and irrigation land management practices when the land-use class $\ell, \ell \in \mathcal{L}$ for a given cell r remains the same. Figure 265- Figure 275 illustrate the computed $\mathbf{BSM}_{mr\ell}$ for different $\ell, \ell \in \mathcal{L}$.

The final biodiversity score for each cell r after accounting for LDS burning as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 180
$\mathbf{BSM}_r^{\mathrm{LDS}} = \mathbf{WBSM}_r^{raw} - \Delta\mathbf{BSM}_r^{\mathrm{LDS}}$	

where,

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- $\mathbf{WBSM}_r^{raw}$ is the weighted biodiversity score raw matrix (Equation 181, and Figure 253, Figure 255, Figure 257, Figure 259)
- $\Delta\mathbf{BSM}_r^{\mathrm{LDS}}$ is the biodiversity degradation from LDS burning (Equation 182 and Figure 263)

The weighted biodiversity score raw matrix for each cell r is computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 181
$\mathbf{WBSM}_r^{raw} = \mathbf{BSM}_r^{raw} \times \mathrm{CAS}_r$	

where,

- $\mathbf{BSM}_r^{raw}$ is the biodiversity score raw matrix (Figure 252, Figure 254, Figure 256, Figure 258, Figure 260)
- CAS_r is the connectivity adjustment score for cell r, (see Equation 185, and Figure 250 and Figure 251)

The biodiversity degradation from LDS burning for each cell r is:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 182
$\Delta\mathbf{BSM}_r^{\mathrm{LDS}} = \mathbf{WBSM}_r^{raw} \times (1 - \lambda_r^{\mathrm{LDS}})$	

where,

- $\mathbf{WBSM}_r^{raw}$ is the weighted biodiversity score raw matrix (Equation 181, and Figure 253, Figure 255, Figure 257, Figure 259)
- λ_r^{LDS} is the biodiversity degradation score under Savanna burning (Equation 183 and Figure 261)

The degradation score under Savanna burning is defined as:

$\lambda_r^{\mathrm{LDS}} = \begin{cases} \gamma_{LDS} & \text{if cell } r \text{ is eligible for savanna burning,} \\ 1 & \text{otherwise} \end{cases}$	Equation 183

where,

- γ_{LDS} is the biodiversity value adjustment for late dry season savanna fire regime ($\gamma_{LDS} = 0.8$)

As mentioned in Equation 183, the value of λ_r^{LDS} is equal to γ_{LDS} for the cells that Savana burning is eligible (Figure 35). The map of λ_r^{LDS} is presented in Figure 261.

The habitat condition-based biodiversity degradation Index is computed as:

$\forall \ell \in \mathcal{L} \quad \exists \quad \ell_{UNL}, \ell_{UNL} \in \mathcal{L}_{\text{Unallocated – natural land}}$	Equation 184

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$\mathbf{BDC}_{\ell}^{HCB} = \begin{cases} \dfrac{\mathbf{HCAS}_{\ell}}{HCAS_{\ell_{UNL}}} & \text{If} \quad \text{Habitate Condition} = \mathbf{HCAS} \\ \mathbf{BDC}_{\ell}^{UD} & \text{otherwise} \end{cases}$	

where,

- $\mathbf{BDC}_{\ell}^{UD}$ is biodiversity degradation Index defined by user
- $\mathbf{HCAS}_{\ell}$ is vector that represents the Habitat Condition Assessment Score for all land use classes (Figure 264)
- $HCAS_{\ell_{UNL}}$ be the Habitat Condition Assessment Score for the Unallocated − natural land class ($HCAS_{\ell_{UNL}} \in \mathbf{HCAS}_{\ell}$)
- $\mathcal{L}_{\text{Unallocated – natural land}}$ is a set that represents unallocated-natural land class (Equation 11)

The Connectivity Adjustment Score CAS_r accounting for the cell's distance to the nearest natural area (Figure 250 and Figure 251). It is computed as:

$\text{CAS}_r = 1 - \dfrac{\text{dist}_r - \text{dist}_{min}}{\text{dist}_{max} - \text{dist}_{min}}$	Equation 185

Where:

- $dist_r$ is the distance of cell r to the nearest natural cell. It is provided as an input data by LUTO 2.0 for Australia.
- dist_{min} is the minimum distance to natural areas in the dataset. It refers to the minimum value available in tensor dist_r .
- dist_{max} is the maximum distance to natural areas in the dataset. It refers to the maximum value available in tensor dist_r.
- CAS_r linearly scales the distance dist_r from the range dist_{min}, dist_{max} to a value between 0 and 1.

When a given cell r is very close to natural areas, then dist_r is small, and close to dist_{min}. Thus, the connectivity score CAS_r will approach 1. This indicates high connectivity. On the other hand, for a given cell r which is far from natural areas, the value of dist_r is large, and close to dist_{max}. Hence, the connectivity score CAS_r will approach 0, that is indicating low connectivity.

It can be concluded that, the CAS_r ranges from 0 to 1, where:

- 1 represents a highly connected area (near natural areas),
- 0 represents a poorly connected area (far from natural areas).

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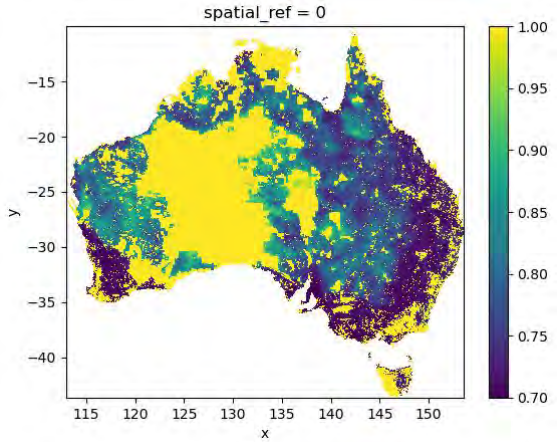

Figure 250 National Connectivity Index (NCI) based on HCAS model (Data provided by Department of Climate Change, Energy, the Environment and Water)

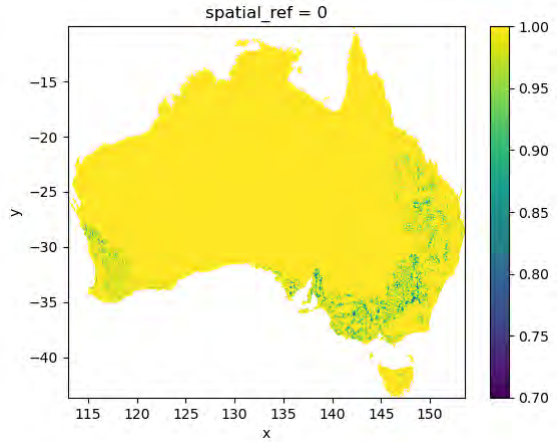

Figure 251 National Connectivity Index (NCI) based on Dispersal-Weighted Index (BWI)

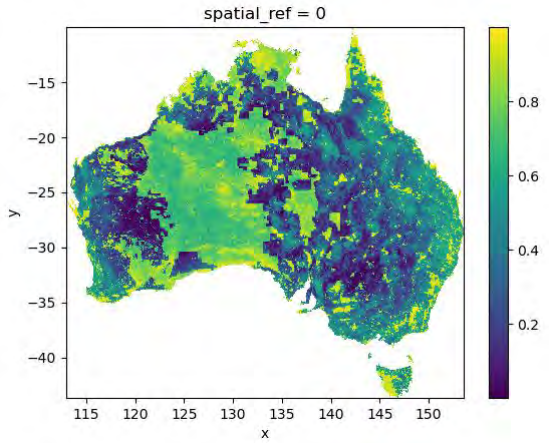

Figure 252 Zonation output scores (0-1) across SSP126 scenario and total raw biodiversity score (153 Million)

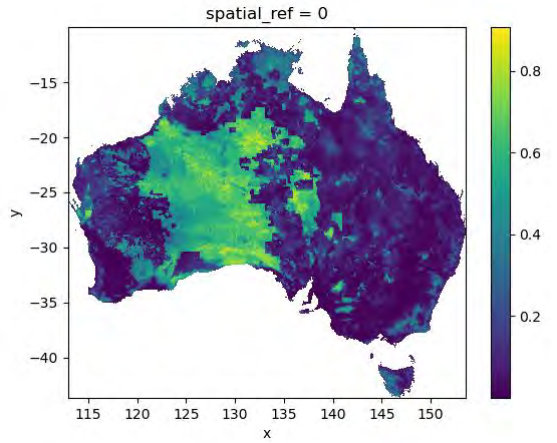

Figure 253 Weighted biodiversity score based on DCCEEW connectivity score under SSP126 scenario

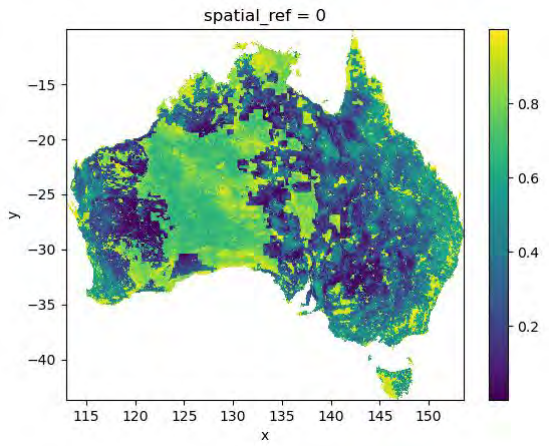

Figure 254 Zonation output scores (0-1) across SSP245 scenario and total raw biodiversity score (153 Million)

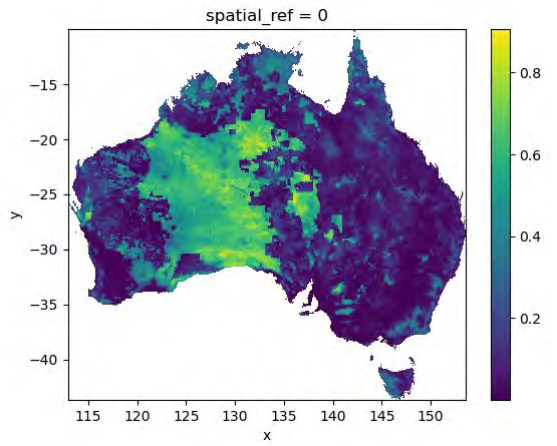

Figure 255 Weighted biodiversity score Based on DCCEEW connectivity score under SSP245 scenario

Deakin University CRICOS Provider Code: 00113B

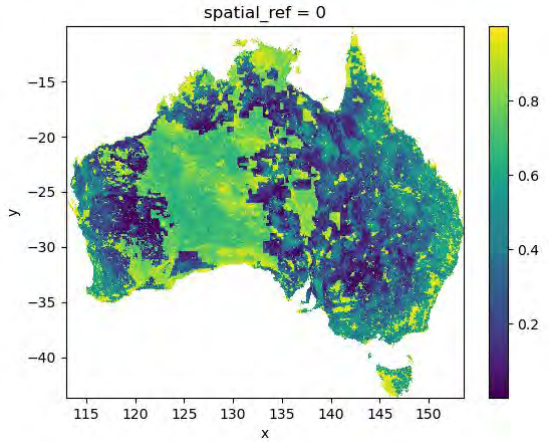

Figure 256 Zonation output scores (0-1) across SSP370 scenario and total raw biodiversity score (153 Million)

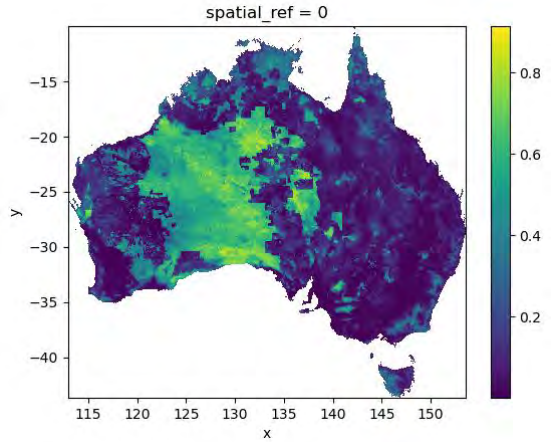

Figure 257 Weighted biodiversity score Based on DCCEEW connectivity score under SSP370 scenario

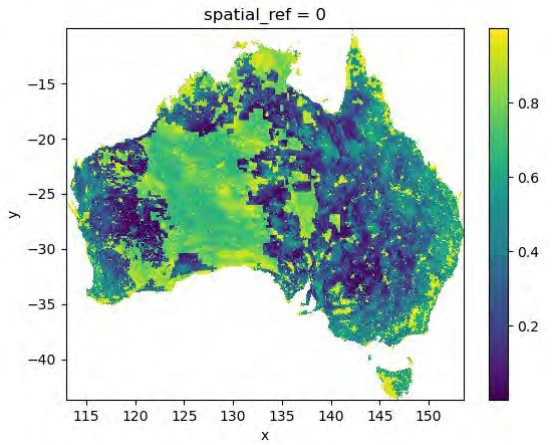

Figure 258 Zonation output scores (0-1) across SSP585 scenario and total raw biodiversity score (153 Million)

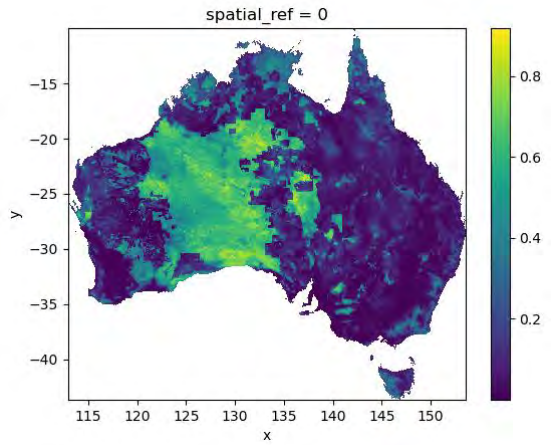

Figure 259 Weighted biodiversity score Based on DCCEEW connectivity score under SSP585 scenario

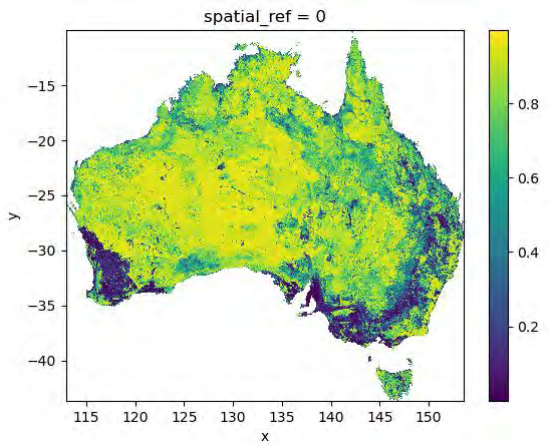

Figure 260 Zonation output scores (0-1) and total raw biodiversity score (153 Million) for high conservation areas (HCAS)

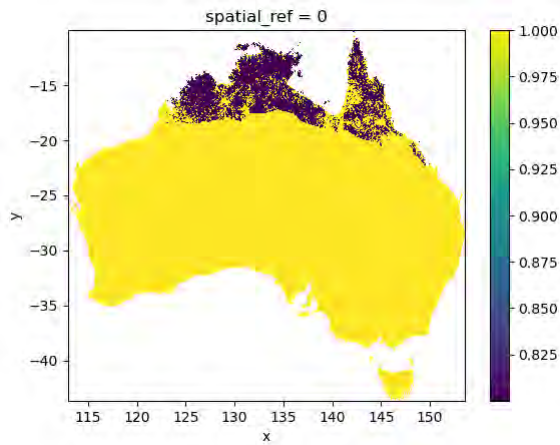

Figure 261 The biodiversity degradation score under Savanna burning

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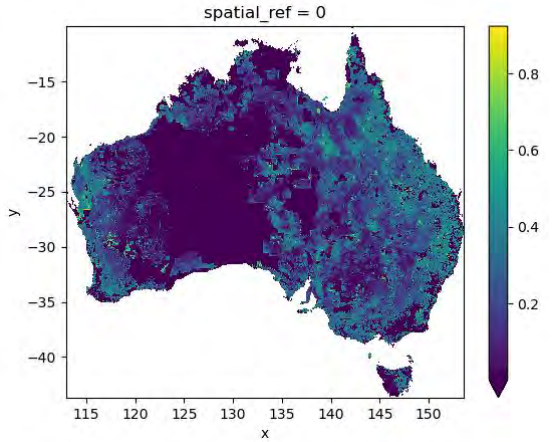

Figure 262 The final biodiversity score after accounting for LDS burning under SSP245 scenario

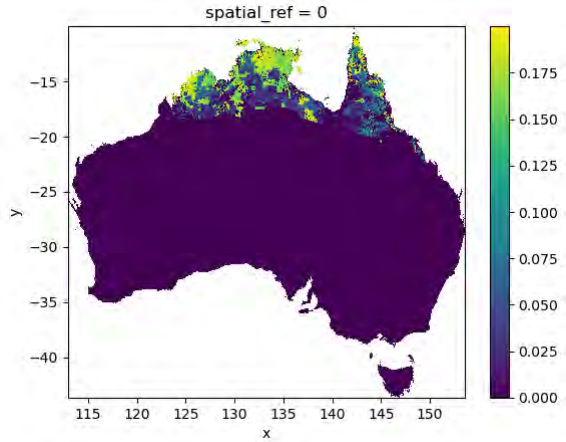

Figure 263 The biodiversity degradation from LDS burning under SSP245 scenario

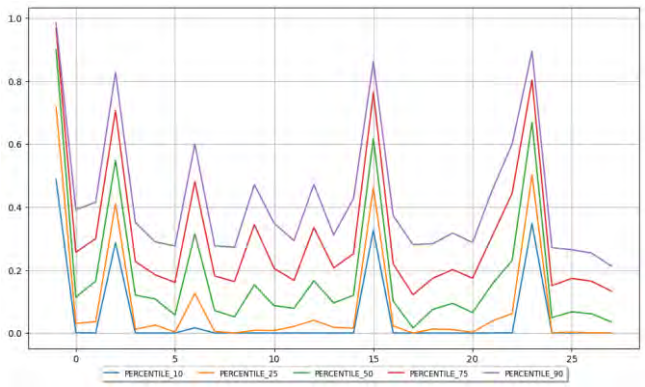

Figure 264 Habitat degradation scale for agricultural land-use

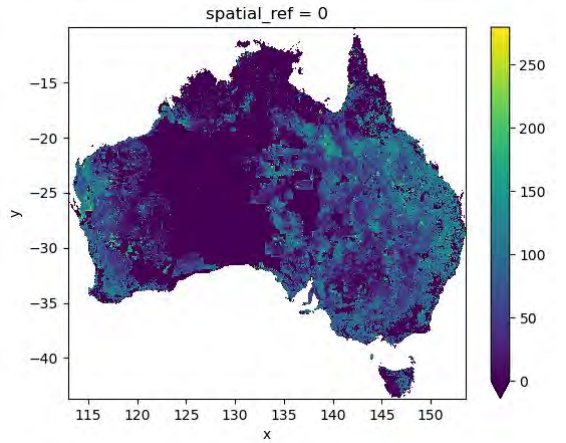

Figure 265 Biodiversity Score Matrix by land management for the class of Grapes

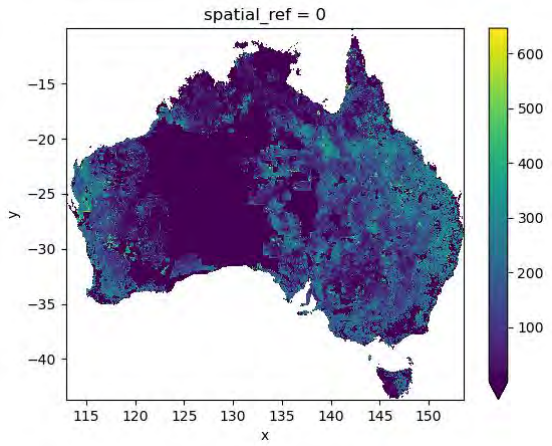

Figure 266 Biodiversity Score Matrix by land management for the class of Beef-Modified Land

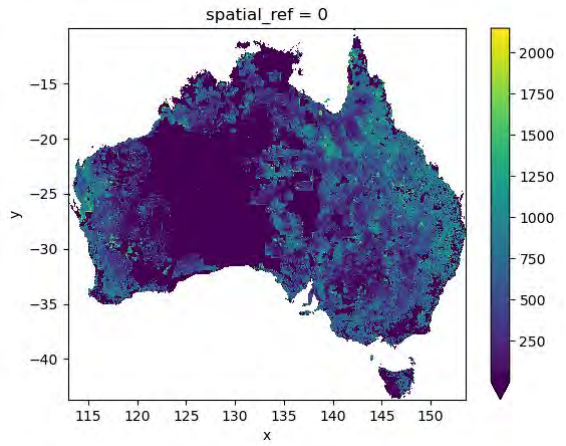

Figure 267 Biodiversity Score Matrix by land management for the class of Beef-Natural Land

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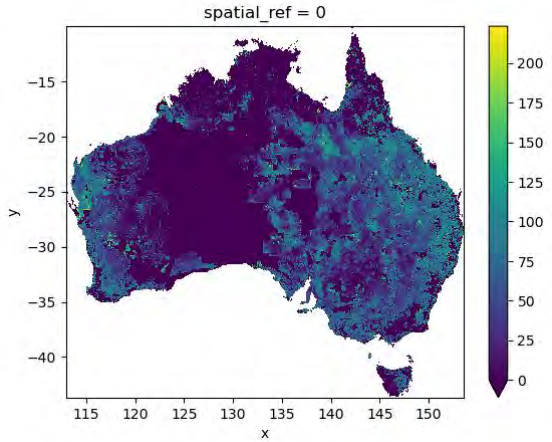

Figure 268 Biodiversity Score Matrix by land management for the class of Dairy-Modified Land

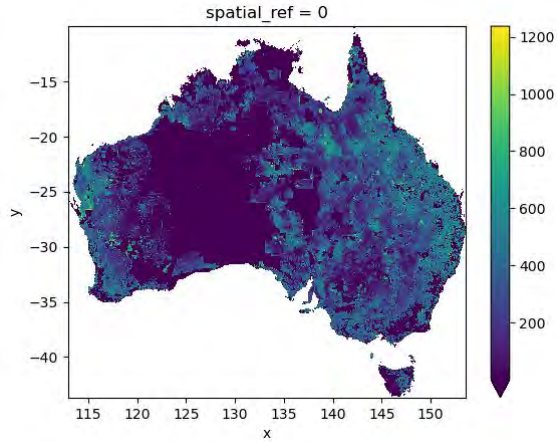

Figure 269 Biodiversity Score Matrix by land management for the class of Dairy-Natural Land

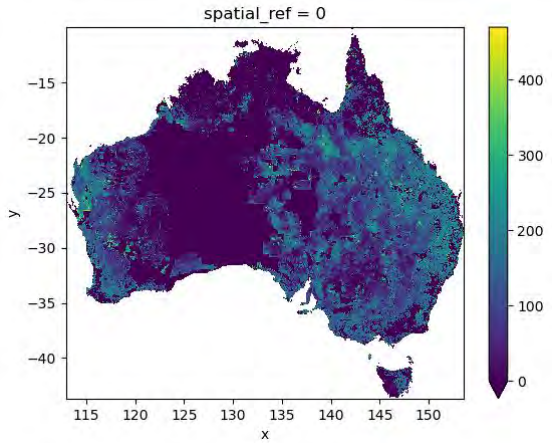

Figure 270 Biodiversity Score Matrix by land management for the class of Sheep-Modified Land

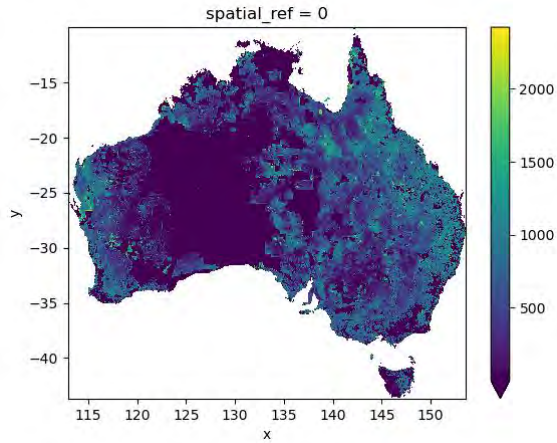

Figure 271 Biodiversity Score Matrix by land management for the class of Sheep-Natural Land

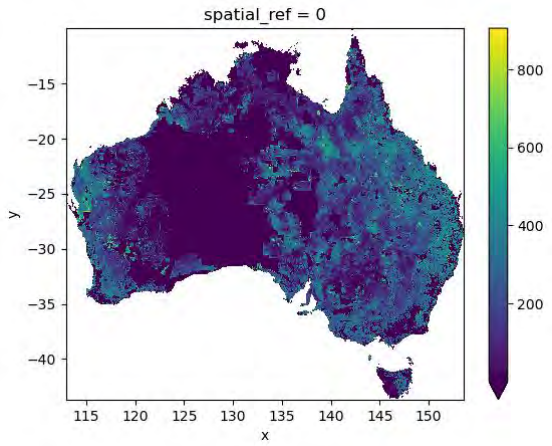

Figure 272 Biodiversity Score Matrix by land mManagement for the class of Unallocated - modified land

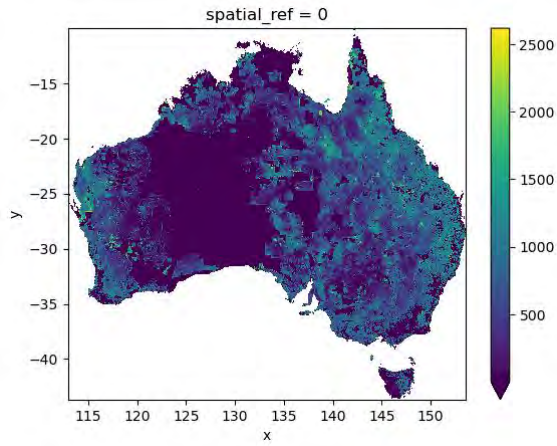

Figure 273 Biodiversity Score Matrix by land management for the class of Unallocated - Natural land

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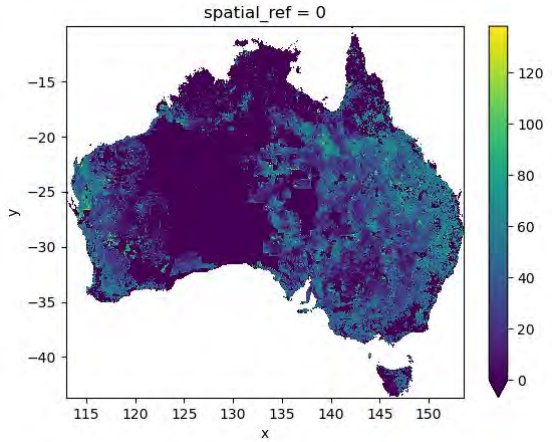

Figure 274 Biodiversity Score Matrix by land management for the class of Winter cereals

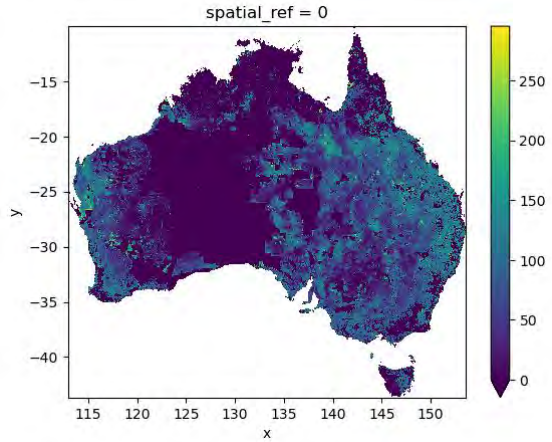

Figure 275 Biodiversity Score Matrix by land management for the class of Summer cereals

10. The impacts of Agricultural Management Practices on the Biodiversity of Agricultural Land uses

In ecological modelling, assessing the potential impacts of different land management practices on biodiversity is essential. The list of agricultural management practices applicable to various land-use types is outlined in Equation 22.

10.1. Asparagopsis Taxiformis Effects on Biodiversity

Let $\mathbf{BSM}_{mr\ell}^{\text{AspTaxifor}}$ be the updated Biodiversity Score Matrix incorporating Asparagopsis taxiformis into land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Asparagopsis taxiformis})$	Equation 186
$\mathbf{BSM}_{mr\ell}^{\text{AspTaxifor}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AspTaxifor}}\right)}$	

where,

- N_c: is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{AspTaxifor}}$ is 6, as asparagopsis taxiformis practice affects beef, sheep, and dairy production across both natural and modified land, $N_{lu} = 6$ (Equation 25).

Note: This matrix is initialized to zero as Asparagopsis taxiformis is assumed not to significantly alter biodiversity outcomes.

10.2. Biodiversity Impact Assessment of Precision Agriculture

Let $\mathbf{BSM}_{mr\ell}^{\text{PrecAgric}}$ be the updated Biodiversity Score Matrix by integrating Precision agriculture into agricultural land management strategies.

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 187
$\mathbf{BSM}_{mr\ell}^{\text{PrecAgric}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{PrecAgric}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{PrecAgric}}$ is 20, as precision agriculture practice affects 20 land use classes (Equation 27), $N_{lu} = 20$

Note: As LUTO 2.0 assumes that precision agriculture does not affect biodiversity metrics, the impact matrix is initialized to zero. This indicates no measurable positive or negative impact on biodiversity across all land management systems, spatial cells, and associated land-use types.

10.3. Biodiversity Impact Assessment of Ecological Grazing

Let $\mathbf{UCM}_{mr\ell}^{\text{EcolGrazing}}$ be the updated Biodiversity Score Matrix for ecological grazing.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Ecological Grazing})$	Equation 188
$\mathbf{BSM}_{mr\ell}^{\text{EcolGrazing}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{EcolGrazing}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{EcolGrazing}}$ is 3, as Ecological Grazing practice affects beef, sheep, and dairy production across modified land (Equation 29), $N_{lu} = 3$

Note: LUTO 2.0 assumes that Ecological Grazing has no significant impact on biodiversity, leading to the initialization of the biodiversity impact matrix to zero. This matrix, generated by the function responsible for assessing the biodiversity impacts of Ecological Grazing, consists of a zero-filled array across all land management systems, spatial cells, and associated land-use types. This assumption implies that Ecological Grazing neither enhances nor detracts from biodiversity values within the model.

10.4. Biodiversity Impact Assessment of Savanna Burning

Let $\mathbf{BSM}_{mr\ell}^{\text{SavBurn}}$ represent the updated Biodiversity Score Matrix incorporating Savanna burning.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 189
$\mathbf{BSM}_{mr\ell}^{\text{SavBurn}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{SavBurn}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.

- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- N_{lu}^{SavBurn} is 4, as Savana burning practice affects beef, sheep, and dairy production across natural land as well as unallocated natural land (Equation 31), $N_{lu} = 4$

The biodiversity impact is computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 190
$\mathbf{BSM}_{mr\ell}^{\text{SavBurn}} = \begin{cases} \mathbf{BSM}_r^{\text{LDS}} \times (1 - \gamma_{\text{LDS}}) \times \mathbf{RA}_r & \text{if cell } r \text{ is eligible for Savanna Burning,} \\ 0 & \text{otherwise} \end{cases}$	

where:

- $\mathbf{BSM}_r^{\text{LDS}}$ is the weighted biodiversity score raw matrix under late-dry season (LDS) burning adjustment factor (Equation 180, and Figure 262)
- γ_{LDS} is the late-dry season (LDS) burning adjustment factor (typically 0.8).
- $\mathbf{RA}_r$ Real area multiplier (Figure 5)

Note: As m represents different land management practices ($m \in \{0,1\}$), and Equation 190 shows that none of the parameters depend on m; therefore, the Biodiversity Score Matrix $\mathbf{BSM}_{mr\ell}^{\text{SavBurn}}$ will be the same for both dry and irrigation land management practices when the land-use class $\ell \in \phi(\text{Savanna Burning})$ for a given cell r remains the same. Figure 276-Figure 279 illustrate the computed $\mathbf{BSM}_{mr\ell}^{\text{SavBurn}}$ for different $\ell \in \mathcal{L}$.

10.5. **Biodiversity Impact Assessment of AgTech EI**

Let $\mathbf{BSM}_{mr\ell}^{\text{AgTech EI}}$ represent the updated Biodiversity Score Matrix integrating AgTech EI.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 191
$\mathbf{BSM}_{mr\ell}^{\text{AgTech EI}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AgTech EI}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{AgTech EI}}$ is 20, as AgTech EI practice affects 20 land use classes (Equation 33), $N_{lu} = 20$

Note: LUTO 2.0 model assumes that AgTech EI (Agricultural Technology with Environmental Impact) has no significant impact on biodiversity, leading to the initialization of the biodiversity impact matrix to zero. This matrix, generated by the function responsible for assessing the biodiversity impacts of AgTech EI, consists of a zero-filled array across all land management systems, spatial cells, and associated land-use types. This assumption implies that AgTech EI neither enhances nor detracts from biodiversity values within the model.

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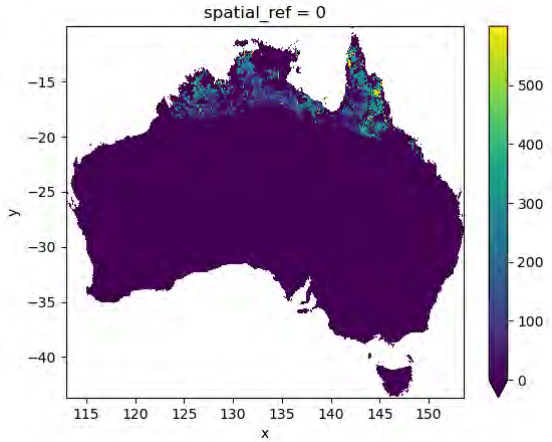	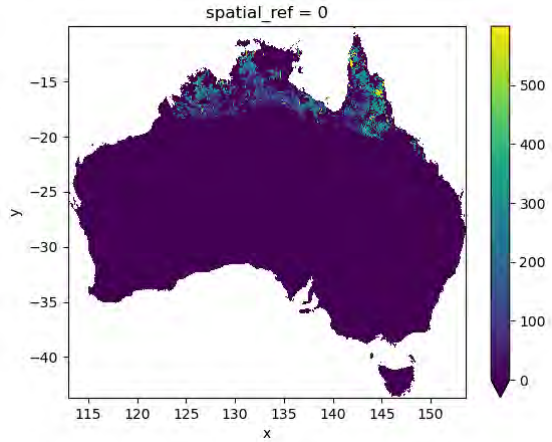
Figure 276 Biodiversity Impact Assessment of Savanna Burning in Land Management Practices for the class of Beef - natural land	Figure 277 Biodiversity Impact Assessment of Savanna Burning in Land Management Practices for the class of Dairy - natural land
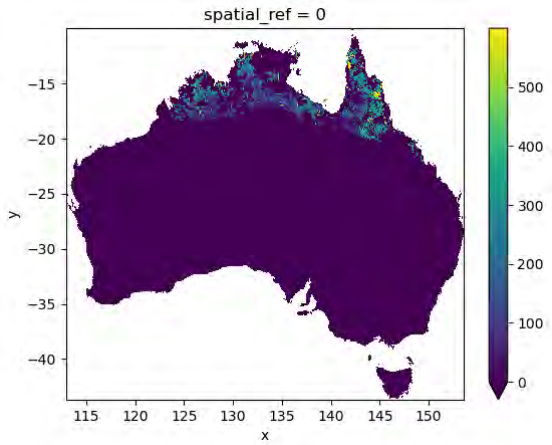	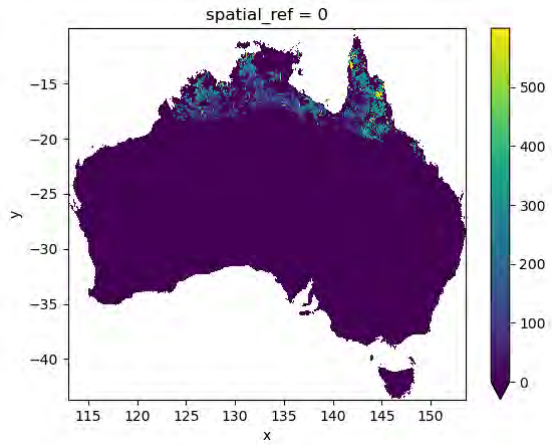
Figure 278 Biodiversity Impact Assessment of Savanna Burning in Land Management Practices for the class of Sheep - natural land	Figure 279 Biodiversity Impact Assessment of Savanna Burning in Land Management Practices for the class of Unallocated - natural land

10.6. Agricultural Management Practices Effects to the biodiversity for all relevant agricultural land use

Define the variable $\mathbf{BSM}^{\text{AGMP}}$, which represents a dictionary of biodiversity score matrices for different agricultural management practices. Each key k maps to the corresponding matrix $\mathbf{BSM}^{k}_{mr\ell}$, as:

$\mathbf{BSM}^{\text{AGMP}} = \left\{ k \rightarrowtail \mathbf{BSM}^{k}_{mr\ell}(y) \mid r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}, \mathbf{BSM}^{k}_{mr\ell}(y) \in \mathbb{R}^{N_k \times N_c \times N^{k}_{lu}} \right\}$	Equation 192

where,

- $\mathcal{K}$ is the set of agricultural management practices that can be applied to different land-use types (see Equation 22)
- N_c is the number of spatial cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (see Equation 21); hence $N_k = 2$.

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- N_{lu}^{k} represents the number of land-use classes affected by each agricultural management practice $\mathcal{K}$ (refer to Equation 24-Equation 32)
- $\mathbb{R}$ represents the set of real numbers
- $\mathbf{BSM}_{mr\ell}^{k}(y)$ is the updated Biodiversity Score Matrix resulting from the integration of the k-th agricultural management practice for year y.

Agricultural management practices are linked to their applicable land-use types through a mapping function ϕ, as defined in Equation 23. This function relates each practice $\boldsymbol{k} \in \boldsymbol{\mathcal{K}}$ to a subset of land-use classes $\mathcal{L}$ (see Equation 1). The specific land-use classes affected by each practice are outlined in Equation 24-Equation 32.

Once initialized using Equation 192, the dictionary $\mathbf{BSM}^{\text{AGMP}}$ is updated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists k, k \in \mathcal{K}$	Equation 193
$\mathbf{BSM}^{\text{AGMP}}(y) = \begin{cases} k \rightarrowtail \mathbf{BSM}_{mr\ell}^{\text{AspTaxifor}}(y) & if \quad k \in \phi(\text{Asparagopsis taxiformis}) \\ k \rightarrowtail \mathbf{BSM}_{mr\ell}^{\text{PrecAgric}}(y) & if \quad k \in \phi(\text{Precision Agriculture}) \\ k \rightarrowtail \mathbf{BSM}_{mr\ell}^{\text{EcolGrazing}}(y) & if \quad k \in \phi(\text{Ecological Grazing}) \\ k \rightarrowtail \mathbf{BSM}_{mr\ell}^{\text{SavBurn}}(y) & if \quad k \in \phi(\text{Savanna Burning}) \\ k \rightarrowtail \mathbf{BSM}_{mr\ell}^{\text{AgTech EI}}(y) & if \quad k \in \phi(\text{AgTech EI}) \end{cases}$	

where,

- $\mathcal{K}$ is the set of agricultural management practices applicable to different land-use types (Equation 22)
- k denotes an individual agricultural management practice from the set
- $\mathbf{BSM}_{mr\ell}^{\text{AspTaxifor}}(y)$ is the biodiversity score matrix updated by integrating *Asparagopsis taxiformis* into agricultural land-use strategies (Equation 187)
- $\mathbf{BSM}_{mr\ell}^{\text{PrecAgric}}(y)$ is the biodiversity score matrix updated by incorporating Precision Agriculture into land management (Equation 188)
- $\mathbf{BSM}_{mr\ell}^{\text{EcolGrazing}}(y)$ is the biodiversity score matrix updated by applying Ecological Grazing strategies (Equation 190)
- $\mathbf{BSM}_{mr\ell}^{\text{SavBurn}}(y)$ is the biodiversity score matrix updated by implementing Savanna Burning practices (Equation 104)
- $\mathbf{BSM}_{mr\ell}^{\text{AgTech EI}}(y)$ is the biodiversity score matrix updated by integrating AgTech EI (Environmental Impact) practices into land use (Equation 191)
- $\phi(\text{Asparagopsis taxiformis})$ refers to the *Asparagopsis taxiformis* practice, which primarily affects livestock production on both natural and modified land-use types (see Equation 25)
- $\phi(\text{Precision Agriculture})$ corresponds to the Precision Agriculture practice, primarily applied to cropping, intensive cropping, and horticultural land uses (see Equation 27)
- $\phi(\text{Ecological Grazing})$ denotes the Ecological Grazing practice, primarily applied to livestock systems on modified land (see Equation 29)
- $\phi(\text{Savanna Burning})$ represents the Savanna Burning practice, which primarily targets livestock operations on natural land as well as unallocated natural land (see Equation 31)
- $\phi(\text{AgTech EI})$ indicates the AgTech Environmental Impact (EI) practice, primarily affecting cropping, intensive cropping, and horticultural land uses (see Equation 33)

10.7. Calculating Biodiversity Limits Based on Targeted Goals for a Given Year

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This section computes the biodiversity limits for a given year, providing a target that must be met or exceeded to ensure the sustainability of biodiversity within the modeled landscape.

$\mathrm{BL}(y) = \boldsymbol{BVC}^{\mathrm{Total}} + \left(\mathrm{BDV}^{\mathrm{Total}} \times \theta(y)\right)$	Equation 194

Where,

- $\mathrm{BL}(y)$: Biodiversity limit for calendar year y
- $\boldsymbol{BVC}^{\mathrm{Total}}$: Current biodiversity value, accounting for land use and management impacts such as savanna burning and livestock (Equation 198).
- $\mathrm{BDV}^{\mathrm{Total}}$: Total biodiversity loss due to land degradation (Equation 205).
- $\theta(y)$: Proportion of degraded land to be restored by year y (Figure 283).

The result produced by Equation 194 is illustrated as a graph in Figure 288.

To compute $\boldsymbol{BVC}^{\mathrm{Total}}$, the current Biodiversity Value per cell $\mathbf{BVC}_r^{\mathrm{Current}}$ is calculated:

$\mathbf{BVC}_r^{\mathrm{Current}} = \mathbf{BSM}_r^{\mathrm{LDS}} - [\mathbf{BSM}_r^{raw} \times (1 - \mathbf{BDH}_r)]$	Equation 195

where,

- $\mathbf{BDH}_r$: Biodiversity degradation habits (Equation 199 and Figure 281)
- $\mathbf{BSM}_r^{\mathrm{LDS}}$: late-dry season (LDS) adjusted biodiversity score (Equation 180, and Figure 262)
- $\mathbf{BSM}_r^{raw}$: Raw biodiversity score matrix (Figure 252, Figure 254, Figure 256, Figure 258, Figure 260)

To ensure only non-negative values are retained:

$\mathbf{BVC}_r^{\mathrm{Current}} = \begin{cases} \mathbf{BVC}_r^{\mathrm{Current}} & \text{if} \quad \mathbf{BVC}_r^{\mathrm{Current}} \geq 0 \\ 0 & \text{otherwise} \end{cases}$	Equation 196

The biodiversity current value, computed using Equation 196, is illustrated in Figure 284. To calculate the total biodiversity value ($\boldsymbol{BVC}^{\mathrm{Total}}$) for the cells within the land use mask (Figure 285) , Equation 197 is applied.

$\mathbf{BVC}_r^{\mathrm{Current}} = \begin{cases} \mathbf{BVC}_r^{\mathrm{Current}} \times \mathbf{RA}_r & \text{if} \quad \mathrm{LUMask}_r = 1 \\ 0 & \text{otherwise} \end{cases}$	Equation 197

where,

- $\mathbf{RA}_r$ Real area multiplier (Figure 5)

Then, $\boldsymbol{BVC}^{\mathrm{Total}}$ is computed as:

$\boldsymbol{BVC}^{\mathrm{Total}} = \sum_{r=1}^{N_r} \mathbf{BVC}_r^{\mathrm{Current}}$	Equation 198

where,

- N_r is the number of pixels

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The biodiversity degradation habits which was employed in Equation 195, is computed as:

$\forall r \in \{1, \dots, N_r \; \exists \ell \, , \ell = \mathbf{LUM}_r$	Equation 199
$\mathbf{BDH}_r = BDH_{\ell_r}^{\mathrm{LUT}}$	

where,

- $BDH_{\ell_r}^{\mathrm{LUT}}$: Look-up table value for biodiversity degradation habits (
- Table *11* and Figure 282)

LUTO 2.0 uses the 50th percentile as the default. Moreover, the computed biodiversity degradation habits based on the 2010 land use map are illustrated in Figure 281.

To compute the total biodiversity value lost due to land degradation ($\mathrm{BDV}^{\mathrm{Total}}$) in Equation 194, the weighted biodiversity degradation value $\mathbf{BDVM}_r$ is first calculated as:

$\mathbf{BDVM}_r = \mathbf{WBDM}_r^{\mathrm{LDS}} + \mathbf{WBDM}_r^{\mathrm{HCAS}}$	Equation 200

where,

- $\mathbf{WBDM}_r^{\mathrm{LDS}}$ is the weighted biodiversity degradation matrix under late-dry season (LDS) burning (Equation 201 and Figure 286)
- $\mathbf{WBDM}_r^{\mathrm{HCAS}}$ is the Weighted biodiversity degradation matrix under HCAS (Equation 202 and Figure 287)

The weighted biodiversity degradation matrix under late-dry season (LDS) burning adjustment factor is computed as:

$\mathbf{WBDM}_r^{\mathrm{LDS}} = \mathbf{WBSM}_r^{raw} \times (1 - \lambda_r^{\mathrm{LDS}})$	Equation 201

where,

- λ_r^{LDS} is the biodiversity degradation score under Savanna burning (Equation 183 and Figure 261)
- $\mathbf{WBSM}_r^{raw}$ is the weighted biodiversity score raw matrix (Equation 181, and Figure 253, Figure 255, Figure 257, Figure 259)

Figure 286 illustrates one of the produced output from Equation 201.

The weighted biodiversity degradation matrix under HCAS is computed as:

$\mathbf{WBDM}_r^{\mathrm{HCAS}} = \mathbf{WBSM}_r^{raw} \times (1 - \mathbf{BDH}_r)$	Equation 202

where,

- $\mathbf{BDH}_r$ represents the biodiversity degradation habits (Equation 199 and Figure 281)
- $\mathbf{WBSM}_r^{raw}$ represents the weighted biodiversity score raw matrix (Equation 181, and Figure 253, Figure 255, Figure 257, Figure 259)

For the weighted biodiversity degradation value $\mathbf{BDVM}_r$, the following condition also must be applied on that:

$\mathbf{BDVM}_r = \begin{cases} \mathbf{WBSM}_r^{raw} & \text{if} \quad \mathbf{BDVM}_r > \mathbf{WBSM}_r^{raw} \\ \mathbf{BDVM}_r & \text{otherwise} \end{cases}$	Equation 203

The weighted biodiversity degradation value $\mathbf{BDVM}_r$ resulting from Equation 203 is illustrated in Figure 284.

To compute the summation of the biodiversity current value for the cells located within the land use mask (Figure 285) , Equation 197 was applied.

$\mathbf{BDVM}_r = \begin{cases} \mathbf{BDVM}_r \times \mathbf{RA}_r & \text{if} \quad \text{LUMask}_\text{r} = 1 \\ 0 & \text{otherwise} \end{cases}$	Equation 204

where,

- $\mathbf{RA}_r$ Real area multiplier (Figure 5)

Then,

$\text{BDV}^{\text{Total}} = \sum_{r=1}^{N_r} \mathbf{BDVM}_r$	Equation 205

where,

- N_r is the number of pixels

Another parameter in Equation 194 is the proportion of degraded land to be restored by year y in order to meet the biodiversity target ($\theta(y)$), defined as:

$\theta_r(y) = \text{BGT}_2(y)$	Equation 206

where,

- $\theta_r(y)$ is the proportion of the degraded land that must be restored by year y, according to the BGT_2 (Figure 283).

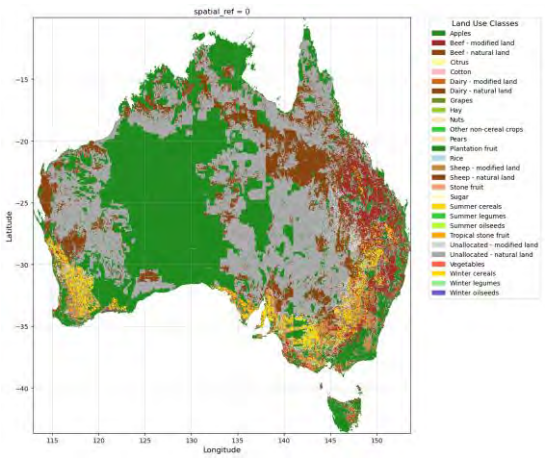

Figure 280 Land use map

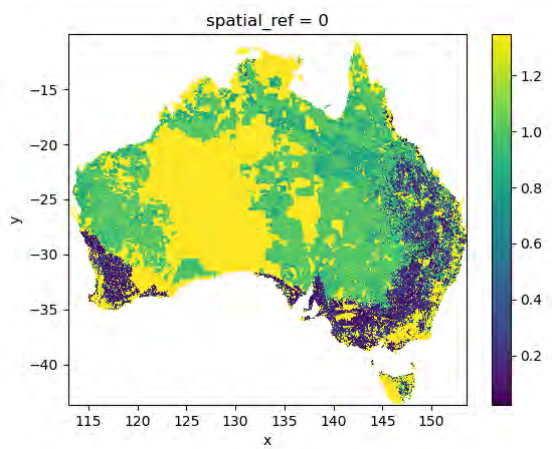

Figure 281 Biodiversity degradation based on the land use class

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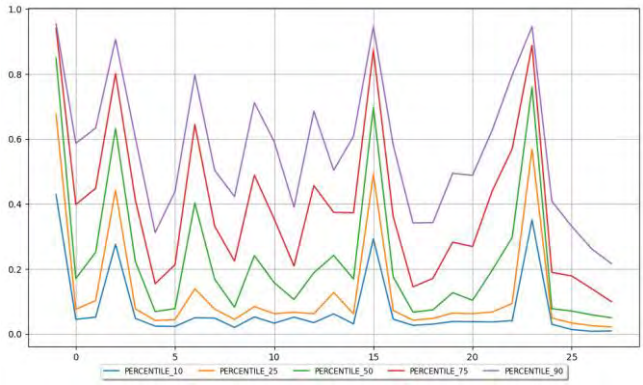

Figure 282 Biodiversity Degradation Scale for Agricultural Land-Use

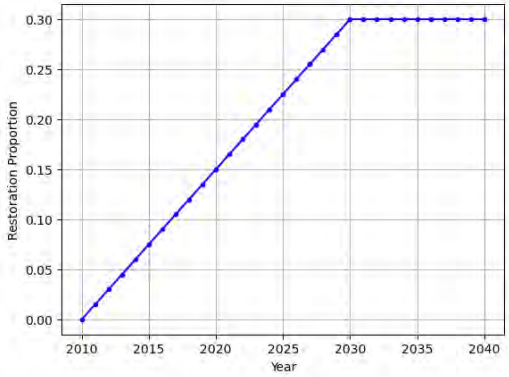

Figure 283 Restoration target for Kunming-Montreal GBF target 2

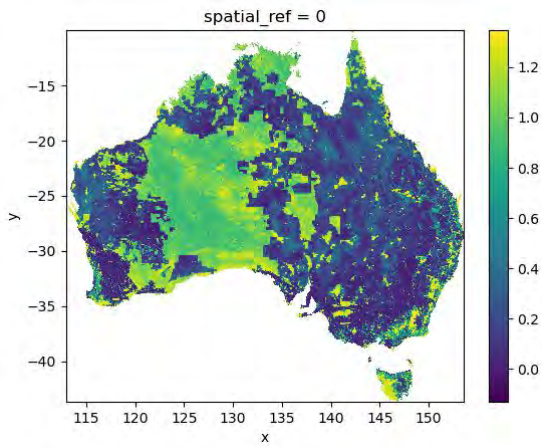

Figure 284 The biodiversity current value

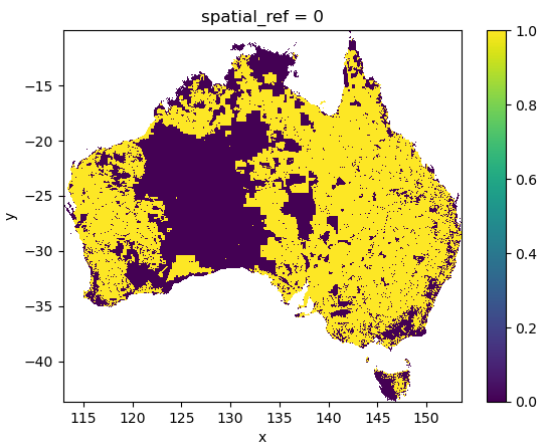

Figure 285 The land use mask

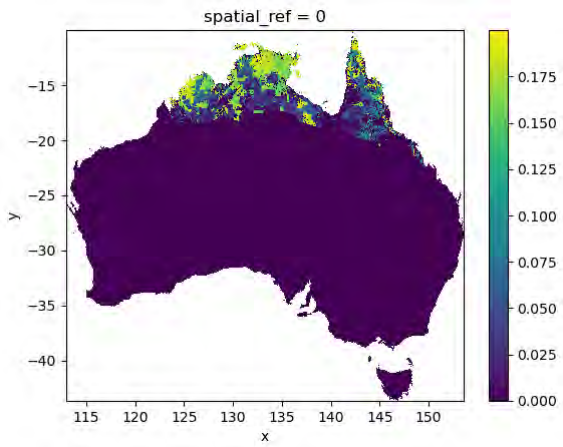

Figure 286 The biodiversity damage under LDS burning

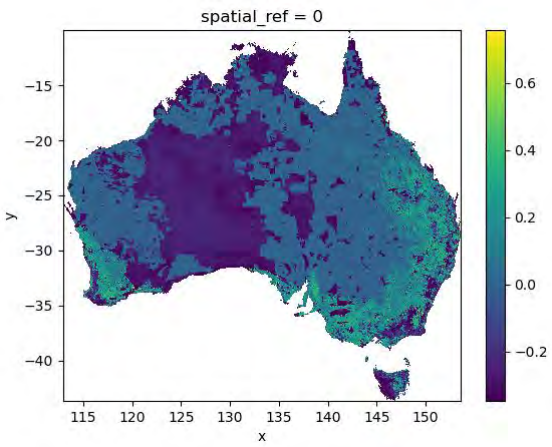

Figure 287 The weighted biodiversity degradation raw matrix under HCAS

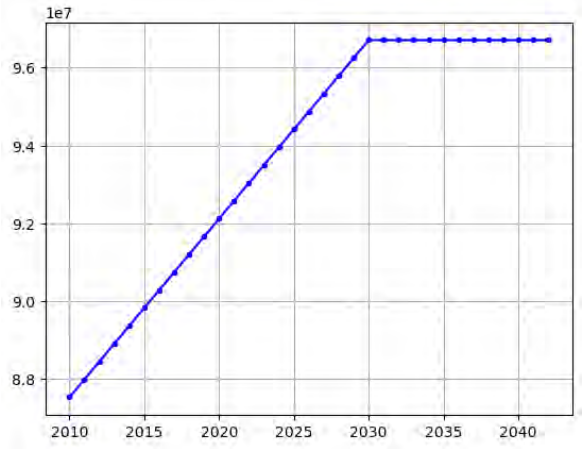

Figure 288 The biodiversity limits

Table 11 The biodiversity degradation habits look up table ($BDH_{\ell_r}^{LUT}$)

Land Use Class	Percentile 10	Percentile 25	Percentile 50	Percentile 75	Percentile 90
Apples	0.0009	0.0306	0.1137	0.2564	0.3913
Beef - modified land	0	0.036	0.1649	0.2996	0.4154
Beef - natural land	0.2868	0.4109	0.548	0.7067	0.8281
Citrus	0	0.0118	0.1203	0.2268	0.3512
Cotton	0	0.0252	0.1081	0.1848	0.2894
Dairy - modified land	0	0.0032	0.057	0.1608	0.2762
Dairy - natural land	0.0166	0.1245	0.3157	0.4805	0.5995
Grapes	0	0.0052	0.0714	0.1808	0.2769
Hay	0	0.0001	0.0514	0.1635	0.2722
Nuts	0	0.0086	0.1527	0.3439	0.4706
Other non-cereal crops	0	0.008	0.0871	0.205	0.3484
Pears	0.0002	0.0209	0.0786	0.1668	0.293
Plantation fruit	0.0001	0.0406	0.1654	0.3346	0.4715
Rice	0	0.0181	0.0957	0.207	0.3113
Sheep - modified land	0	0.0154	0.1197	0.2519	0.4272
Sheep - natural land	0.3264	0.4624	0.6173	0.7632	0.8613
Stone fruit	0	0.0228	0.1008	0.2195	0.3723
Sugar	0	0	0.0164	0.1215	0.2806
Summer cereals	0	0.0127	0.0753	0.1739	0.2835
Summer legumes	0	0.0109	0.0943	0.2013	0.3175
Summer oilseeds	0	0.0025	0.0651	0.1739	0.2873
Tropical stone fruit	0.0002	0.0382	0.1556	0.3089	0.4548
Unallocated - modified land	0.0003	0.0621	0.2309	0.4437	0.5999
Unallocated - natural land	0.3475	0.5019	0.6683	0.8035	0.8946
Vegetables	0	0.0009	0.0488	0.1503	0.2711
Winter cereals	0	0.0023	0.0674	0.1736	0.2643
Winter legumes	0	0.0005	0.0611	0.1644	0.2542
Winter oilseeds	0	0	0.0352	0.1333	0.2124

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- Economics/Agricultural/ revenue.py

11. The Revenue

11.1. Crop Revenue Calculation

The revenue of crops ($\mathbf{Rev}_{mr\ell}^{AG}(y)$) for the set of $\mathcal{L}_{\text{Crops}} - \{\text{Pears, Rice}\}$, where $\mathcal{L}_{\text{Crops}}$ is defined in Equation 15, is calculated as:

$\mathbf{Rev}_{mr\ell}^{AG}(y) = \mathbf{CQY}_{mr\ell}^{AG}(y) \times \mathbf{MPP}_{mr\ell}^{AG} \times RevM_{\ell}^{AG}(y)$	Equation 207

where,

- $\mathbf{CQY}_{mr\ell}^{AG}(y)$: Crop yield quantity (see Equation 121 and Figure 167-Figure 172)
- $\mathbf{MPP}_{mr\ell}^{AG}$: Market price of product (AUD/tonne) (Figure 289-Figure 294)
- $RevM_{\ell}^{AG}(y)$: Revenue multiplier

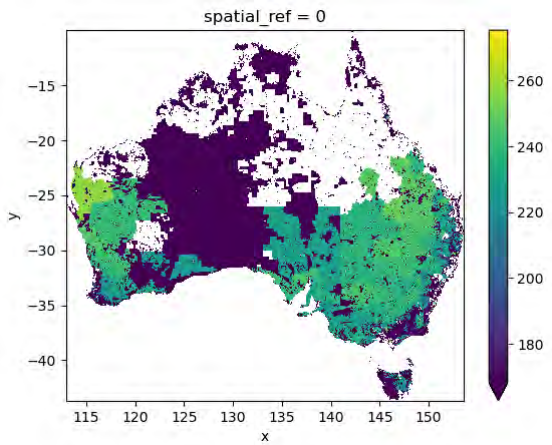

Figure 289 Market price of Winter cereals under dry land management system

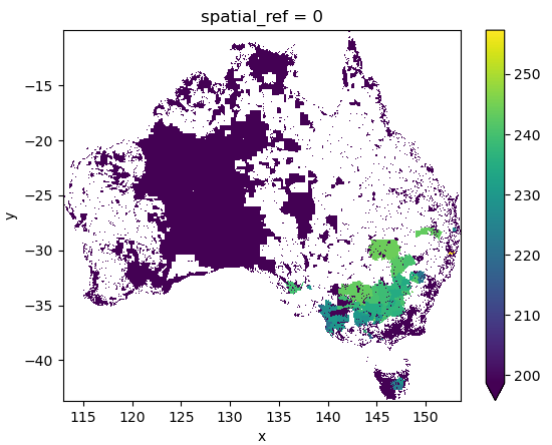

Figure 290 Market price of Winter cereals under irrigation land management system

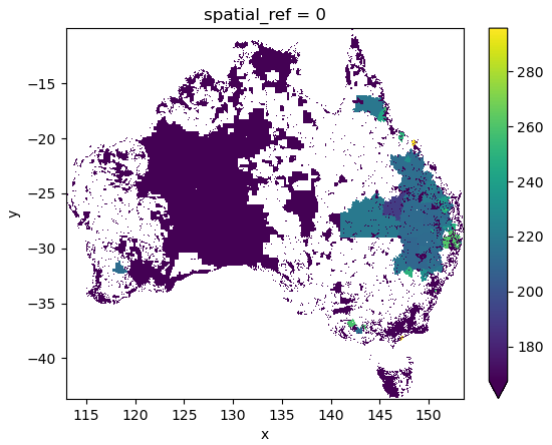

Figure 291 Market price of Summer cereals under dry land management system

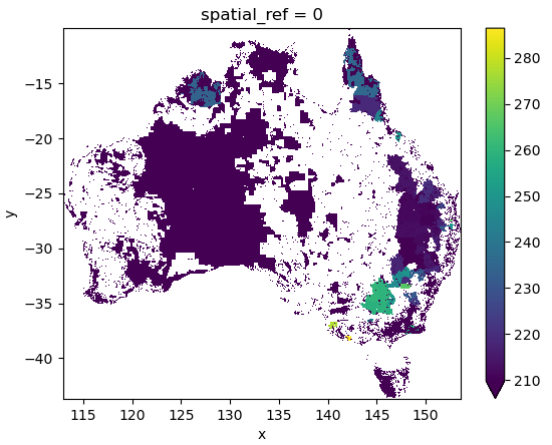

Figure 292 Market price of Summer cereals under irrigation land management system

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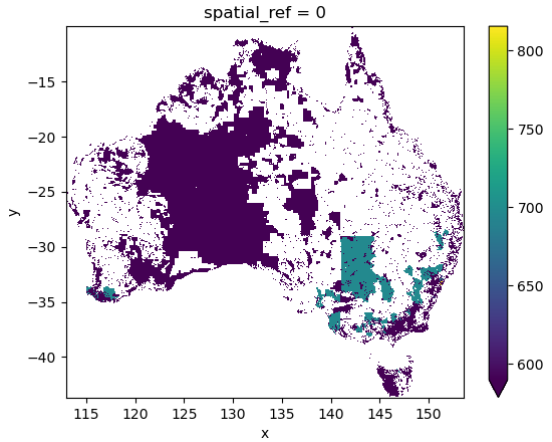

Figure 293 Market price of Grapes under dry land management system

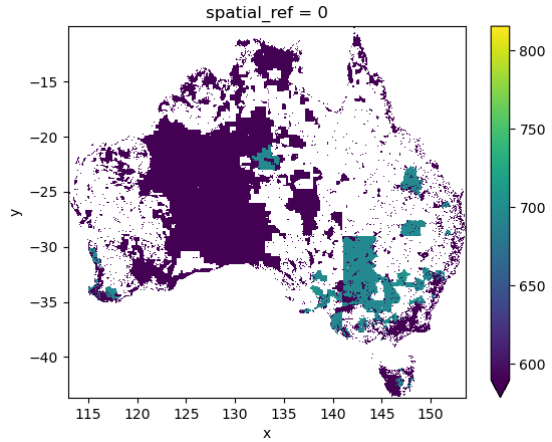

Figure 294 Market price of Grapes under irrigation land management system

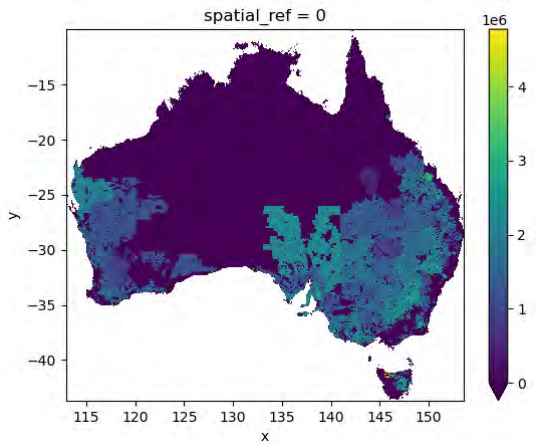

Figure 295 Revenue of Winter cereals under dry land management system

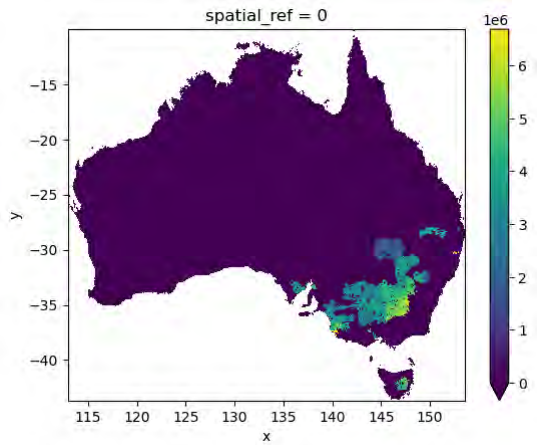

Figure 296 Revenue of Winter cereals under irrigation land management system

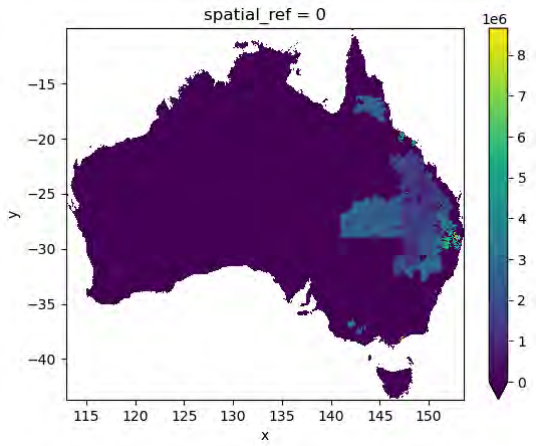

Figure 297 Revenue of Summer cereals under dry land management system

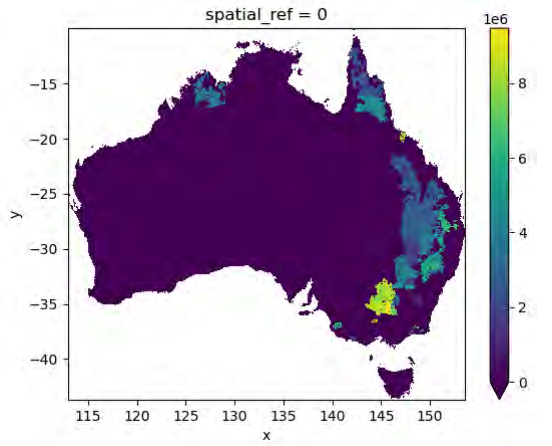

Figure 298 Revenue of Summer cereals under irrigation land management system

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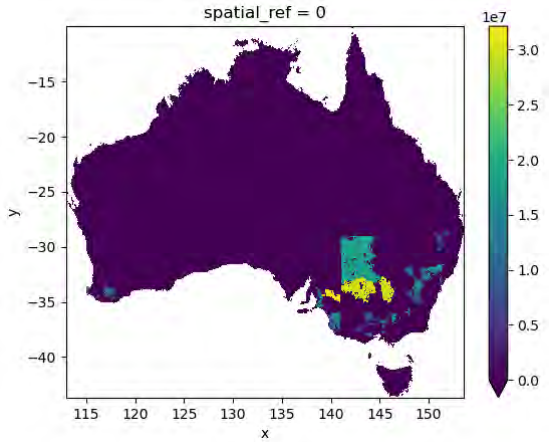	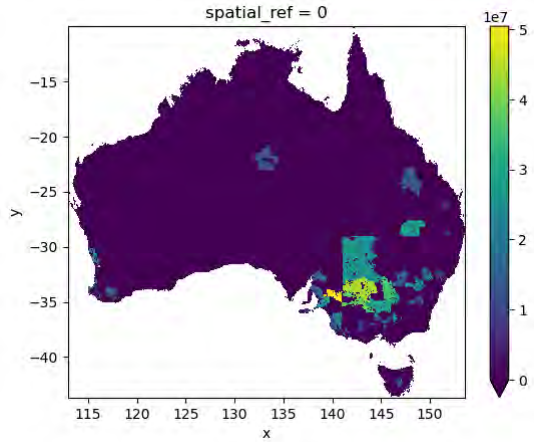
Figure 299 Revenue of Grapes under dry land management system	Figure 300 Revenue of Grapes under irrigation land management system

11.2. Livestock Revenue Calculation

The revenue per cell for different livestock types (LS) is calculated as the sum of multiple revenue components.

11.2.1. Beef Revenue

$\forall r \in \{1, \dots, N_r\}\ \exists \ell, \ell \in \mathcal{L}^{\text{Beef}}_{\text{Commodities}}, \mathcal{L}^{\text{Beef}}_{\text{Commodities}} = \{\text{Beef Meat, Beef Lexp}\}$	
$\mathbf{Reven}^{Beef}_{Meat}(y) = \mathbf{YPot}^{LS}_{mr\ell}(y) \times \mathbf{BQ}^{BeefMeat}_{r} \times \mathbf{AGEC}^{\text{Beef,P1}}_{r} \times LivPM^{LS}_{\ell}(y) \times \mathbf{RA}_{r}$	Equation 208
$\mathbf{Reven}^{Beef}_{LEXP}(y) = \mathbf{YPot}^{LS}_{mr\ell}(y) \times \mathbf{BQ}^{BeefLEXP}_{r} \times \mathbf{AGEC}^{\text{Beef,P3}}_{r} \times LivPM^{LS}_{\ell}(y) \times \mathbf{RA}_{r}$	Equation 209

where,

- $\mathbf{YPot}^{LS}_{mr\ell}(y)$: Yield potential for livestock ℓ (Equation 113 and Figure 117-Figure 128)
- $\mathbf{BQ}^{BeefMeat}_{r}$: Base quantity for Beef Meat (Equation 115 and Figure 141)
- $\mathbf{BQ}^{BeefLEXP}_{r}$: Base quantity for Beef Live export (LEXP) (Equation 116 and Figure 142)
- $\mathbf{AGEC}^{\text{Beef,P1}}_{r}$: Market price of product (AUD/tonne of meat) (Figure 301)
- $\mathbf{AGEC}^{\text{Beef,P3}}_{r}$: Market price of product (AUD/tonne of animal) (Figure 302)
- $LivPM^{LS}_{\ell}(y)$: Livestock multiplier
- $\mathbf{RA}_{r}$: Real area (Figure 5)

The computed revenue from Beef Meat and Beef Live Export in modified land (dry and irrigation) is shown in Figure 307-Figure 310, and in natural land in Figure 319-Figure 322.

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11.2.2. Sheep Revenue

$\forall r \in \{1, \dots, N_r\}\ \exists \ell, \ell \in \mathcal{L}^{\text{Sheep}}_{\text{Commodities}}, \mathcal{L}^{\text{Sheep}}_{\text{Commodities}} = \{\text{Sheep Meat, Sheep Wool, Sheep Lexp}\}$	
$\mathbf{Reven}^{Sheep}_{Meat}(y) = \mathbf{YPot}^{LS}_{mr\ell}(y) \times \mathbf{BQ}^{SheepMeat}_{r} \times \mathbf{AGEC}^{\text{Sheep,P1}}_{r} \times LivPM^{LS}_{\ell}(y) \times \mathbf{RA}_r$	Equation 210
$\mathbf{Reven}^{Sheep}_{Wool}(y) = \mathbf{YPot}^{LS}_{mr\ell}(y) \times \mathbf{BQ}^{SheepWool}_{r} \times \mathbf{AGEC}^{\text{Sheep,P2}}_{r} \times LivPM^{LS}_{\ell}(y) \times \mathbf{RA}_r$	Equation 211
$\mathbf{Reven}^{Sheep}_{LEXP}(y) = \mathbf{YPot}^{LS}_{mr\ell}(y) \times \mathbf{BQ}^{SheepLEXP}_{r} \times \mathbf{AGEC}^{\text{Sheep,P3}}_{r} \times LivPM^{LS}_{\ell}(y) \times \mathbf{RA}_r$	Equation 212

- $\mathbf{YPot}^{LS}_{mr\ell}(y)$ represents the yield potential for livestock ℓ (Equation 113 and Figure 117-Figure 128)
- $\mathbf{BQ}^{SheepMeat}_{r}$: Base quantity for sheep meat (Equation 117)
- $\mathbf{BQ}^{SheepWool}_{r}$: Base quantity for sheep wool (Equation 118)
- $\mathbf{BQ}^{SheepLEXP}_{r}$: Base quantity for sheep live export (Equation 119)
- $\mathbf{AGEC}^{\text{Sheep,P1}}_{r}$: Market price of product (AUD/tonne of meat) (Figure 303)
- $\mathbf{AGEC}^{\text{Sheep,P2}}_{r}$: Market price of product (AUD/tonne of wool) (Figure 304)
- $\mathbf{AGEC}^{\text{Sheep,P3}}_{r}$: Market price of product (AUD/tonne of animal) (Figure 305)
- $LivPM^{LS}_{\ell}(y)$: Livestock multiplier
- $\mathbf{RA}_r$: Real area (Figure 5)

The computed revenue from Sheep products in **modified land** (dry and irrigated) is shown in Figure 311-Figure 316, and in **natural land** in Figure 323-Figure 328.

11.2.3. Dairy Revenue

$\forall r \in \{1, \dots, N_r\}\ \exists \ell, \ell \in \mathcal{L}^{\text{Dairy}}_{\text{Commodities}}, \mathcal{L}^{\text{Dairy}}_{\text{Commodities}} = \{\text{Dairy}\}$	
$\mathbf{Reven}^{Dairy}_{Milk}(y) = \mathbf{YPot}^{LS}_{mr\ell}(y) \times \mathbf{BQ}^{Dairy}_{r} \times \mathbf{AGEC}^{\text{Dairy,P1}}_{r} \times LivPM^{LS}_{\ell}(y) \times \mathbf{RA}_r$	Equation 213

where,

- $\mathbf{YPot}^{LS}_{mr\ell}(y)$: Yield potential for livestock ℓ (Equation 113 and Figure 117-Figure 128)
- $\mathbf{BQ}^{Dairy}_{r}$: Base quantity for sheep meat (Equation 120)
- $\mathbf{AGEC}^{\text{Dairy,P1}}_{r}$: Market price of product (AUD/tonne of meat) (Figure 306)
- $LivPM^{LS}_{\ell}(y)$: Livestock multiplier
- $\mathbf{RA}_r$: Real area (Figure 5)

The computed revenue from Dairy in **modified land** (Figure 317 and Figure 318) and **natural land** (Figure 329 and Figure 330) is presented accordingly.

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11.2.4. Revenue Matrix for each livestock class

The revenue for each product $p \in \mathcal{L}^{LS}_{\text{Commodities}}$ (Equation 39), produced by each livestock type $\ell \in \mathcal{L}^{\text{Livestock}}_{\text{Commodities}}$ (Equation 38), is represented as ($\mathbf{Reven}^{\ell}_{p}(y)$). In this vector $\mathbf{Reven}^{\ell}_{p}(y)$, if a product p is not produced by livestock type ℓ, its value is set to zero. For example, $\mathbf{Reven}^{\ell=Beef}_{p=Wool}(y) = 0$, since beef cattle do not produce wool.

The output of this step is a matrix with 4 columns, where for all

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}^{\text{Livestock}}_{\text{Commodities}}, p \in \mathcal{L}^{LS}_{\text{Commodities}}$	
$\mathbf{Rev}^{LS}_{mr\ell p}(y) = \left[\mathbf{Reven}^{\ell}_{p=Milk}(y) \quad \mathbf{Reven}^{\ell}_{p=Wool}(y) \quad \mathbf{Reven}^{\ell}_{p=LEXP}(y) \quad \mathbf{Reven}^{\ell}_{p=Milk}(y)\right]$	Equation 214

As Equation 214 shows, each column corresponds to a different product source p of livestock type ℓ. Each row of $\mathbf{Rev}^{LS}_{\ell}(y)$ is corresponded to a different cell in the study area's grid, as defined in the LUTO 2.0 model.

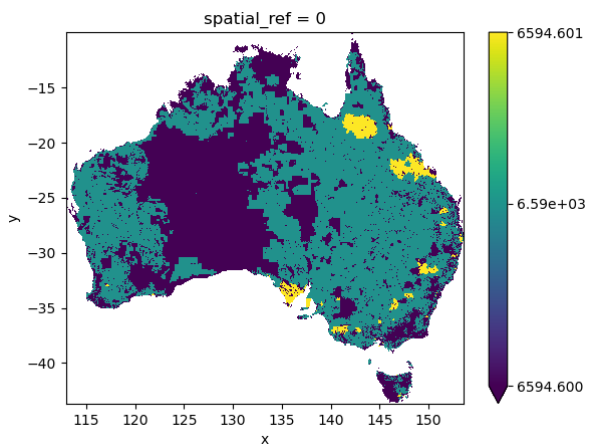

Figure 301 Market price of Beef Meat per quantity (AUD Per tonne of meat)

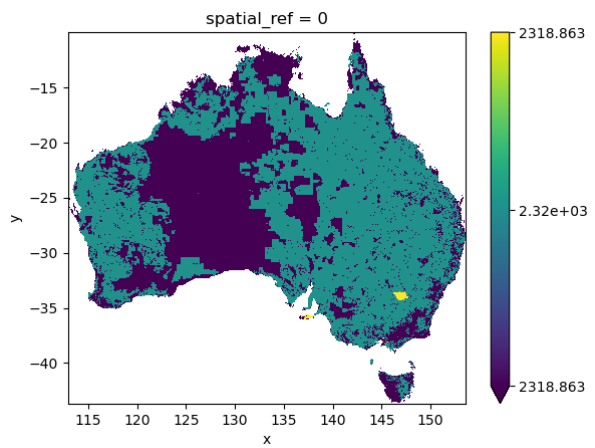

Figure 302 Market price of Beef live exports (LEXP) per quantity (AUD Per tonne of animal)

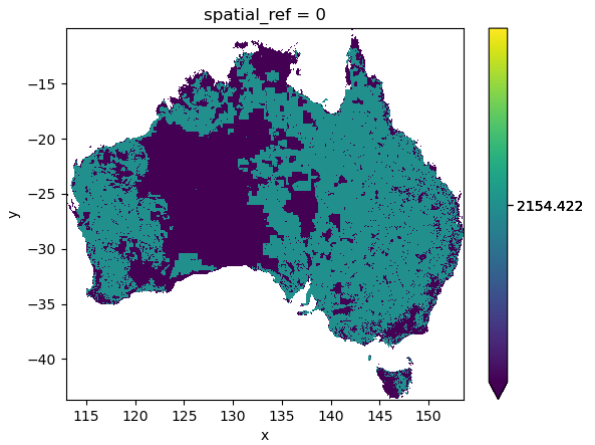

Figure 303 Market price of Sheep Meat per quantity (AUD Per tonne of meat)

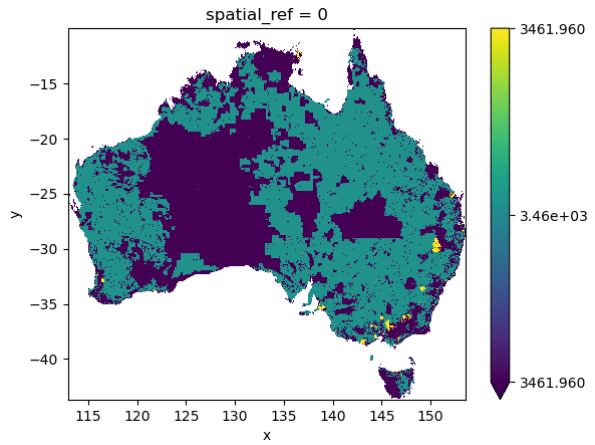

Figure 304 Market price of Sheep Wool per quantity (AUD Per tonne of Wool)

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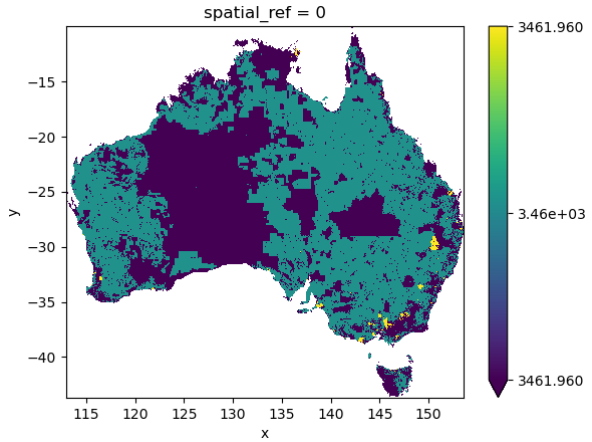

Figure 305 Market price of Sheep live exports (LEXP) per quantity (AUD Per tonne of animal)

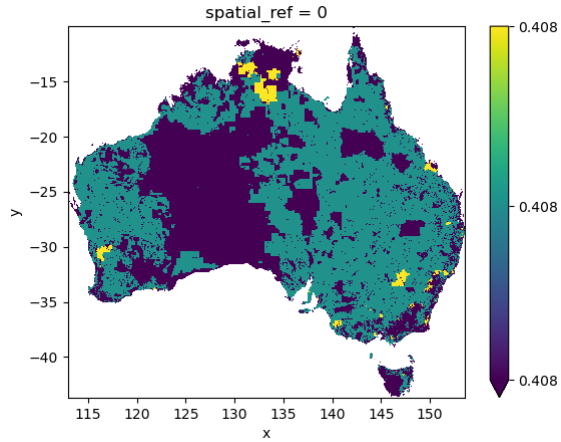

Figure 306 Market price of Dairy per quantity (AUD Per Litre of Milk)

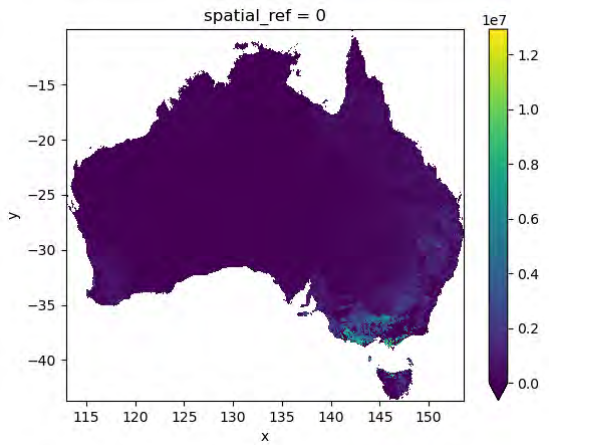

Figure 307 Computed Revenue from Beef Meat in Modified Land under Dry Land Management System

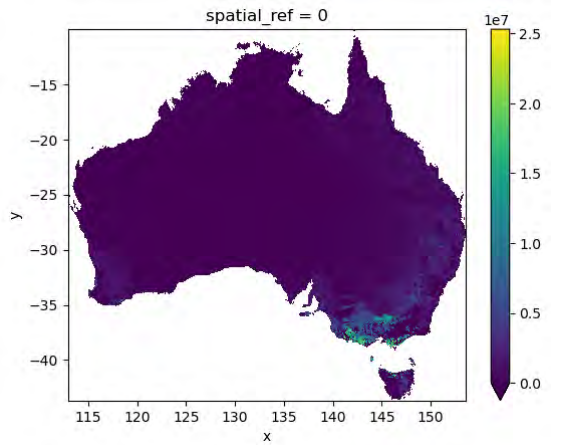

Figure 308 Computed Revenue from Beef Meat in Modified Land under Irrigation Land Management System

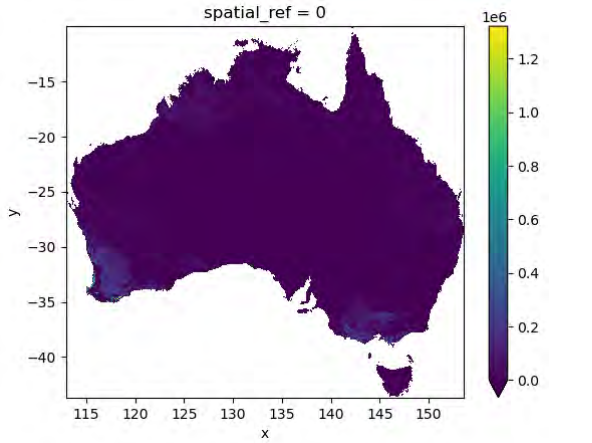

Figure 309 Computed Revenue from Beef live exports (LEXP) in Modified Land under Dry Land Management System

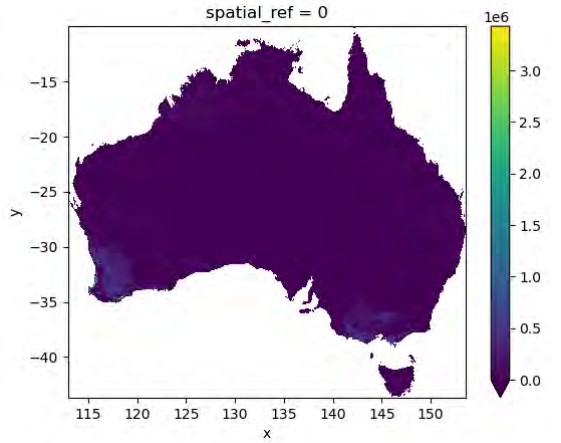

Figure 310 Computed Revenue from Beef live exports (LEXP) in Modified Land under Irrigation Land Management System

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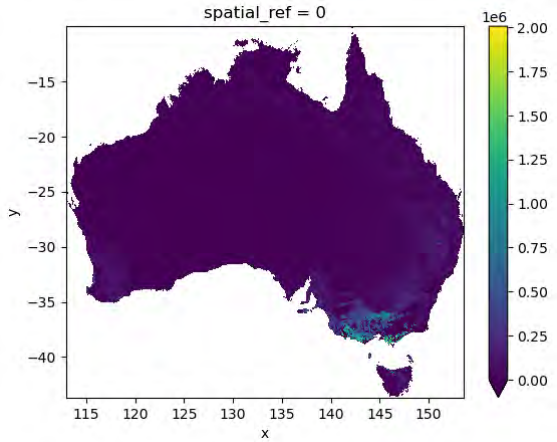

Figure 311 Computed Revenue from Sheep Meat in Modified Land under Dry Land Management System

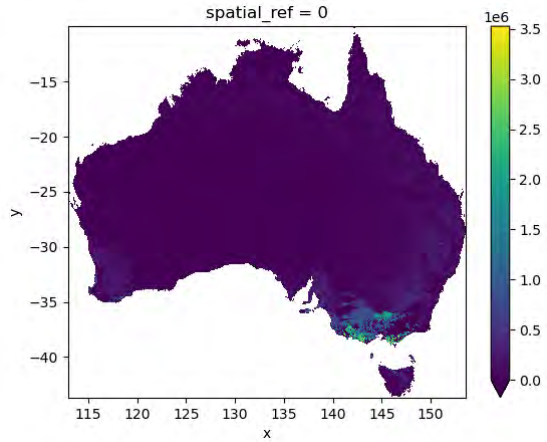

Figure 312 Computed Revenue from Sheep Meat in Modified Land under Irrigation Land Management System

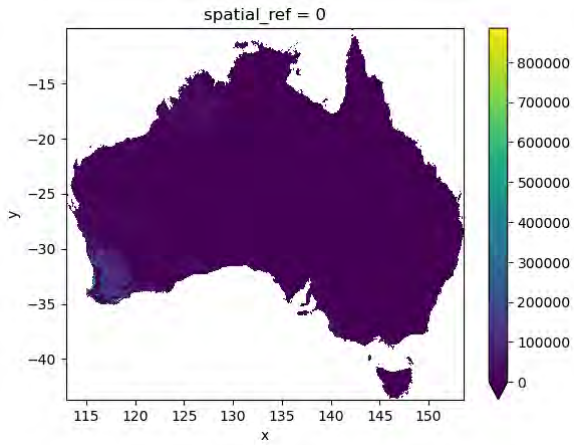

Figure 313 Computed Revenue from Sheep live exports (LEXP) in Modified Land under Dry Land Management System

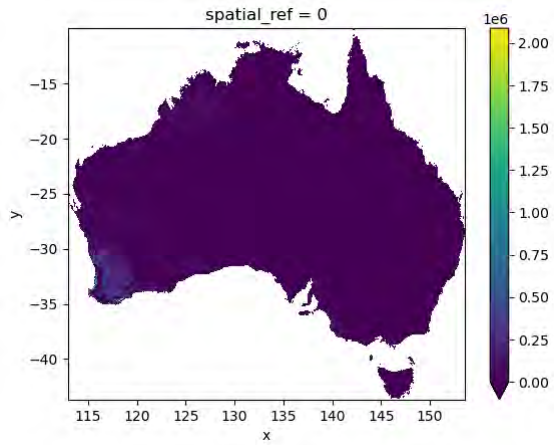

Figure 314 Computed Revenue from Sheep live exports in Modified Land under Irrigation Land Management System

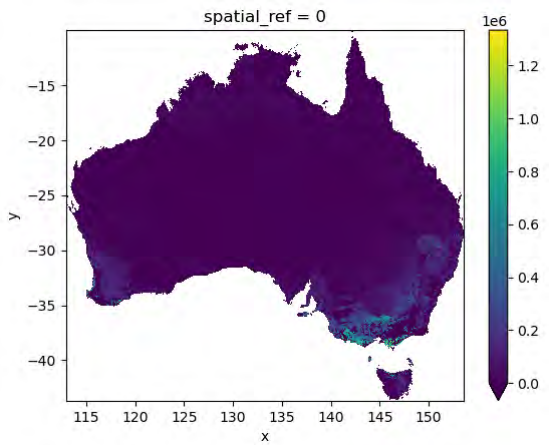

Figure 315 Computed Revenue from Sheep Wool in Modified Land under Dry Land Management System

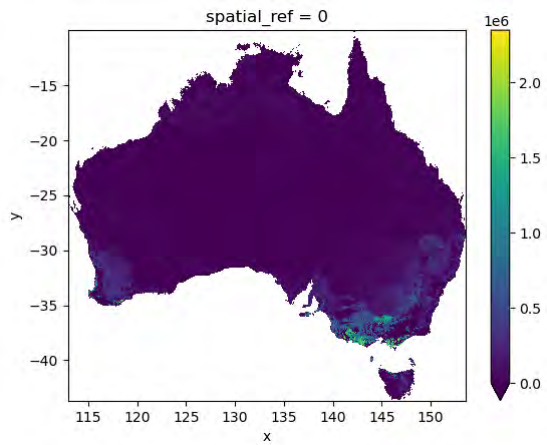

Figure 316 Computed Revenue from Sheep Wool in Modified Land under Irrigation Land Management System

Deakin University CRICOS Provider Code: 00113B

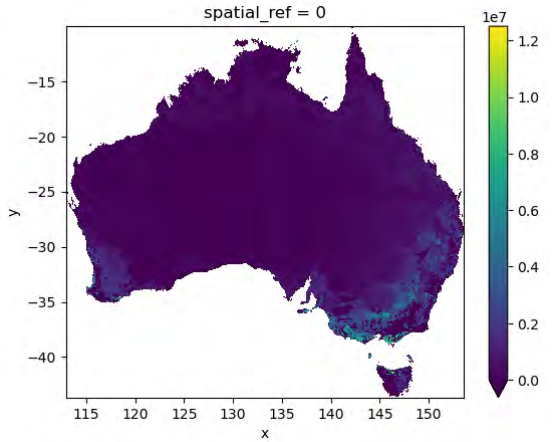

Figure 317 Computed Revenue from Dairy in Modified Land under Dry Land Management System

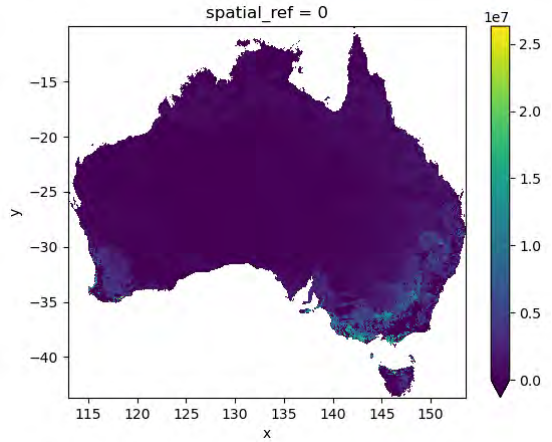

Figure 318 Computed Revenue from Dairy in Modified Land under Irrigation Land Management System

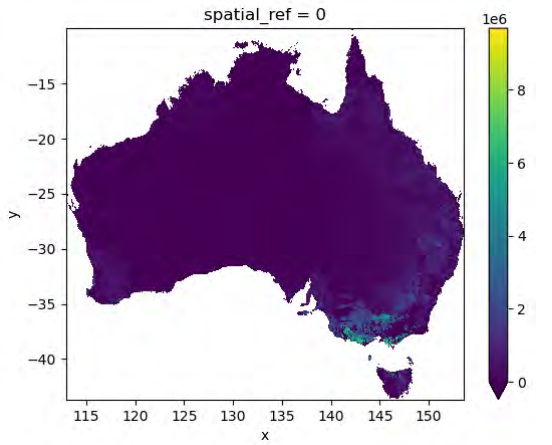

Figure 319 Computed Revenue from Beef Meat in Natural Land under Dry Land Management System

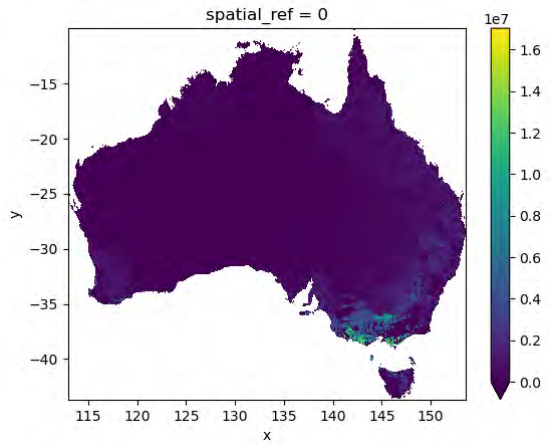

Figure 320 Computed Revenue from Beef Meat in Natural Land under Irrigation Land Management System

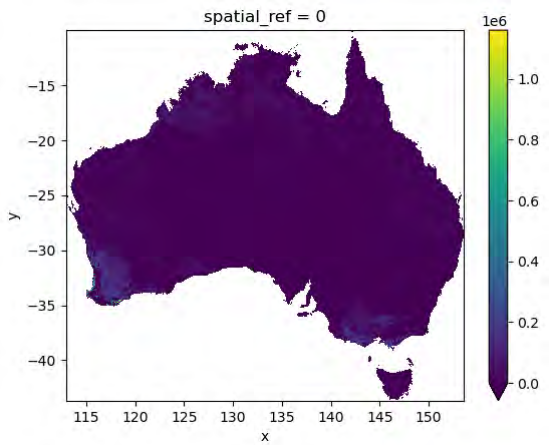

Figure 321 Computed Revenue from Beef live exports (LEXP) in Natural Land under Dry Land Management System

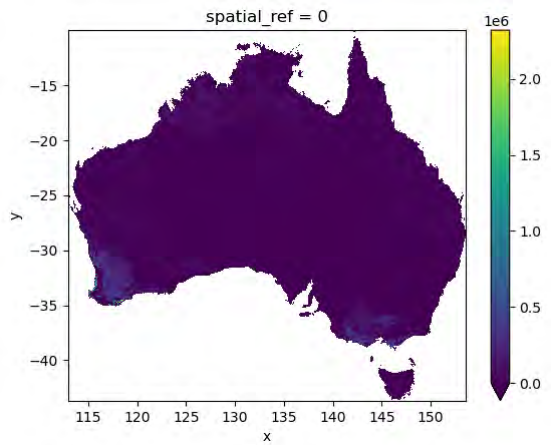

Figure 322 Computed Revenue from Beef live exports (LEXP) in Natural Land under Irrigation Land Management System

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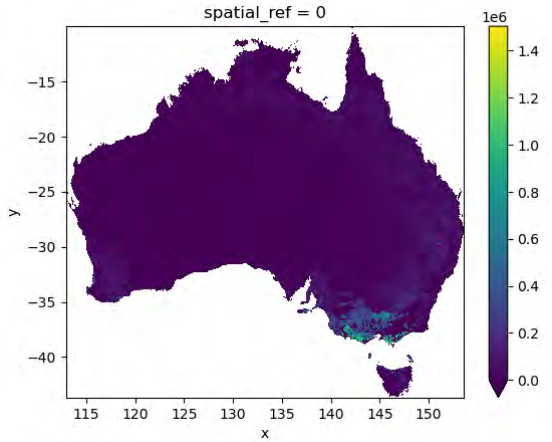

Figure 323 Computed Revenue from Sheep Meat in Natural Land under Dry Land Management System

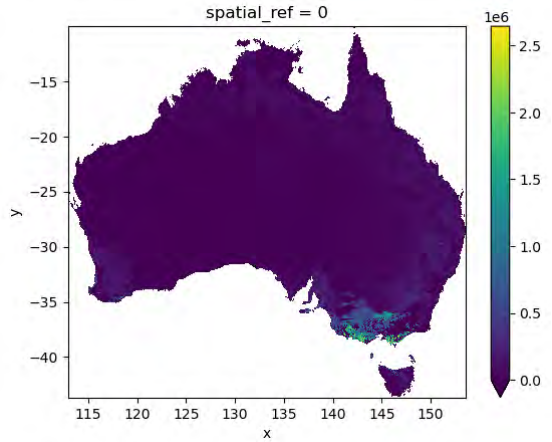

Figure 324 Computed Revenue from Sheep Meat in Natural Land under Irrigation Land Management System

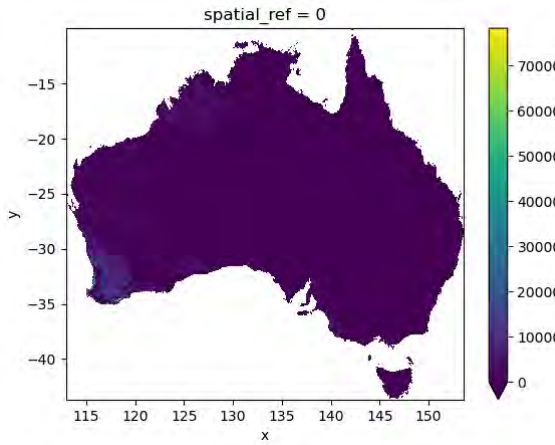

Figure 325 Computed Revenue from Sheep live exports (LEXP) in Natural Land under Dry Land Management System

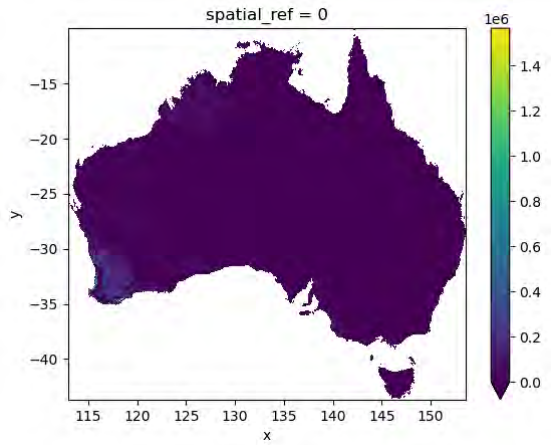

Figure 326 Computed Revenue from Sheep live exports in Natural Land under Irrigation Land Management System

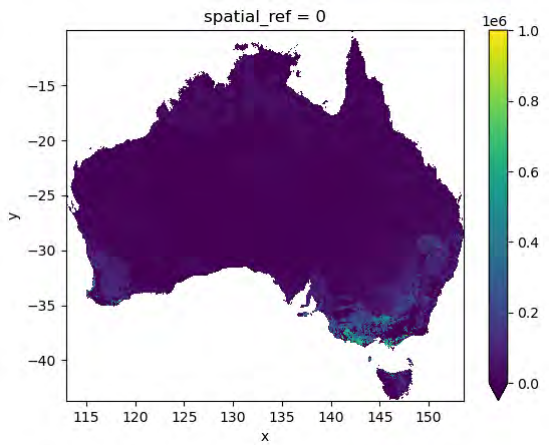

Figure 327 Computed Revenue from Sheep Wool in Natural Land under Dry Land Management System

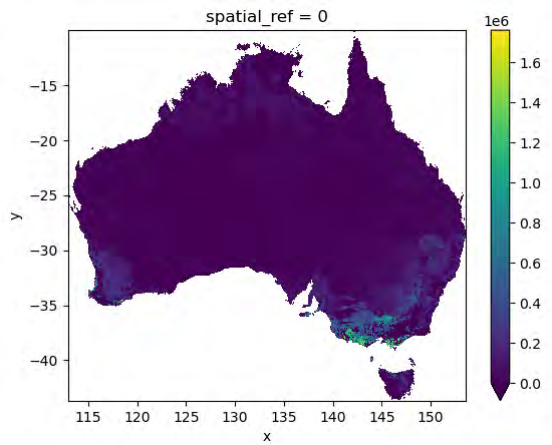

Figure 328 Computed Revenue from Sheep Wool in Natural Land under Irrigation Land Management System

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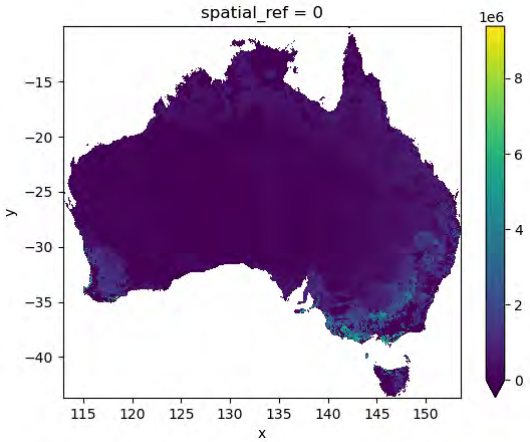	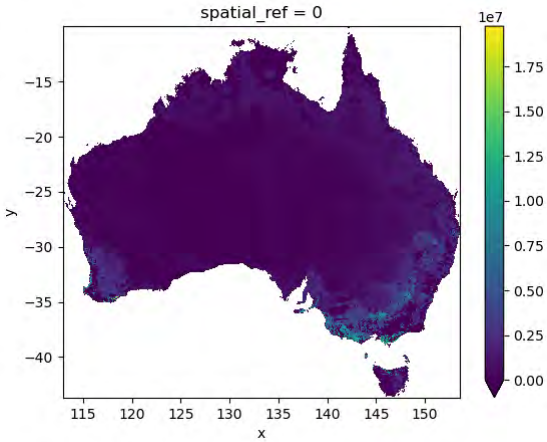
Figure 329 Computed Revenue from Dairy in Natural Land under Dry Land Management System	Figure 330 Computed Revenue from Dairy in Natural Land under Irrigation Land Management System

11.3. Revenue Matrix

To compute the revenue matrix $\mathbf{Revenue}_{mr\ell}$, which includes both **crop revenue** (Section 11.1) and livestock revenue (Section 11.2), it is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 215
$\mathbf{Revenue}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_k = 2$: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21)
- $N_{lu} = 28$, Number of land use classes (Equation 1), including crop, livestock, and unallocated land types

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, p \mid \ell \in \mathcal{L}, p \in \mathcal{L}^{LS}_{\mathrm{Commodities}}$	Equation 216
$\mathbf{Revenue}_{mr\ell}(y) = \begin{cases} \mathbf{Rev}^{AG}_{mr\ell}(y) & \text{if } \ell \in \mathcal{L}_{\mathrm{Crops}} \\ \sum_{p \in \mathcal{L}^{LS}_{\mathrm{Commodities}}} \mathbf{Rev}^{LS}_{mr\ell p}(y) & \text{if } \ell \in \mathcal{L}_{\mathrm{Livestock}} \end{cases}$	

where,

- $\mathbf{Rev}^{AG}_{mr\ell}(y)$: Crop revenue (Equation 207) for crops in $\mathcal{L}_{\mathrm{Crops}} - \{\mathrm{Pears}, \mathrm{Rice}\}$
- $\mathbf{Rev}^{LS}_{mr\ell p}(y)$: Revenue matrix (Equation 214) for all products $p \in \mathcal{L}^{LS}_{\mathrm{Commodities}}$ that might be produced by each livestock type $\ell \in \mathcal{L}^{\mathrm{Livestock}}_{\mathrm{Commodities}}$
- $\mathcal{L}^{LS}_{\mathrm{Commodities}}$: Set of all livestock commodity types (Equation 39)
- $\mathcal{L}_{\mathrm{Crops}}$: Set of all crop land use types (Equation 15)

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- $\mathcal{L}_{\text{Livestock}}$: Set of all livestock land use types (Equation 16)

12. Impacts of Agricultural Management Practices on Revenue

In ecological modeling, assessing the influence of agricultural management practices on biodiversity and economic returns is essential. The applicable management practices for various land uses are described in Equation 22.

12.1. Asparagopsis Taxiformis Effects on Revenue for all relevant agricultural land use

Let $\mathbf{RevM}_{mr\ell}^{\text{AspTaxifor}}$ represent the updated revenue matrix after integrating *Asparagopsis taxiformis* into the agricultural land management system.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Asparagopsis taxiformis})$	Equation 217
$\mathbf{RevM}_{mr\ell}^{\text{AspTaxifor}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AspTaxifor}}\right)}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_k = 2$: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21).
- $N_{lu}^{\text{AspTaxifor}} = 6$, Number of land use classes affected by *Asparagopsis taxiformis* (Equation 25).

To update the revenue matrix for land uses affected by *Asparagopsis taxiformis* $\mathbf{RevM}_{mr\ell}^{\text{AspTaxifor}}$:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell\ , \ell \in \phi(\text{Asparagopsis taxiformis})$	Equation 218
$\mathbf{RevM}_{mr\ell}^{\text{AspTaxifor}}(y) = \\ = \begin{cases} \mathbf{Revenue}_{mr\ell}(y) \times \left(1 - PIM_{\ell}^{\text{AspTaxifor}}(y)\right) & \text{if } \ell \in \phi(\text{Asparagopsis taxiformis}) \wedge PIM_{\ell}^{\text{AspTaxifor}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Asparagopsis taxiformis}) \vee PIM_{\ell}^{\text{AspTaxifor}}(y) = 1 \end{cases}$	

where,

- $PIM_{\ell}^{\text{AspTaxifor}}(y)$: Productivity impact multiplier
- $\mathbf{Revenue}_{mr\ell}(y)$: Original revenue data for year y for all land uses included in $\phi(\text{Asparagopsis taxiformis})$ (Equation 29), under both dry and irrigated land management systems, as computed using Equation 216.

In the current version of LUTO 2.0, the productivity impact multiplier for $\ell_{mr} \in \phi(\text{Asparagopsis taxiformis})$ is $PIM_{\ell}^{\text{AspTaxifor}}(y) = 1$ for all years. Therefore, the computed $\mathbf{RevM}_{mr\ell}^{\text{AspTaxifor}}$ for all the classes available in $\phi(\text{Asparagopsis taxiformis})$ under both dry and irrigation land management systems are zero

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12.2. Precision Agriculture Effects on Revenue for all relevant agricultural land use

Let $\mathbf{RevM}_{mr\ell}^{\text{PrecAgric}}$ represent the updated revenue matrix after integrating Precision agriculture into management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 219
$\mathbf{RevM}_{mr\ell}^{\text{PrecAgric}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{PrecAgric}}\right)}$	

where,

- N_c: Number of land-use map cells $\mathbf{LUM}^{\text{BYear}}$.
- $N_k = 2$: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21).
- $N_{lu}^{\text{PrecAgric}} = 20$: Number of land uses affected (Equation 27).

To update the revenue matrix for precision agriculture $\mathbf{RevM}_{mr\ell}^{\text{PrecAgric}}$:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 220
$\mathbf{RevM}_{mr\ell}^{\text{PrecAgric}}(y) = = \begin{cases} \mathbf{Revenue}_{mr\ell}(y) \times \left(1 - PIM_{\ell}^{\text{PrecAgric}}(y)\right) & \text{if } \ell \in \phi(\text{Precision Agriculture}) \wedge PIM_{\ell}^{\text{PrecAgric}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Precision Agriculture}) \vee PIM_{\ell}^{\text{PrecAgric}}(y) = 1 \end{cases}$	

where,

- $PIM_{\ell}^{\text{PrecAgric}}(y)$: Productivity impact multiplier (Figure 331 and Figure 332)
- $\mathbf{Revenue}_{mr\ell}(y)$: Original revenue value for year y for all land uses included in $\phi(\text{Precision Agriculture})$ (Equation 29), under both dry and irrigated land management systems, as computed using Equation 216.

The updated revenue matrices reflecting the integration of precision agriculture for winter cereals, summer cereals, and grapes under both dry and irrigated systems are illustrated in Figure 333 - Figure 338.

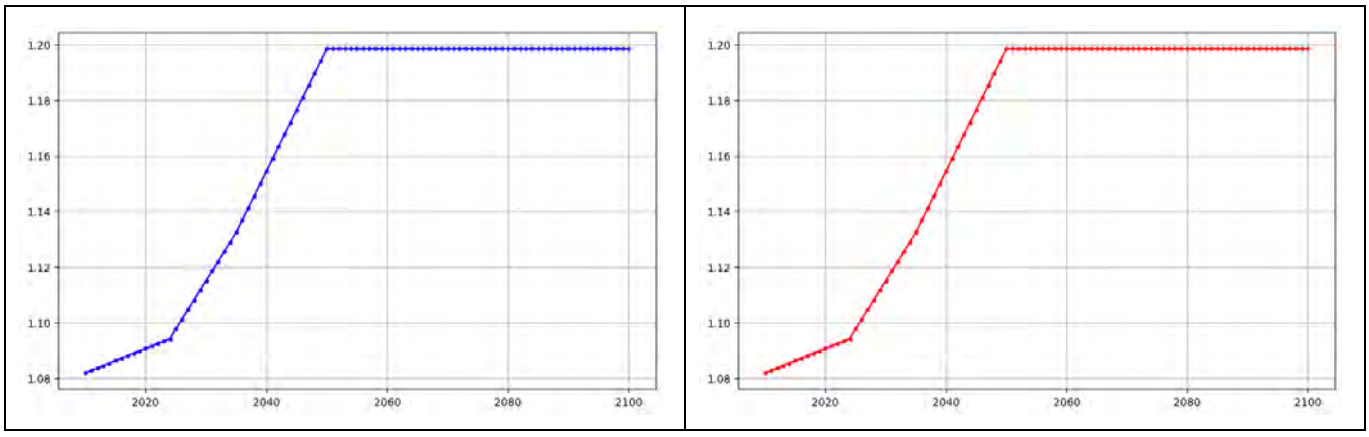

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Figure 331 Assessing the productivity impact multiplier for cropping through precision agriculture integration in land management strategies

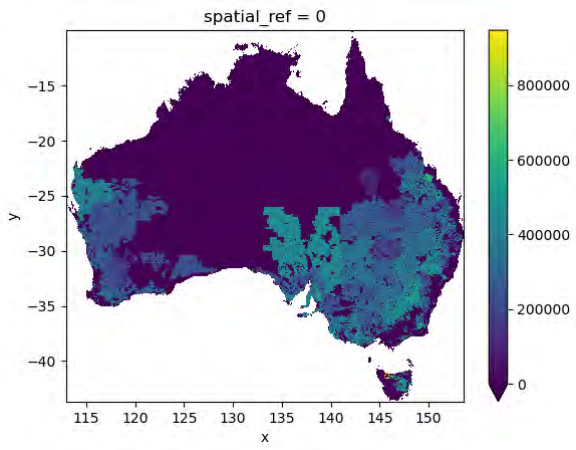

Figure 332 Evaluating the productivity impact multiplier in horticulture with integration of precision agriculture into land management strategies

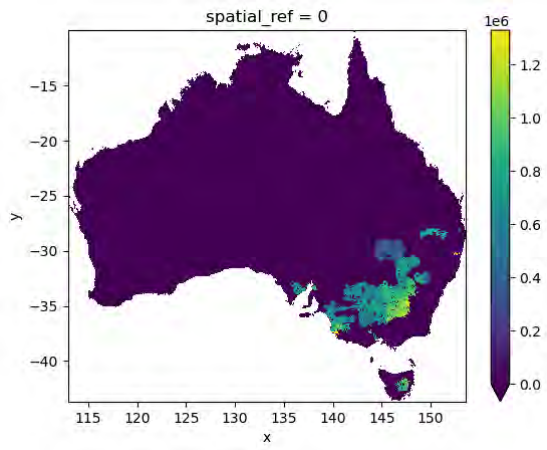

Figure 333 Updated revenue matrix with precision agriculture integration into agricultural land management strategies for winter cereals under dry land management system

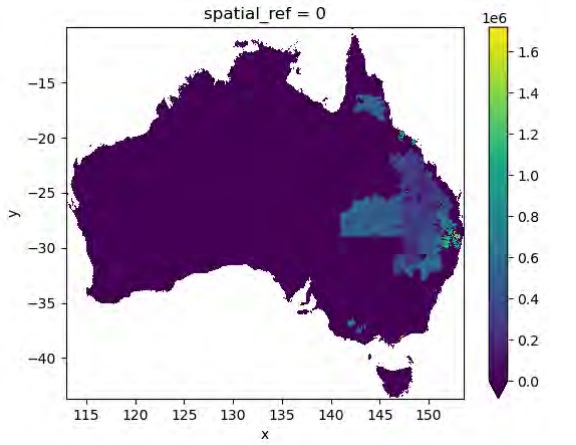

Figure 334 Updated revenue matrix with precision agriculture integration into agricultural land management strategies for winter cereals under irrigation land management system

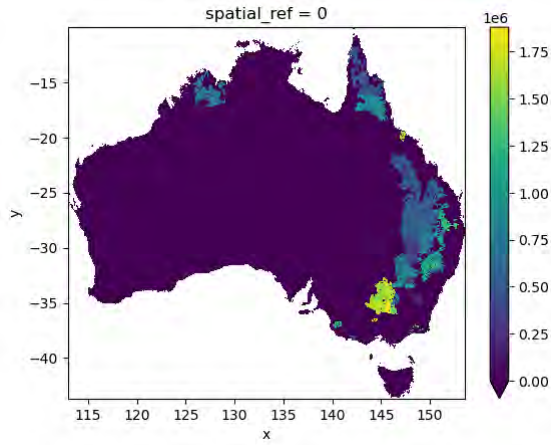

Figure 335 Updated revenue matrix with precision agriculture integration into agricultural land management strategies for summer cereals under dry land management system

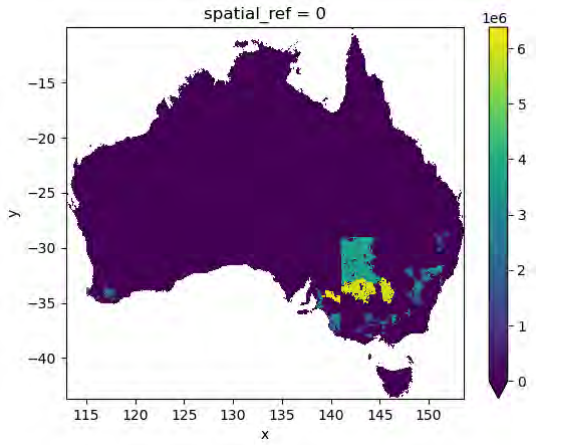

Figure 336 Updated revenue matrix with precision agriculture integration into agricultural land management strategies for summer cereals under irrigation land management system

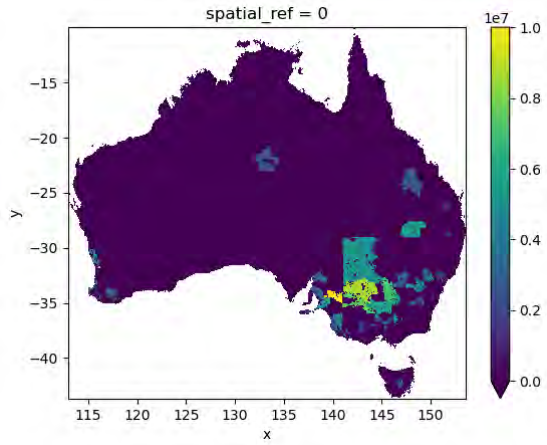

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Figure 337 Updated revenue matrix with precision agriculture integration into agricultural land management strategies for grapes under dry land management system	Figure 338 Updated revenue matrix with precision agriculture integration into agricultural land management strategies for grapes under irrigation land management system

12.3. Ecological Grazing Effects on Revenue for all relevant agricultural land use

Let $\mathbf{RevM}_{mr\ell}^{\text{EcolGrazing}}$ represent the updated revenue matrix after integrating Ecological Grazing into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Ecological Grazing})$	Equation 221
$\mathbf{RevM}_{mr\ell}^{\text{EcolGrazing}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{EcolGrazing}}\right)}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_k = 2$: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21).
- $N_{lu}^{\text{EcolGrazing}} = 3$: Number of land use classes affected by Ecological Grazing, including beef, sheep, and dairy production on modified land (Equation 29).

To update the revenue matrix for land uses where Ecological Grazing $\mathbf{RevM}_{mr\ell}^{\text{EcolGrazing}}$ can be applied:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Ecological Grazing})$	Equation 222
$\mathbf{RevM}_{mr\ell}^{\text{EcolGrazing}}(y) = = \begin{cases} \mathbf{Revenue}_{mr\ell}(y) \times \left(1 - PIM_{\ell}^{\text{EcolGrazing}}(y)\right) & \text{if } \ell \in \phi(\text{Ecological Grazing}) \wedge PIM_{\ell}^{\text{EcolGrazing}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{Ecological Grazing}) \vee PIM_{\ell}^{\text{EcolGrazing}}(y) = 1 \end{cases}$	

where,

- $PIM_{\ell}^{\text{EcolGrazing}}(y)$ is the productivity impact multiplier. In the current version of LUTO 2.0, $PIM_{\ell}^{\text{EcolGrazing}}(y) = 0.84$.
- $\mathbf{Revenue}_{mr\ell}(y)$ represents the original revenue data for year y, for all land uses in $\phi(\text{Ecological Grazing})$ (Equation 29) under dry and irrigation land management systems, computed by Equation 216.

The updated revenue matrix reflecting Ecological Grazing $\phi(\text{Ecological Grazing})$ integration across all applicable land use classes and management systems (dry and irrigated) is illustrated in Figure 339-Figure 344.

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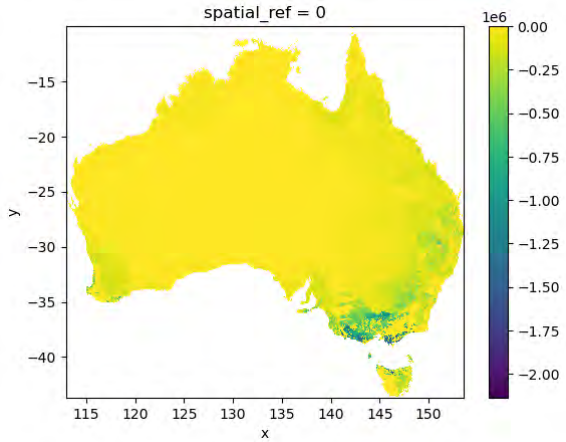

Figure 339 Updated revenue matrix with Ecological Grazing integration into agricultural land management strategies for Beef in modified land under a dryland management system

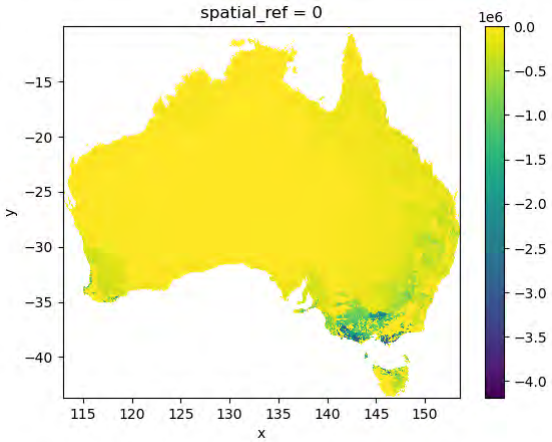

Figure 340 Updated revenue matrix with Ecological Grazing integration into agricultural land management strategies for Beef in modified land under an irrigation land management system

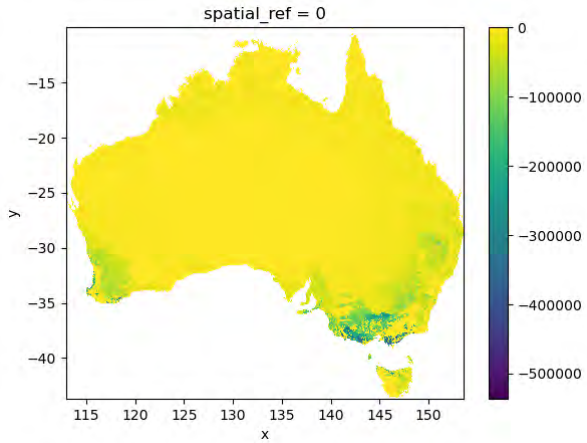

Figure 341 Updated revenue matrix with Ecological Grazing integration into agricultural land management strategies for Sheep in modified land under a dryland management system

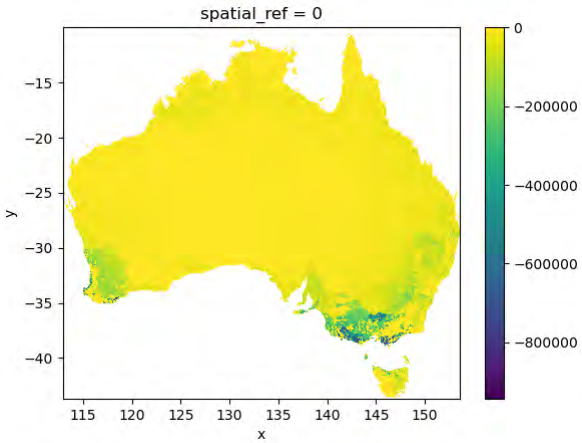

Figure 342 Updated revenue matrix with Ecological Grazing integration into agricultural land management strategies for Sheep in modified land under an irrigation land management system

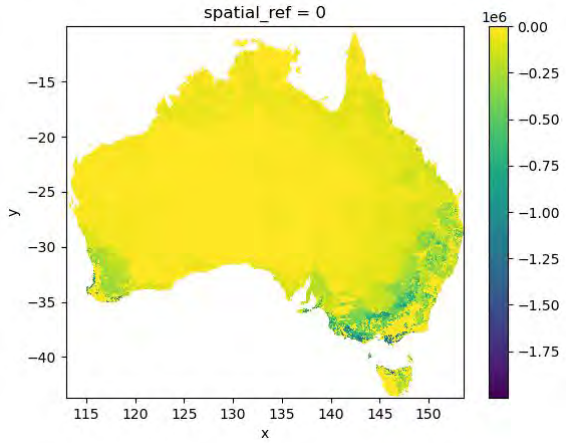

Figure 343 Updated revenue matrix with Ecological Grazing integration into agricultural land management strategies for Dairy under a dryland management system

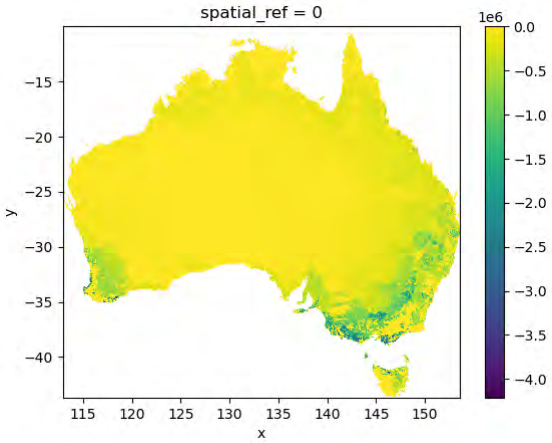

Figure 344 Updated revenue matrix with Ecological Grazing integration into agricultural land management strategies for Dairy under an irrigation land management system

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12.4. Savanna Burning Effects on Revenue for all relevant agricultural land use

Let $\mathbf{RevM}_{mr\ell}^{\text{SavBurn}}$ represent the updated revenue matrix incorporating the Savanna Burning practice into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 223
$\mathbf{RevM}_{mr\ell}^{\text{SavBurn}} = 0_{(N_k \times N_c \times N_{lu}^{\text{SavBurn}})}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_k = 2$: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21).
- $N_{lu}^{\text{SavBurn}} = 4$: Land use classes affected by Savanna Burning, including beef, sheep, and dairy production on natural land, as well as unallocated natural land (Equation 31).

To update $\mathbf{RevM}_{mr\ell}^{\text{SavBurn}}$ for land uses where Savana Burning is applicable.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 224
$\mathbf{RevM}_{mr\ell}^{\text{SavBurn}}(y) = \mathbf{GEG}_{mr\ell}^{\text{SavBurn}} \times CO2Price(y)$	

where,

- $\mathbf{GEG}_{mr\ell}^{\text{SavBurn}}$: GHG emissions matrix derived from implementing the Savanna Burning practice on livestock and unallocated natural land (Equation 104 and Figure 101-Figure 104)
- $CO2Price(y)$: Market price of CO_2 (AUD per Tonne of CO_2) (Figure 349)

The updated revenue matrix reflecting Savanna Burning integration across all relevant land use classes—under both dry and irrigation management systems—is illustrated in: Figure 345-Figure 348.

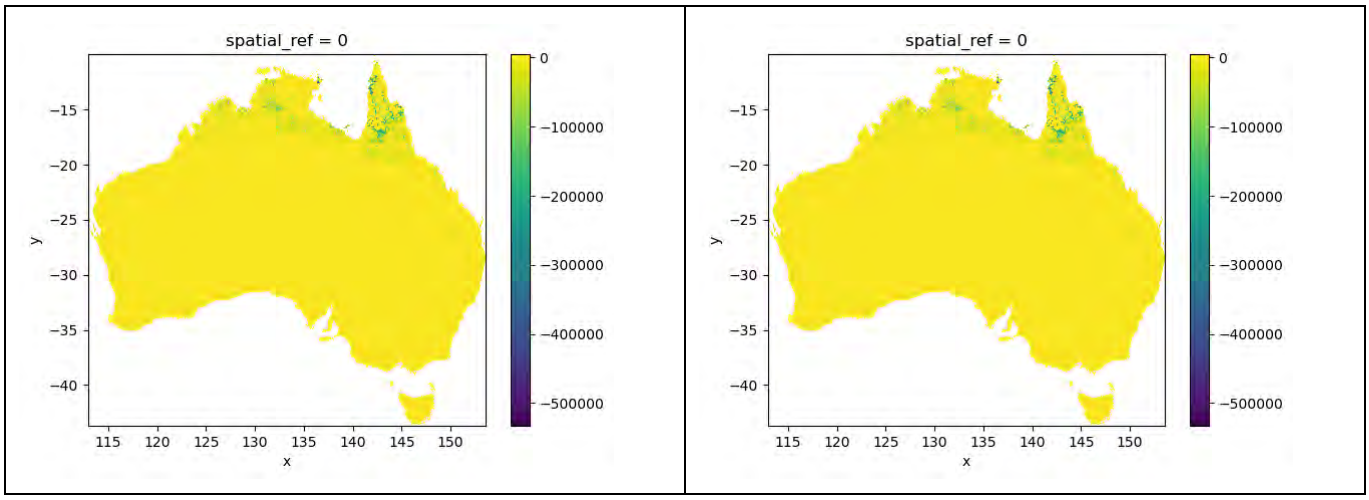

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Figure 345 Updated revenue matrix with Savanna Burning integration into agricultural land management strategies for Beef - natural land under dry and irrigated land management system	Figure 346 Updated revenue matrix with Savanna Burning integration into agricultural land management strategies for Sheep - natural land under dry and irrigated land management system
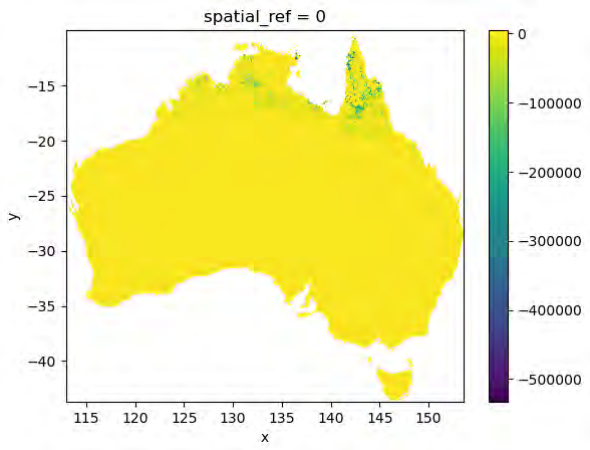	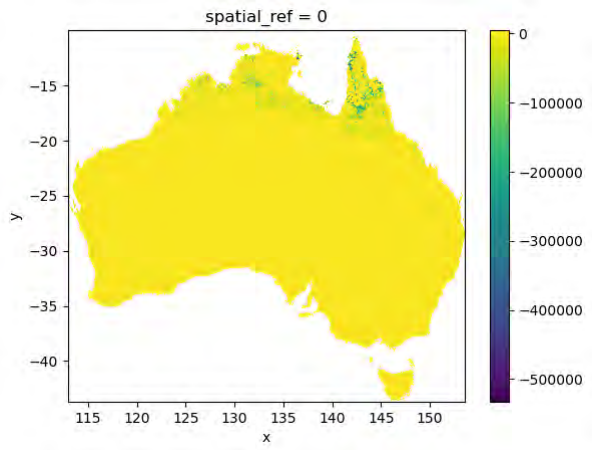
Figure 347 Updated revenue matrix with Savanna Burning integration into agricultural land management strategies for Dairy-natural land under dry and irrigated land management system	Figure 348 Updated revenue matrix with Savanna Burning integration into agricultural land management strategies for Unallocated-natural land under dry and irrigated land management system
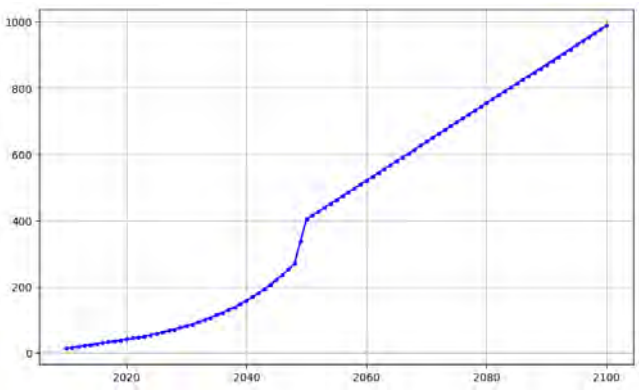	
Figure 349 Market price of CO_2 (AUD per Tonne of CO_2)	

12.5. AgTech EI Effects on Revenue for all relevant agricultural land use

Let $\mathbf{RevM}_{mr\ell}^{\text{AgTech EI}}$ represent the updated Revenue Matrix reflecting the integration of AgTech EI into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 225
$\mathbf{RevM}_{mr\ell}^{\text{AgTech EI}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AgTech EI}}\right)}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_k = 2$: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21).

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- $N_{lu}^{\text{AgTech EI}} = 20$: Number of land use classes affected by AgTech EI (Equation 33)

Let update $\mathbf{RevM}_{mr\ell}^{\text{SavBurn}}$ for land uses where AgTech EI can be applied:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 226
$\mathbf{RevM}_{mr\ell}^{\text{AgTech EI}}(y) = \begin{cases} \mathbf{Revenue}_{mr\ell}(y) \times \left(1 - PIM_{\ell}^{\text{AgTech EI}}(y)\right) & \text{if } \ell \in \phi(\text{AgTech EI}) \wedge PIM_{\ell}^{\text{AgTech EI}}(y) \neq 1 \\ 0 & \text{if } \ell \notin \phi(\text{AgTech EI}) \vee PIM_{\ell}^{\text{AgTech EI}}(y) = 1 \end{cases}$	

where,

- $PIM_{\ell}^{\text{AgTech EI}}(y)$: Productivity impact multiplier (Same as used in Equation 220; Figure 331 and Figure 332)
- $\mathbf{Revenue}_{mr\ell}(y)$: Original revenue data for year y, for land uses in $\phi(\text{AgTech EI})$ (Equation 29) under both dry and irrigated land management systems, computed using Equation 216.

The updated revenue matrices showing AgTech EI integration under both dry and irrigated land management systems are illustrated in: Figure 350-Figure 355.

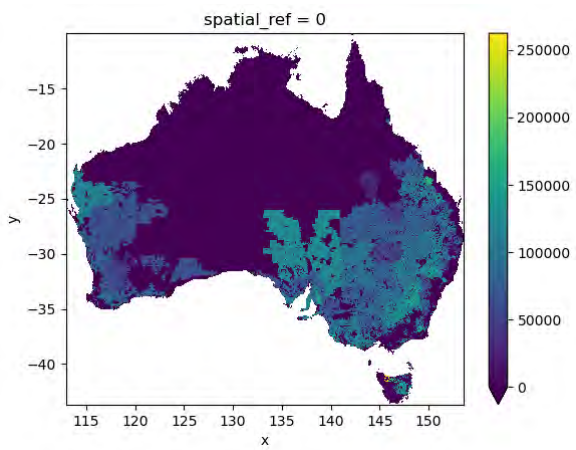

Figure 350 Updated revenue matrix with AgTech EI integration into agricultural land management strategies for winter cereals under dryland management system

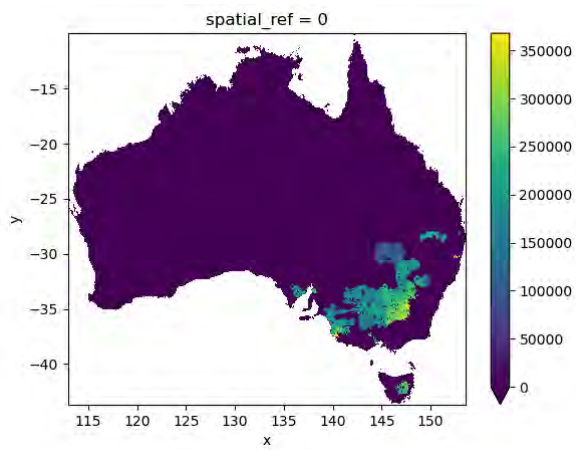

Figure 351 Updated revenue matrix with AgTech EI integration into agricultural land management strategies for winter cereals under irrigation land management system

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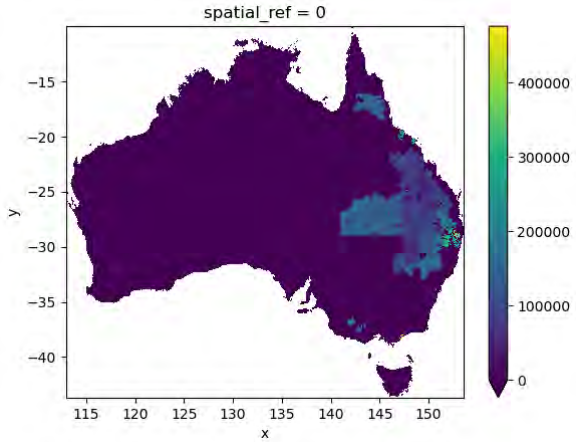

Figure 352 Updated revenue matrix with AgTech EI integration into agricultural land management strategies for summer cereals under dryland management system

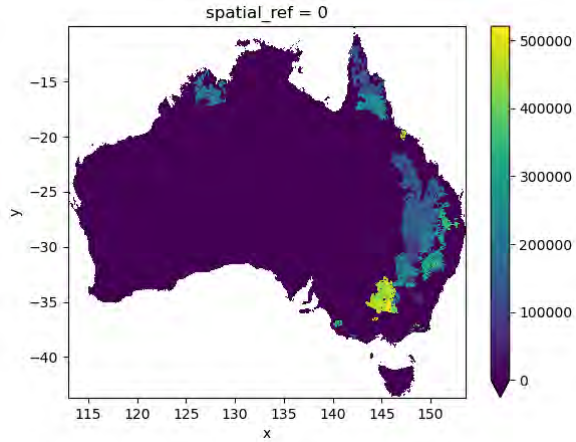

Figure 353 Updated revenue matrix with AgTech EI integration into agricultural land management strategies for summer cereals under irrigation land management system

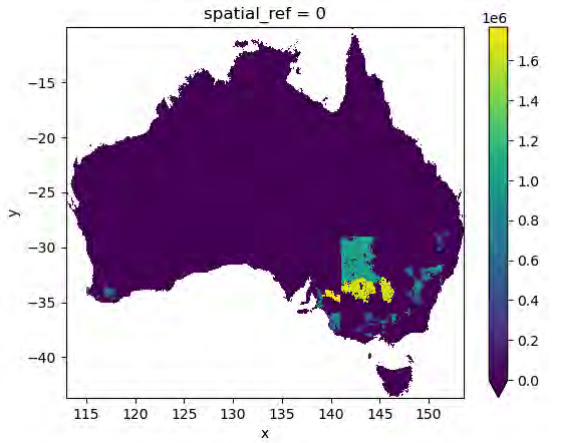

Figure 354 Updated revenue matrix with AgTech EI integration into agricultural land management strategies for grapes under dryland management system

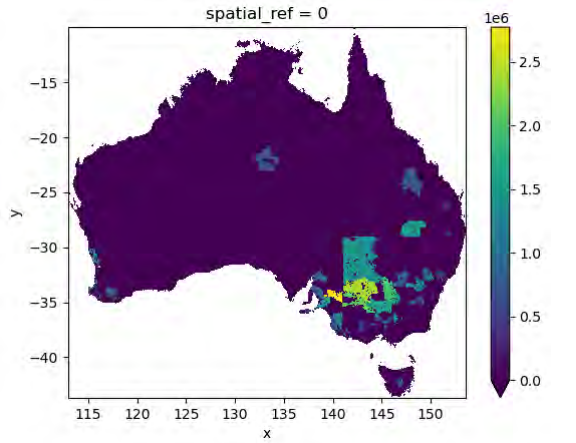

Figure 355 Updated revenue matrix with AgTech EI integration into agricultural land management strategies for grapes under irrigation land management system

12.6. Agricultural Management Practices Effect on Revenue for all Relevant Agricultural Land Uses

Define the variable $\text{Revenue}^{\text{AGMP}}$, which represents a dictionary of agricultural management practice variables. This dictionary maps each practice $\boldsymbol{k} \in \boldsymbol{\mathcal{K}}$ to its corresponding revenue matrix $\mathbf{RevM}^{k}_{mr\ell}(\boldsymbol{y})$, as follows:

$\mathbf{Revenue}^{\text{AGMP}}_{k} = \left\{ k \rightarrowtail \mathbf{RevM}^{k}_{mr\ell}(y) \mid r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}, \mathbf{RevM}^{k}_{mr\ell}(y) \in \mathbb{R}^{N_k \times N_c \times N^{k}_{lu}} \right\}$	Equation 227

where,

- $\mathcal{K}$: Set of agricultural management practices applicable to different land use types (Equation 22)
- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.

- $N_k = 2$: Number of agricultural management practices (dry and irrigated), $m \in \mathcal{M}$ (Equation 21)
- N_{lu}^k: Number of land use classes affected by each agricultural management practice $\mathcal{K}$ (Equation 24-Equation 32)
- $\mathbb{R}$: Set of real numbers
- $\mathbf{RevM}_{mr\ell}^k(y)$: Revenue matrix after integrating the k-th agricultural management practice into land use strategies.

Regarding the agricultural management practices, $\mathcal{K}$ is the set that lists all agricultural management practices applicable to different land use types (Equation 22). As described in Equation 23, there exists a mapping function ϕ that relates elements from the set of agricultural management practices (the domain $\mathcal{K}$) to the set of land uses $\mathcal{L}$ (defined in Equation 1) that are relevant or applicable to each practice. The specific land uses associated with each agricultural management practice are detailed in Equation 24-Equation 32.

Then, the initialized $\text{Revenue}_k^{\text{AGMP}}(y)$ (Equation 227) is updated, as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists k, k \in \mathcal{K}$	Equation 228
$\mathbf{Revenue}_k^{\text{AGMP}}(y) = \begin{cases} k \rightarrowtail \mathbf{RevM}_{mr\ell}^{\text{AspTaxifor}}(y) & \text{if} \quad k \in \phi(\text{Asparagopsis taxiformis}) \\ k \rightarrowtail \mathbf{RevM}_{mr\ell}^{\text{PrecAgric}}(y) & \text{if} \quad k \in \phi(\text{Precision Agriculture}) \\ k \rightarrowtail \mathbf{RevM}_{mr\ell}^{\text{EcolGrazing}}(y) & \text{if} \quad k \in \phi(\text{Ecological Grazing}) \\ k \rightarrowtail \mathbf{RevM}_{mr\ell}^{\text{SavBurn}}(y) & \text{if} \quad k \in \phi(\text{Savanna Burning}) \\ k \rightarrowtail \mathbf{RevM}_{mr\ell}^{\text{AgTech EI}}(y) & \text{if} \quad k \in \phi(\text{AgTech EI}) \end{cases}$	

where,

- $\mathcal{K}$: A set of agricultural management practices list that can be applied to different land use types (Equation 22)
- k: The agricultural management practice type
- $\mathbf{RevM}_{mr\ell}^{\text{AspTaxifor}}(y)$: Revenue matrix from integrating *Asparagopsis taxiformis* (Equation 218)
- $\mathbf{RevM}_{mr\ell}^{\text{PrecAgric}}(y)$: Revenue matrix from integrating Precision Agriculture (Equation 220)
- $\mathbf{RevM}_{mr\ell}^{\text{EcolGrazing}}(y)$: Revenue matrix from integrating Ecological Grazing (Equation 222)
- $\mathbf{RevM}_{mr\ell}^{\text{SavBurn}}(y)$: Revenue matrix from integrating Savanna Burning (Equation 224)
- $\mathbf{RevM}_{mr\ell}^{\text{AgTech EI}}(y)$: Revenue matrix from integrating AgTech EI (Equation 226)
- $\phi(\text{Asparagopsis taxiformis})$: Affects livestock on natural and modified land (Equation 25)
- $\phi(\text{Precision Agriculture})$: Applies to cropping, intensive cropping, and horticulture (Equation 27)
- $\phi(\text{Ecological Grazing})$: Applies to livestock on modified land (Equation 29)
- $\phi(\text{Savanna Burning})$: Applies to livestock and unallocated land on natural land (Equation 31)
- $\phi(\text{AgTech EI})$: Affects cropping, intensive cropping, and horticulture (Equation 33)
- $\text{Revenue}_k^{\text{AGMP}}$: represents a dictionary where each key $k \in \mathcal{K}$ maps to a 3D matrix of revenue matrix $\mathbf{RevM}_{mr\ell}^k(y)$ that quantifies revenue under a specific agricultural management practice across the landscape.

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- Economics/Agricultural/ transition.py

13. The Transition Matrix

13.1. The Boolean Exclusion Matrix for the Base Year

Let $\mathbf{XCM}_{mr\ell}^{BYear}$ represent the Boolean exclusion matrix for the base year, initialized as:

$\mathbf{XCM}_{mr\ell}^{BYear} = 0_{(N_k \times N_c \times N_{lu})}$	Equation 229

In this section, $\mathbf{XCM}_{mr\ell}$ should be converted to $\mathbf{XCM}_{mr\ell}^{BYear}$ Then have to update Equation 224 for other years.

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_k = 2$: Number of agricultural management practices $m \in \mathcal{M}$ (Equation 21).
- N_{lu}=28: Number of agricultural land-use classes.

To update the values of the Boolean exclusion matrix $\mathbf{XCM}_{mr\ell}^{BYear}$ for each given cell r, a Statistical Area Level Map (**SALM**) is used. This map consists of N_a polygons. In the LUTO 2.0 model, it is assumed that landholders consider only those land uses available within their respective region $a \in \{1, \cdots, N_a\}$ when deciding land use transitions.

A spatial overlay of the raster-based land-use map $\mathbf{LUM}^{\mathrm{BYear}}$ and the polygon-based $\mathbf{SALM}_a$ is performed to extract valid land-use labels. A pixel with coordinates $\mathrm{P(x,y)}$ is considered to be within a polygon $\mathcal{P}$ (represented by vertex set $\{(x_1, y_1), (x_2, y_2), \cdots, (x_n, y_n)\}$) if and only if $\mathrm{P(x,y)} \in \mathcal{P}$. It can be mathematically written as a point-in-polygon function, $\mathrm{PIP}(x, y, \mathcal{P})$, where:

$\mathrm{PIP}(x, y, \mathcal{P}) = \begin{cases} 1 & \text{if } (x, y) \text{ is inside } \mathcal{P} \\ 0 & \text{otherwise} \end{cases}$	Equation 230

From this overlay, for each area $\mathbf{SALM}_a$, a set of valid land use classes $\mathcal{L}_a$ is extracted:

$\ell_{mr} \in \mathcal{L}_a$	Equation 231
$\mathcal{L}_a \subseteq \mathcal{L}$ and $\mathcal{L}_a \neq \emptyset$	

where,

- ℓ_{mr}: Land use class of cell r under land management m, from $\mathbf{LUM}_{mr}^{\mathrm{BYear}}$.
- $\mathcal{L}_a$: Set of land use class labels found within region a , derived from the vector–raster overlay
- $\mathcal{L}$: The full set of national-level land use classes (Equation 1).

Therefore, it can be summarized that this procedure extracted the land use label of all available pixels in each polygon of $\mathbf{SALM}_a$. This process produced a tensor which is called the Boolean exclusion matrix $\mathbf{XCM}_{mr\ell}^{BYear}$.

The values of $\mathbf{XCM}_{mr\ell}^{BYear}$ is updated as:

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$\forall r \in \{1, \dots, N_r\}, a \in \{1, \cdots, N_a\}, m \in \{0,1\}, \exists\, \ell_{mr}, \ell_{mr} = \mathbf{LUM}_{mr}^{\mathrm{BYear}} \mid \ell_{mr} \in \mathcal{L}_a$	Equation 232
$\mathbf{XCM}_{0,r,\ell_r}^{BYear} = \begin{cases} \text{True} & \text{If} \quad m = 0, \ell_{0r} \in \mathcal{L}_a, \mathcal{P}_{\mathbf{XCM}_{mrl}} = 1 \\ \text{False} & \text{Otherwise} \end{cases}$	
$\mathbf{XCM}_{1,r,\ell_r}^{BYear} = \begin{cases} \text{True} & \text{If} \quad m = 1, \ell_{1r} \in \mathcal{L}_a, \mathcal{P}_{\mathbf{XCM}_{mrl}} = 1 \\ \text{False} & \text{Otherwise} \end{cases}$	

The flowchart illustrating the initialization and update procedure for $\mathbf{XCM}_{mr\ell}^{BYear}$ is presented in Figure 356.

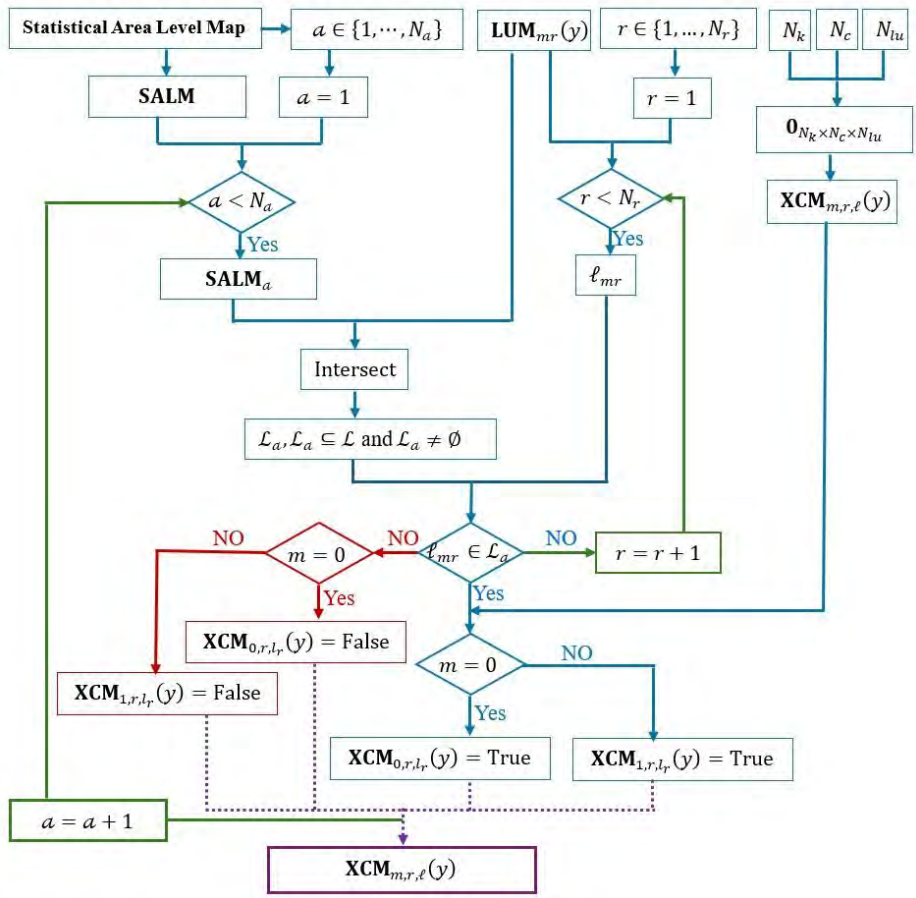

Figure 356 Boolean exclusion matrix initialization and update process. Should be updated

The resulting Boolean exclusion matrix $\mathbf{XCM}_{mr\ell}^{BYear}$ for selected land use classes is shown in Figure 357-Figure 368. Since this matrix is computed for the base year, a similar matrix must also be generated for subsequent years. For more details, refer to Section 13.6.

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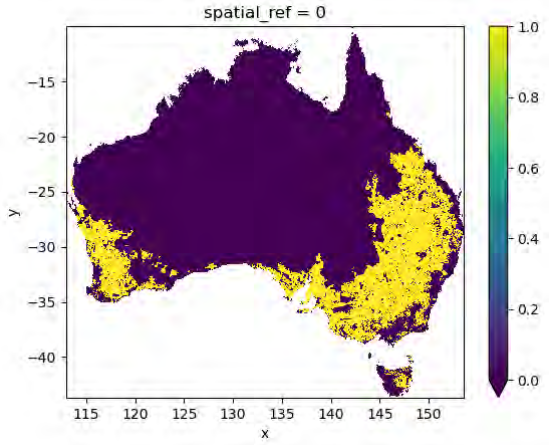

Figure 357 Boolean exclusion matrix for the class of winter cereals under dryland management

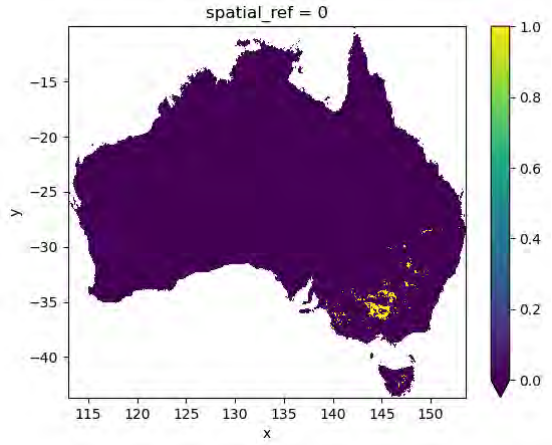

Figure 358 Boolean exclusion matrix for the class of winter cereals under irrigation land management

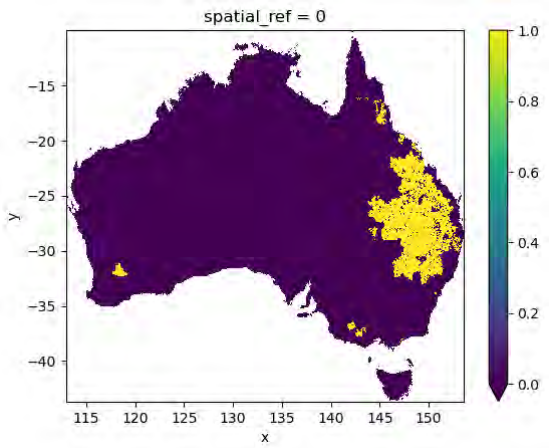

Figure 359 Boolean exclusion matrix for the class of summer cereals under dryland management

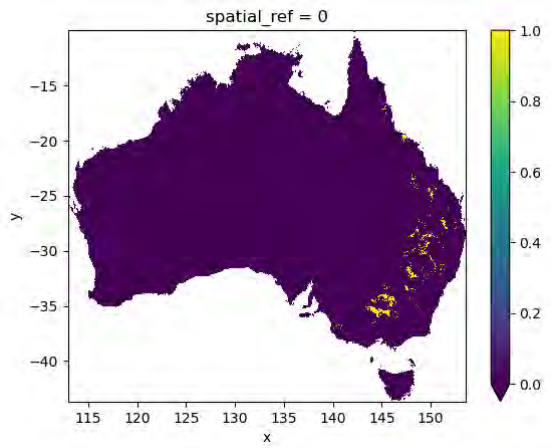

Figure 360 Boolean exclusion matrix for the class of summer cereals under irrigation land management

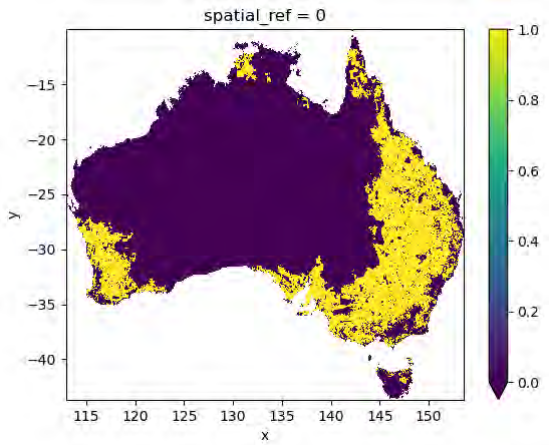

Figure 361 Boolean exclusion matrix for the class of Hay under dryland management

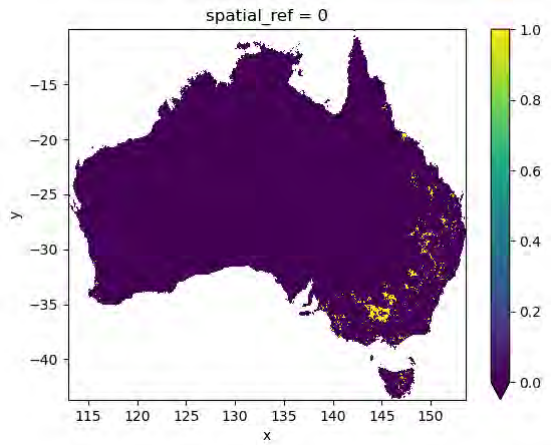

Figure 362 Boolean exclusion matrix for the class of Hay under irrigation land management

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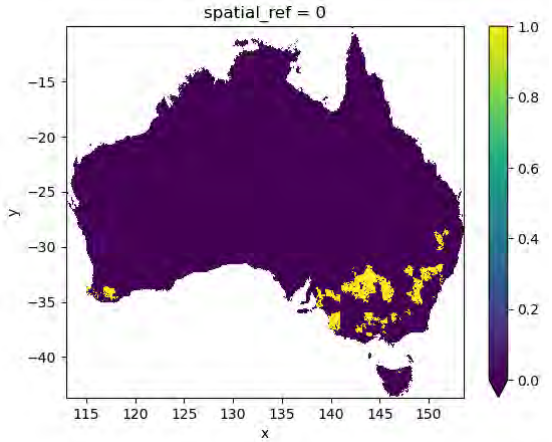

Figure 363 Boolean exclusion matrix for the class of Grapes under dryland management

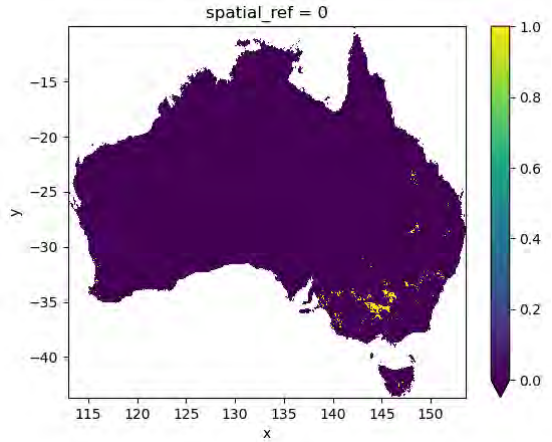

Figure 364 Boolean exclusion matrix for the class of Grapes under irrigation land management

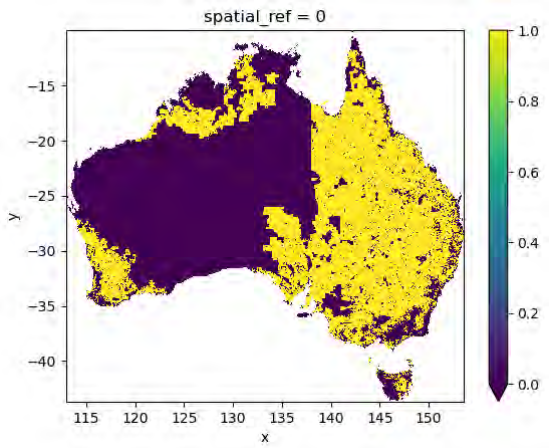

Figure 365 Boolean exclusion matrix for the class of Beef - modified land under dryland management

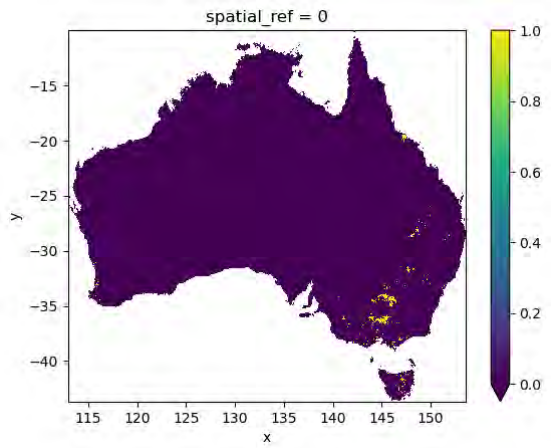

Figure 366 Boolean exclusion matrix for the class of Beef - modified land under irrigation land management

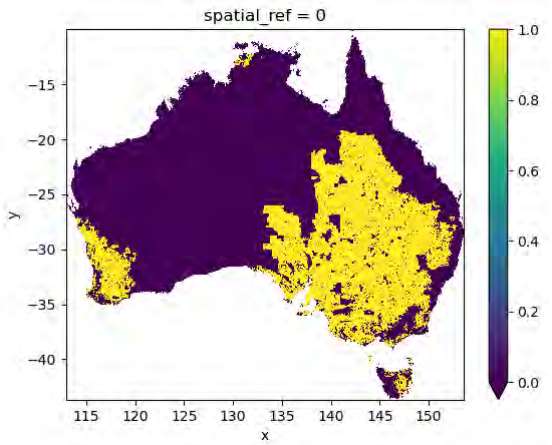

Figure 367 Boolean exclusion matrix for the class of Sheep - modified land under dryland management

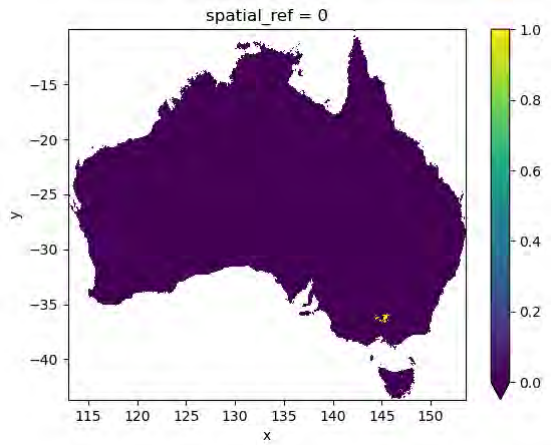

Figure 368 Boolean exclusion matrix for the class of Sheep - modified land under irrigation land management

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13.2. Boolean Land-Use and Land Management Matrix

l_{mrj} = lumap2ag_l_mrj(lumap, lmmap)

Let $\mathbf{BLuLmM}_{mr\ell}$ be a Boolean tensor representing the land-use and land management matrix. It is initialized as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 233
$\mathbf{BLuLmM}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_k = 2$: Number of land management strategies $m \in \mathcal{M}$ (dry and irrigation)
- $N_{lu} = 28$: Number of agricultural land-use classes

The values of $\mathbf{BLuLmM}_{mr\ell}$ are updated based on land-use classes and land management strategy as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists \ell_r, \ell_r = \mathbf{LUM}_r^{\mathrm{BYear}}$	Equation 234
$\mathbf{BLuLmM}_{0,r,\ell_r} = \begin{cases} \text{True} & \text{If} \quad \mathbf{LMM}_r = 0 \ \wedge \ \ell_r = \mathbf{LUM}_r^{\mathrm{BYear}} \\ \text{False} & \text{Otherwise} \end{cases}$	
$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \exists \ell_r, \ell_r = \mathbf{LUM}_r^{\mathrm{BYear}}$	
$\mathbf{BLuLmM}_{1,r,\ell_r} = \begin{cases} \text{True} & \text{If} \quad \mathbf{LMM}_r = 1 \ \wedge \ \ell_r = \mathbf{LUM}_r^{\mathrm{BYear}} \\ \text{False} & \text{Otherwise} \end{cases}$	

Where,

- $\mathbf{LMM}_r$: Land management map (Figure 370)
- $\mathbf{LUM}_r^{\mathrm{BYear}}$: Land use map for the base year, 2010 (Figure 371)

By applying Equation 234, the Boolean matrix $\mathbf{BLuLmM}_{mr\ell}$ is computed and visualized in (Figure 372-Figure 383).

To identify cells not assigned to agricultural land use ($\ell \in \{1, \dots, 28\}$), compute the logical negation of $\mathbf{BLuLmM}_{mr\ell}$:

$\mathbf{BLuLmM}_{mr\ell}^{NOT} = \neg \mathbf{BLuLmM}_{mr\ell}$	Equation 235

Where $\neg$ is the logical NOT operation, flipping each element from 'True' to 'False' and vice versa. Therefore, $\mathbf{BLuLmM}_{mr\ell}^{\mathrm{NOT}}$ can be written as:

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$\neg\mathbf{BLuLmM}_{mr\ell}\begin{cases}\text{True} & \text{If } \mathbf{BLuLmM}_{mr\ell} = \text{False}\\ \text{False} & \text{If } \mathbf{BLuLmM}_{mr\ell} = \text{True}\end{cases}$	Equation 236

The resulting tensor $\mathbf{BLuLmM}^{\text{NOT}}_{mr\ell}$ has the same dimensions as $\mathbf{BLuLmM}_{mr\ell}$. Visualizations for selected classes are presented in Figure 384-Figure 387.

The flowchart illustrating the initialization and update procedure for the Boolean land-use and land management matrix is presented in Figure 369. It should be updated

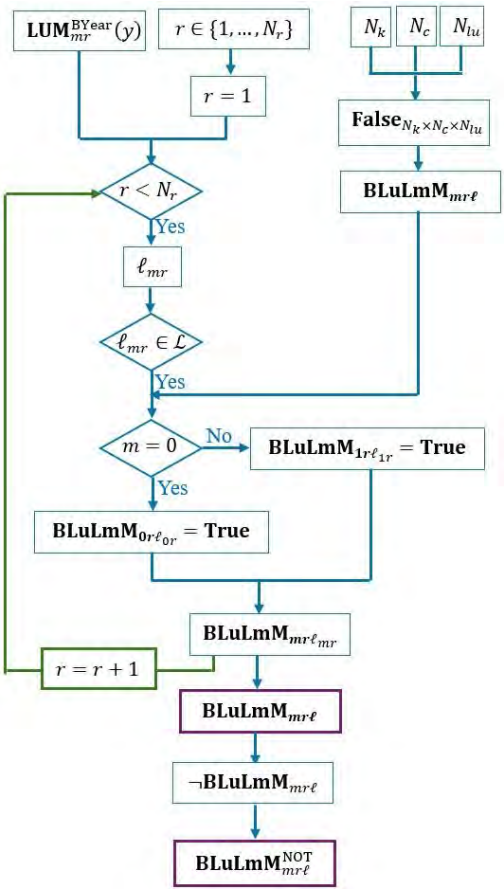

Figure 369 Boolean Land-Use and Land Management Matrix

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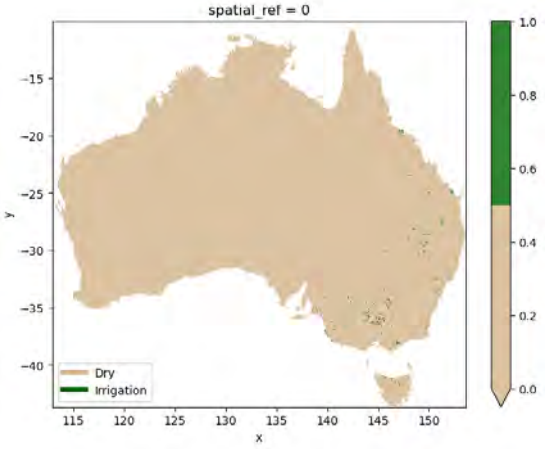

Figure 370 Land management map ($\mathbf{LMM}_r$)

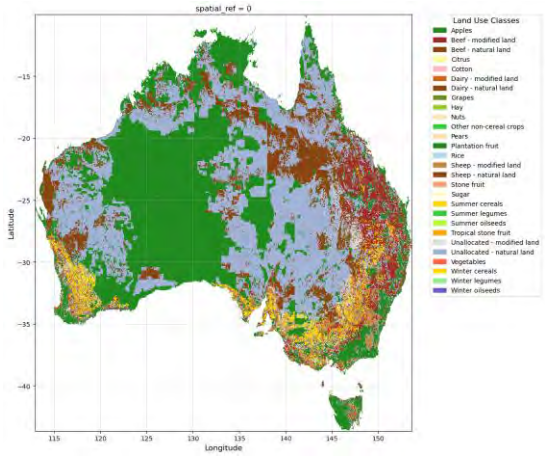

Figure 371 Land use map

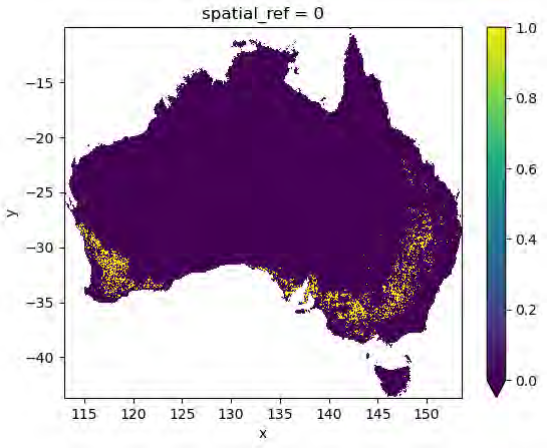

Figure 372 Boolean Land-Use and Land Management Matrix for the class of winter cereals under dry land management

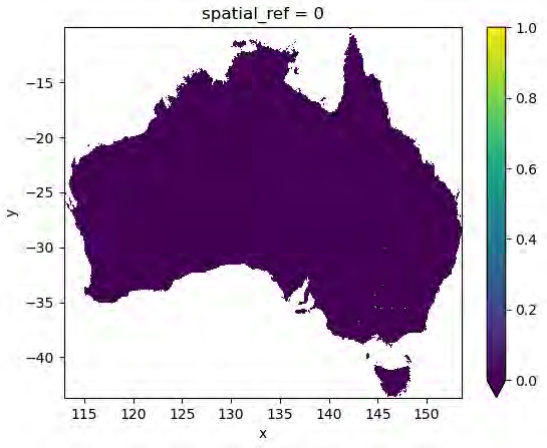

Figure 373 Boolean Land-Use and Land Management Matrix for the class of winter cereals under irrigation land management

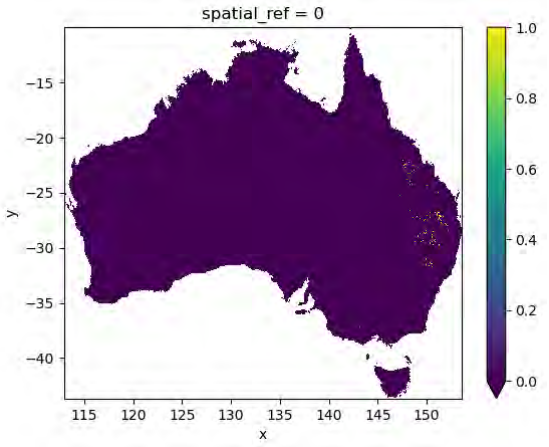

Figure 374 Boolean Land-Use and Land Management Matrix for the class of summer cereals under dry land management

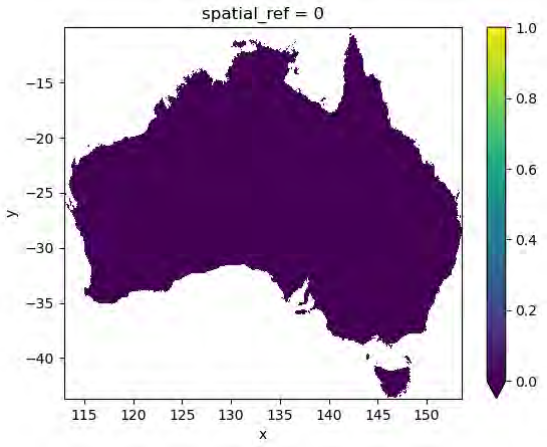

Figure 375 Boolean Land-Use and Land Management Matrix for the class of summer cereals under irrigation land management

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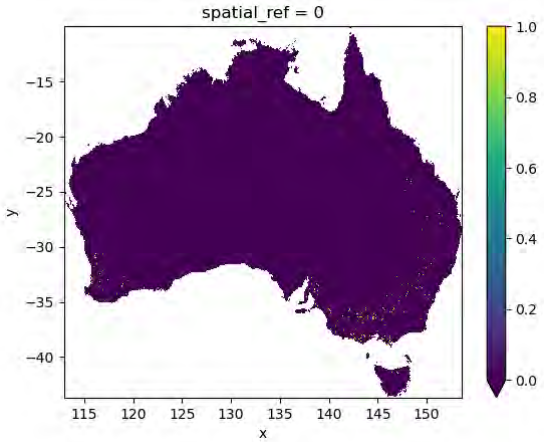


Figure 376 Boolean Land-Use and Land Management Matrix for the class of Hay under dry land management

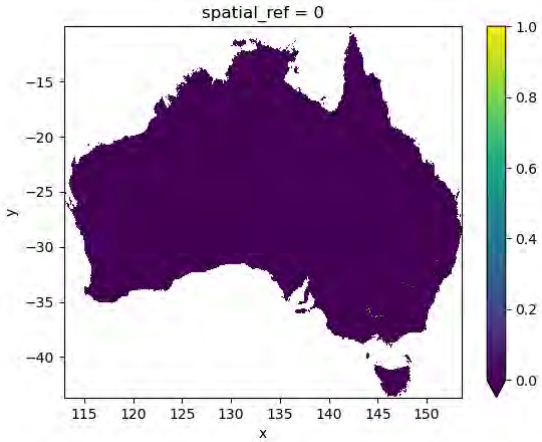


Figure 377 Boolean Land-Use and Land Management Matrix for the class of Hay under irrigation land management

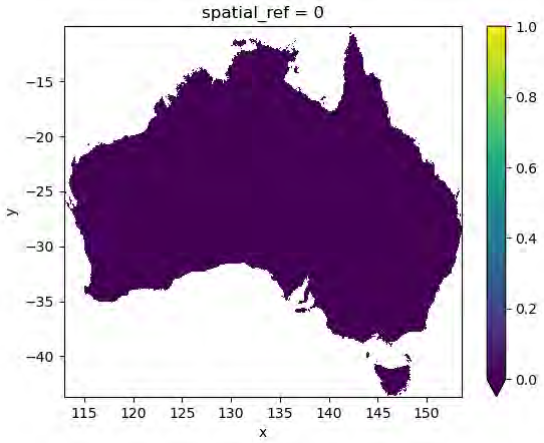


Figure 378 Boolean Land-Use and Land Management Matrix for the class of Grapes under dry land management

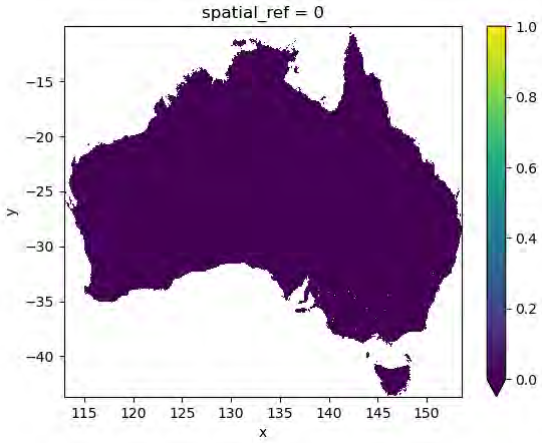
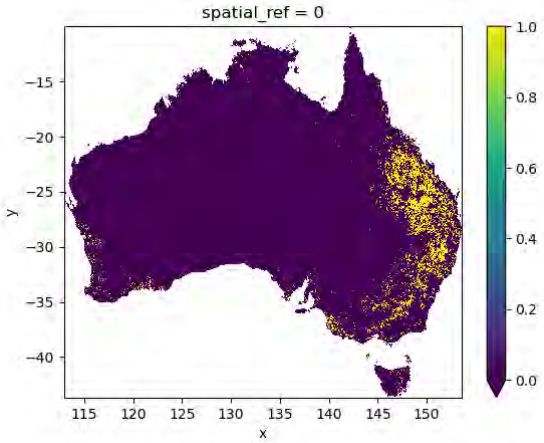


Figure 379 Boolean Land-Use and Land Management Matrix for the class of Grapes under irrigation land management



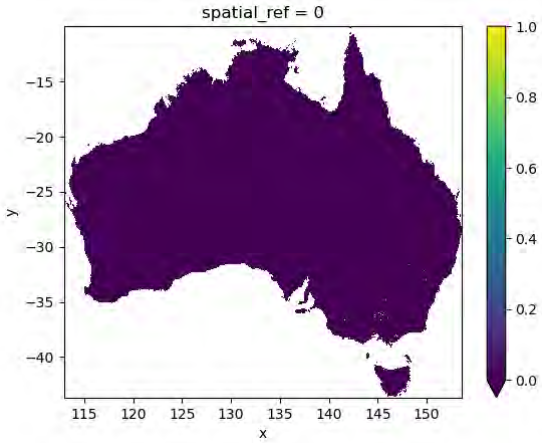


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Figure 380 Boolean Land-Use and Land Management Matrix for the class of Beef - modified land under dry land management

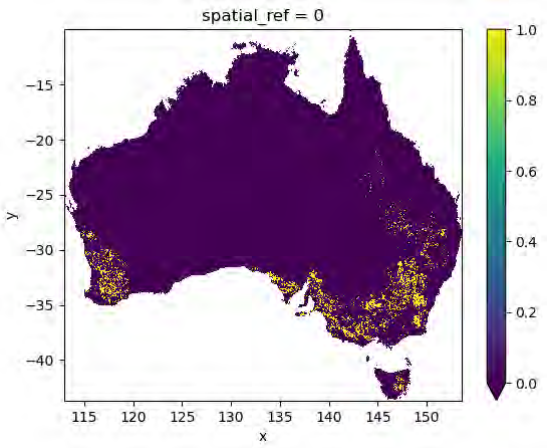

Figure 381 Boolean Land-Use and Land Management Matrix for the class of Beef - modified land under irrigation land management

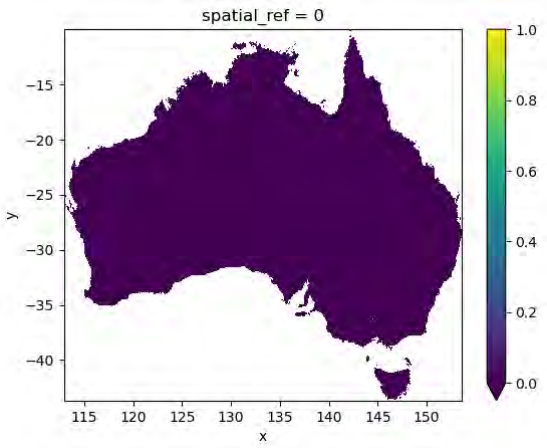

Figure 382 Boolean Land-Use and Land Management Matrix for the class of Sheep - modified land under dry land management

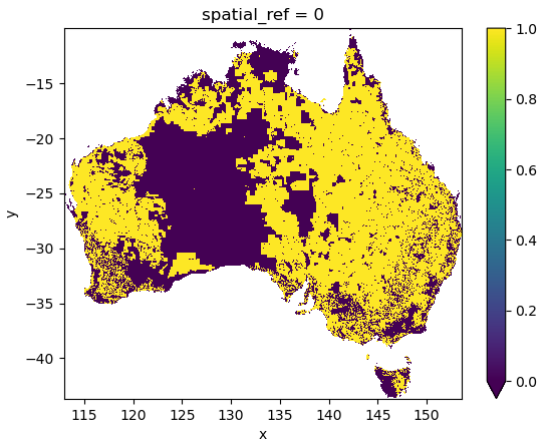

Figure 383 Boolean Land-Use and Land Management Matrix for the class of Sheep - modified land under irrigation land management

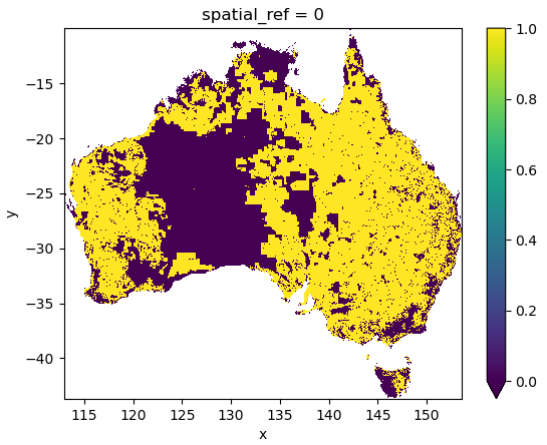

Figure 384 The negation of the Boolean Land-Use and Land Management Matrix for the class of winter cereals under dry land management

Figure 385 The negation of the Boolean Land-Use and Land Management Matrix for the class of summer cereals under dry land management

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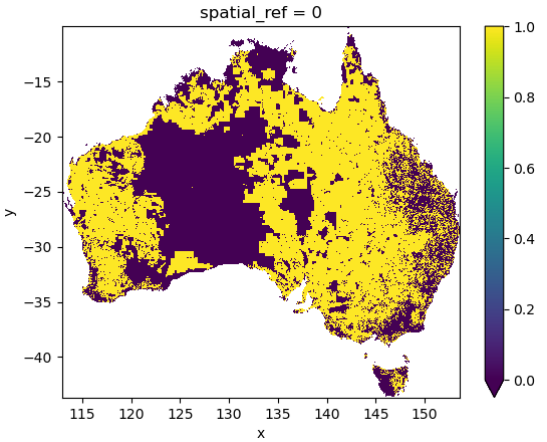	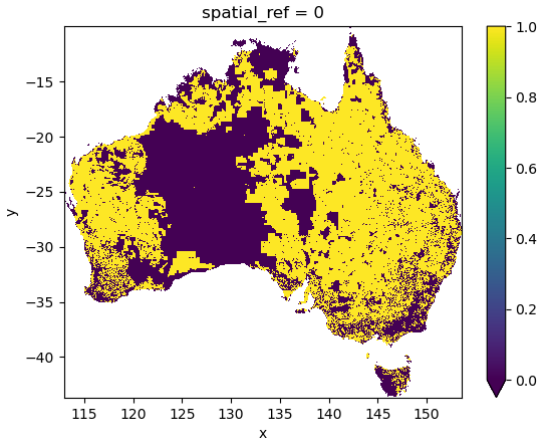
Figure 386 The negation of the Boolean Land-Use and Land Management Matrix for the class of Beef - modified land under dry land management	Figure 387 The negation of the Boolean Land-Use and Land Management Matrix for the class of Sheep - modified land under dry land management

13.3. **Identification of Agricultural Cells**

$$\mathrm{A, N = tools.get_ag_and_non_ag_cells(lumap)}$$

Let **AgCells** be a Boolean tensor identifying agricultural cells, and **NonAgCells** be a Boolean tensor identifying non-agricultural cells. To determine whether a cell belongs to either category, we use the following land-use index definitions:

- $\mathcal{L}_{\text{AgrLand}}$: Set of agricultural land-use category indices (Equation 12)
- $\mathcal{L}_{\text{NonAgrLand}}$: Set of non-agricultural land-use category indices (Equation 13)
- $\mathcal{L}_{\text{AgNonAgLand}}$: Set of all agricultural and non-agricultural land-use categories (Equation 14)

To produce **AgCells** and **NonAgCells**, LUTO 2.0 uses a threshold value $NonAg^{Base}$ as:

$NonAg^{Base} = 100$	Equation 237

By considering either $NonAg^{Base}$ or the agricultural land-use index set $\mathcal{L}_{\text{AgrLand}}$, we can define the Boolean indicator for agricultural cells $\mathbf{AgCells}_r$ as:

$\forall r \in \{1, \dots, N_r\} \; \exists \; \ell_r, \ell_r = \mathbf{LUM}_r^{\text{BYear}}$	Equation 238
$\mathbf{AgCells}_r = \begin{cases} \text{True} & \text{If} \quad \ell_r \in \mathcal{L}_{\text{AgrLand}} \vee \ell_r < NonAg^{Base} \\ \text{False} & \text{Otherwise} \end{cases}$	

Similarly, by considering $NonAg^{Base}$ or the non-agricultural land-use index set $\mathcal{L}_{\text{NonAgrLand}}$, the Boolean indicator for non-agricultural cells $\mathbf{NonAgCells}_r$ is defined as:

$\forall r \in \{1, \dots, N_r\} \; \exists \; \ell_r, \ell_r = \mathbf{LUM}_r^{\text{BYear}}$	

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$\mathbf{NonAgCells}_r = \begin{cases} \text{True} & \text{If} \quad \ell_r \in \mathcal{L}_{\text{NonAgrLand}} \vee \ell_r \geq NonAg^{Base} \\ \text{False} & \text{Otherwise} \end{cases}$	Equation 239

Where:

- $NonAg^{Base} = 100$ (as defined in Equation 237)
- $\mathbf{LUM}_r^{\text{BYear}}$: Land use label of cell r for the base year
- $\mathcal{L}_{\text{AgrLand}}$: Index set of agricultural land-use categories (Equation 12)
- $\mathcal{L}_{\text{NonAgrLand}}$: Index set of non-agricultural land-use categories (Equation 13)

The **flowchart** for initializing and updating the values of **AgCells** and **NonAgCells** is presented in Figure 388. The flow chart must be updated.

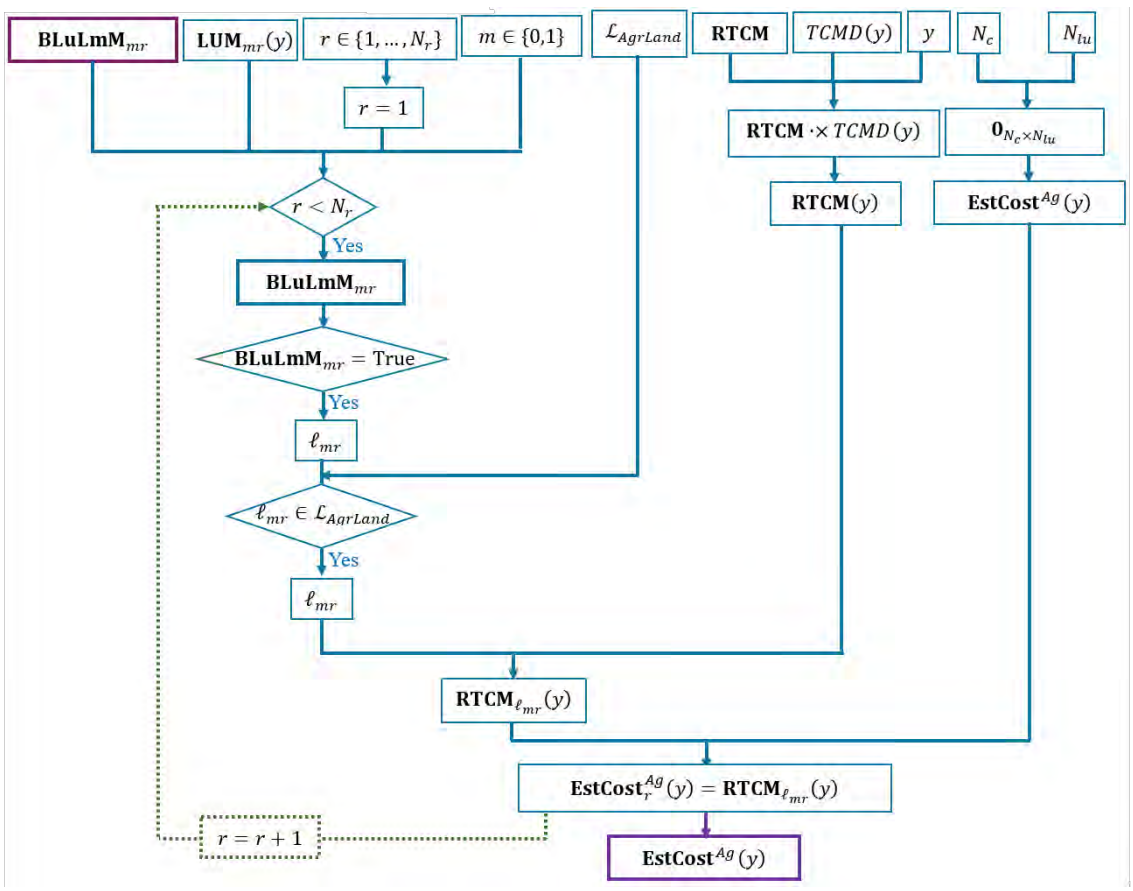

Figure 388 Identification of Agricultural and Non-Agricultural Cells This flowchart should be updated.

13.4. Boolean Agricultural Natural Land-Use Matrix

Let $\mathbf{BNatAgLuM}_r$ be a Boolean tensor indicating whether a cell is classified under natural agricultural land uses, as defined in the set $\mathcal{L}_{\text{NatAgLu}}$ (Equation 18). The matrix is computed as:

$\forall r \in \{1, \dots, N_r\} \exists\, \ell_r, \ell_r = \mathbf{LUM}_r^{\text{BYear}}$	

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$\mathbf{BNatAgLuM}_r = \begin{cases} \text{True} & \text{If} \quad \ell_r \in \mathcal{L}_{NatAgLu} \\ \text{False} & \text{Otherwise} \end{cases}$	Equation 240

The flowchart for initializing and updating the values of identify agricultural and non-agricultural cells is illustrated in Figure 407. This flowchart should be updated.

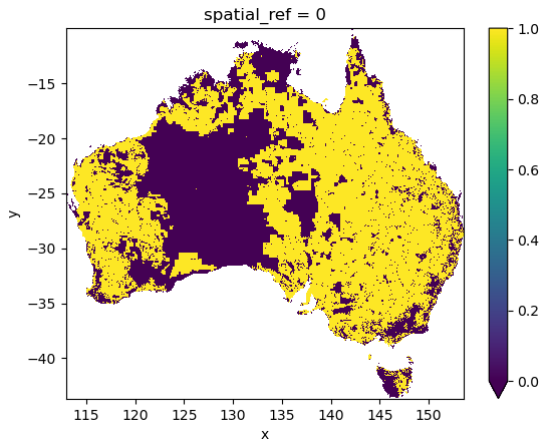	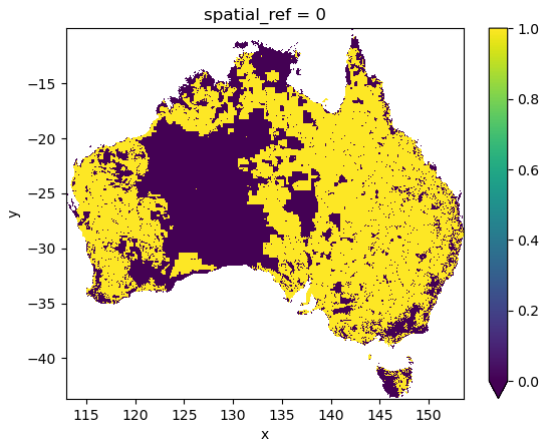
Figure 389 The Boolean agricultural land use map	Figure 390 Boolean Agricultural Natural Land-Use map

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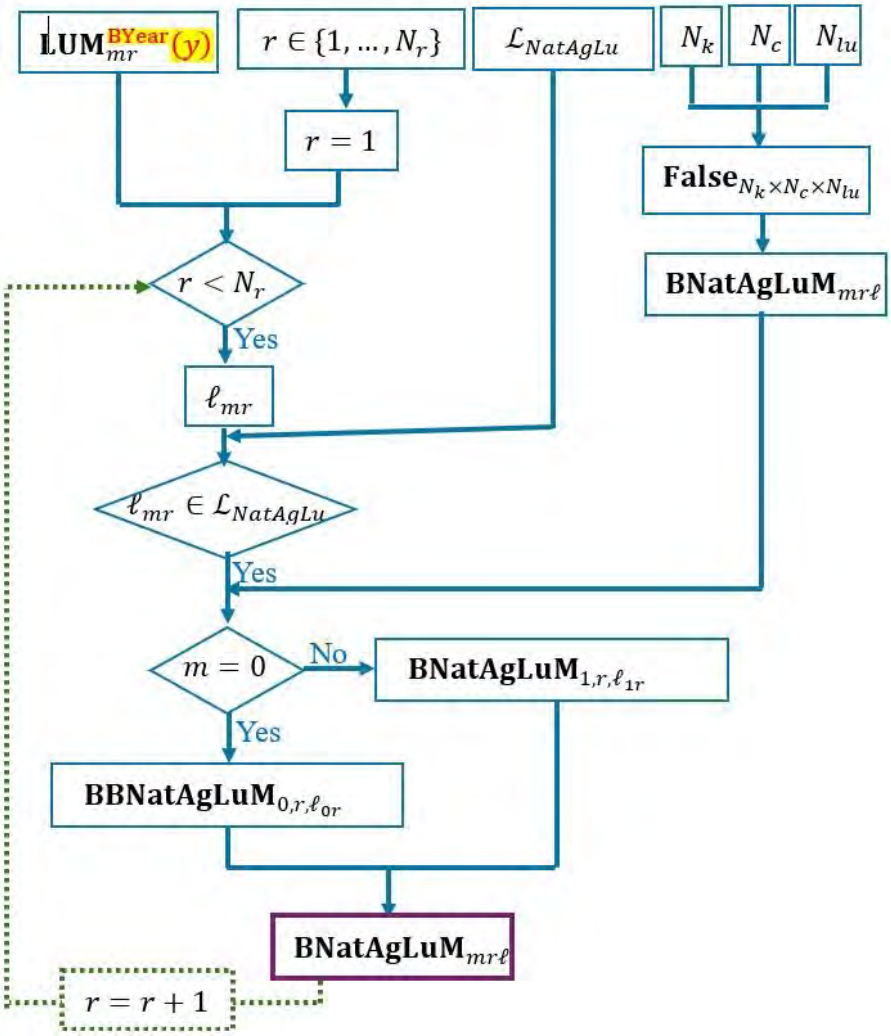

Figure 391 Identification of Agricultural Natural Land-Use Cells This flowchart should be updated.

13.5. Transition Cost Matrix from current land-use ℓ_i to all other land-uses ℓ_j

The raw transition cost matrix **RTCM** is a square matrix of size $N_c \times N_c$, where each element $\mathbf{RTCM}_{\ell_i,\ell_j}$ represents the transition cost ($/ha) from land-use class ℓ_i to ℓ_j (Figure 392). Here, $\ell_i, \ell_j \in \mathcal{L}$, and $\mathcal{L}$, the set of all land uses classes Equation 1.

To develop the transition cost matrix for each cell—representing the cost of transitioning from its current land-use class ℓ_i to a potential new class ℓ_j—we define $\mathbf{TCM}_{r\ell}$ as follows:

$\forall, r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	
$\mathbf{TCM}_{r\ell} = \mathrm{False}_{N_c \times N_{lu}}$	Equation 241

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.

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- N_{lu} is the number of agricultural land-use categories; hence, $N_{lu} = 28$.

The transition costs from the current land-use ℓ_i to all other land-use classes ℓ_j, based on the current land-use map $\mathbf{LUM}_r(y)$, are computed in dollars per hectare ($/ha) using Equation 242. For non-agricultural cells, the base-year land-use map $\mathbf{LUM}_r^{\text{BYear}}$ is used instead, to determine which land-use classes are possible for each cell.

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L} \; \exists \; \ell_r^{AG}, \ell_r, \ell_r = \mathbf{LUM}_r(y), \ell_r^{AG} = \mathbf{AgCells}_r$	Equation 242
$\mathbf{TCM}_r(y) = \begin{cases} \mathbf{RTCM}_{\ell_r} \times TCM(y) & \text{If} \quad \ell_r^{AG} = \text{True} \wedge \ell_r \in \mathcal{L}_{\text{AgrLand}} \\ 0 & \text{Otherwise} \end{cases}$	
$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}} \; \exists \; \ell_r^{NonAG}, \ell_r, \ell_r = \mathbf{LUM}_{mr}^{\text{BYear}}, \ell_r^{NonAG} = \mathbf{NonAgCells}_r$	
$\mathbf{TCM}_r(y) = \begin{cases} \mathbf{RTCM}_{\ell_r} \times TCM(y) & \text{If} \quad \ell_r^{NonAG} = \text{True} \wedge \ell_r \in \mathcal{L}_{\text{NonAgrLand}} \wedge \mathbf{TCM}_r = 0 \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{AgCells}_r$**:** Boolean tensor for agricultural cells (Equation 238)
- $\mathbf{NonAgCells}_r$: Boolean tensor for non-agricultural cells (Equation 239)
- $TCM(y)$: Transition cost multiplier
- $\mathcal{L}_{\text{AgrLand}}$: Set of agricultural land-use categories (Equation 12)
- $\mathcal{L}_{\text{NonAgrLand}}$: Set of non-agricultural land-use categories (Equation 14)

To identify the NaN values in $\mathbf{TCM}_r$, which may represent disallowed transitions between land-use classes, we apply Equation 243.

$\forall r \in \{1, \dots, N_r\} \; \exists \; \ell_r, \ell_r = \mathbf{TCM}_r$	Equation 243
$\mathbf{TCM}_r = \begin{cases} 0 & \text{If} \quad \ell_r = \text{NaN} \\ 1 & \text{Otherwise} \end{cases}$	

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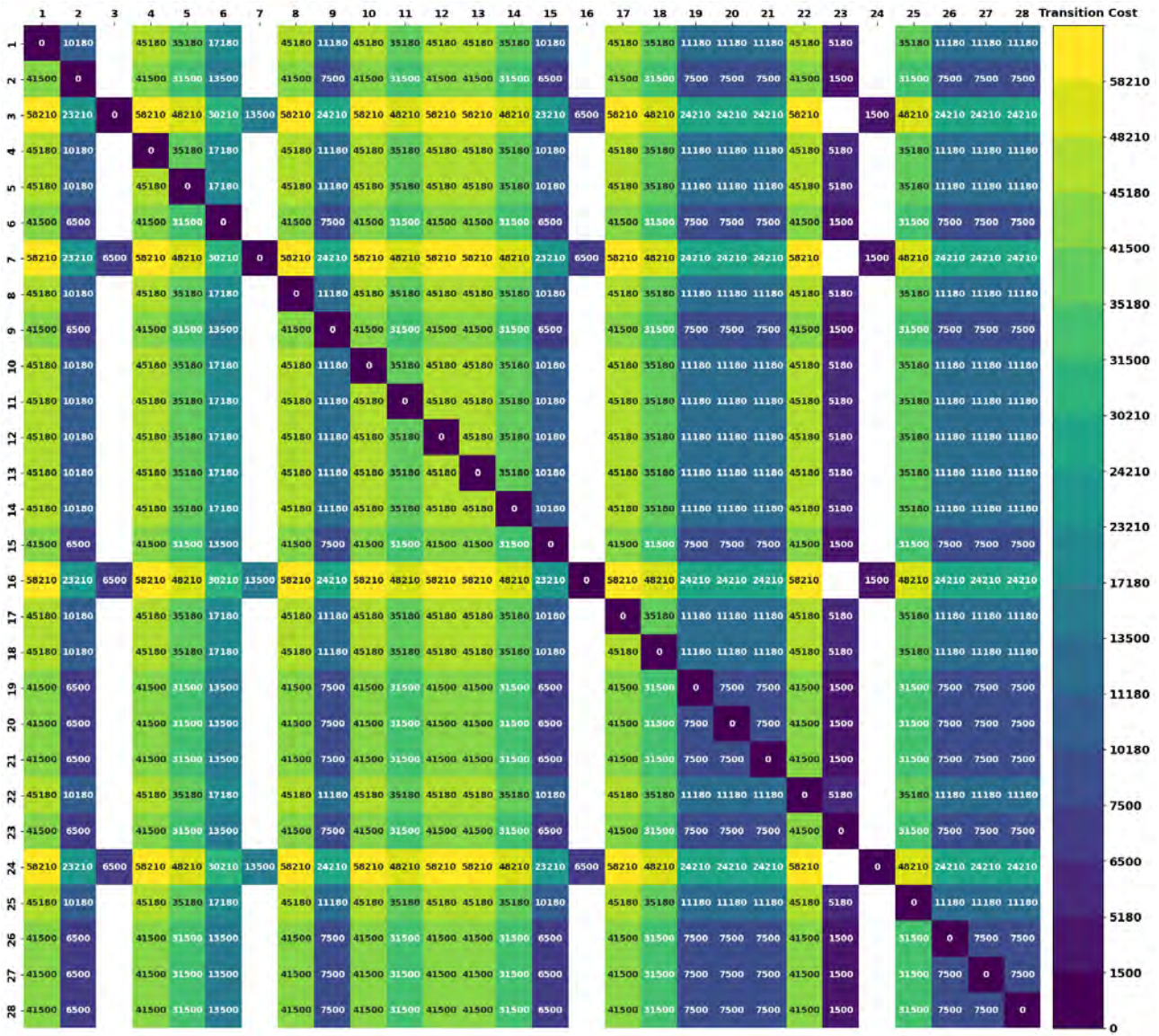

Figure 392 Raw transition cost matrix **RTCM** (AUD/ha)

13.6. **Boolean Exclusion Matrix for Subsequent Years**

The Boolean exclusion matrix for subsequent years, denoted as $\mathbf{XCM}_{mr\ell}$, builds upon the methodology established for the base year (see Section 13.1), while incorporating updates to reflect changes in land use and land management over time.

As farmers adjust their practices in response to economic, environmental, and policy factors, the land-use map for a given year $\mathbf{LUM}_r(y)$ used in the transition cost matrix $\mathbf{TCM}_r$ (Equation 242), captures the spatial and categorical shifts in land use. Consequently, the exclusion matrix $\mathbf{XCM}_{mr\ell}$ must be regenerated annually to account for these dynamics.

To achieve this, the matrix from the base year $\mathbf{XCM}_{mr\ell}^{BYear}$ (Equation 232) is combined with the updated transition cost matrix $\mathbf{TCM}_r$. This approach ensures that $\mathbf{XCM}_{mr\ell}$ reflects the most current state of the landscape, excluding disallowed land-use transitions and adapting to evolving land management practices.

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The update process is mathematically defined as:

$$\mathbf{XCM}_{mr\ell} = \mathbf{XCM}_{mr\ell}^{BYear} \times \mathbf{TCM}_{r}$$	Equation 244

The resulting updated Boolean exclusion matrix $\mathbf{XCM}_{mr\ell}$ is a critical input for modeling future land-use transitions, policy evaluations, and planning strategies. Its dynamic nature allows for accurate simulation of land-use scenarios under various assumptions and drivers of change.

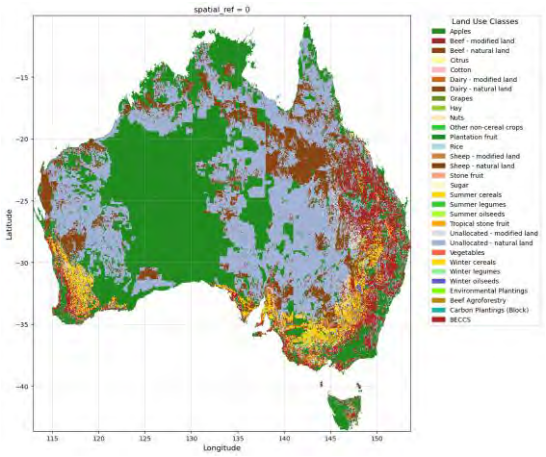

Figure 393 Land Use Map - Year: 2050

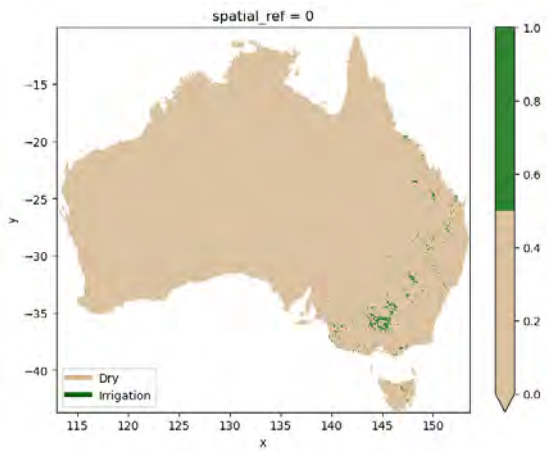

Figure 394 Land Management Map - Year: 2050

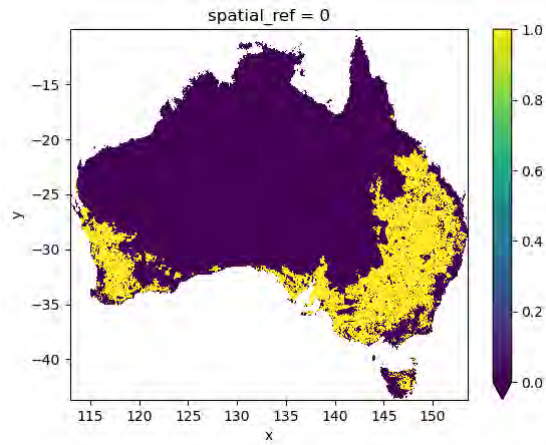

Figure 395 Boolean exclusion matrix for the class of winter cereals under dryland management in the year 2050

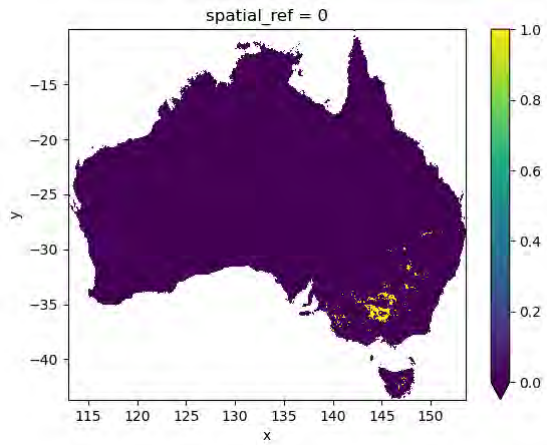

Figure 396 Boolean exclusion matrix for the class of winter cereals under irrigation land management in the year 2050

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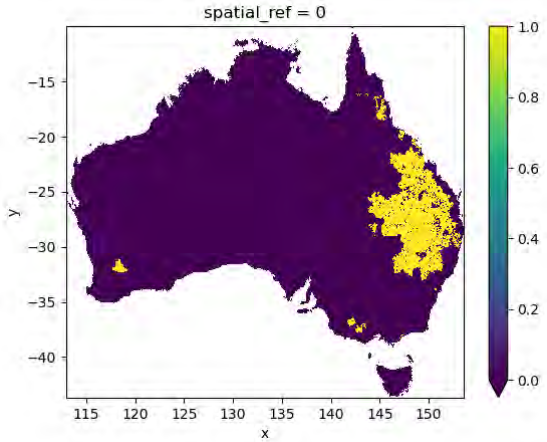

Figure 397 Boolean exclusion matrix for the class of summer cereals under dryland management in the year 2050

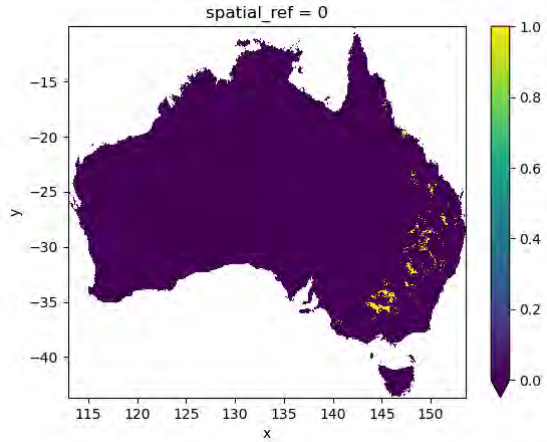

Figure 398 Boolean exclusion matrix for the class of summer cereals under irrigation land management in the year 2050

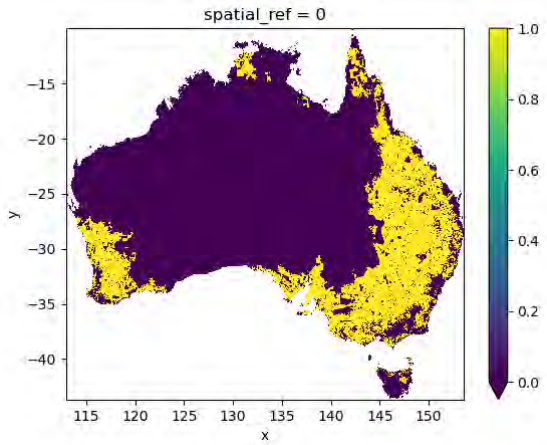

Figure 399 Boolean exclusion matrix for the class of Hay under dryland management in the year 2050

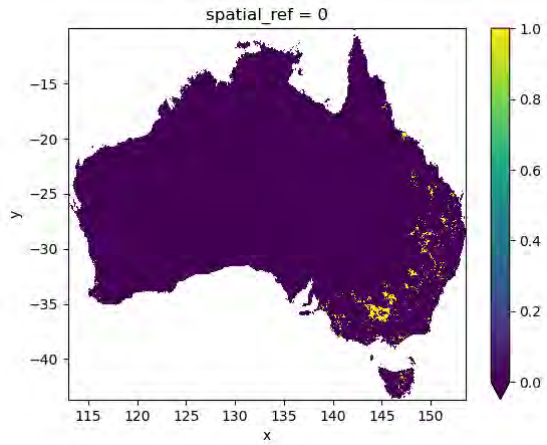

Figure 400 Boolean exclusion matrix for the class of Hay under irrigation land management in the year 2050

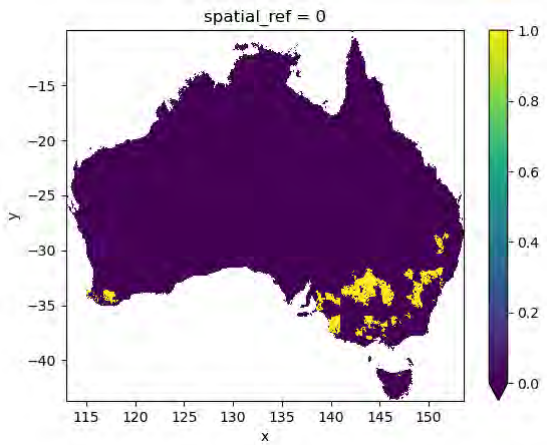

Figure 401 Boolean exclusion matrix for the class of Grapes under dryland management in the year 2050

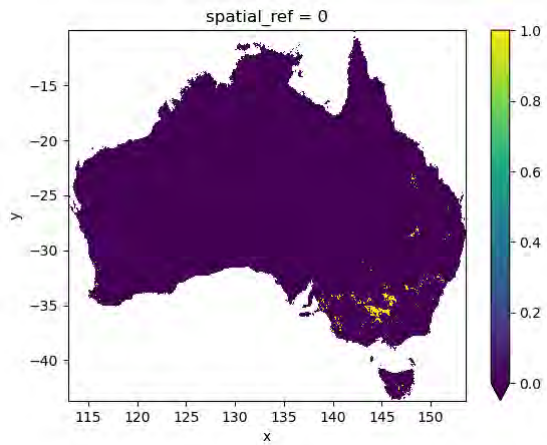

Figure 402 Boolean exclusion matrix for the class of Grapes under irrigation land management in the year 2050

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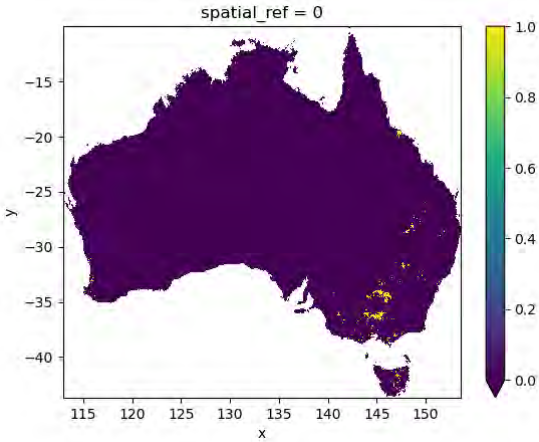	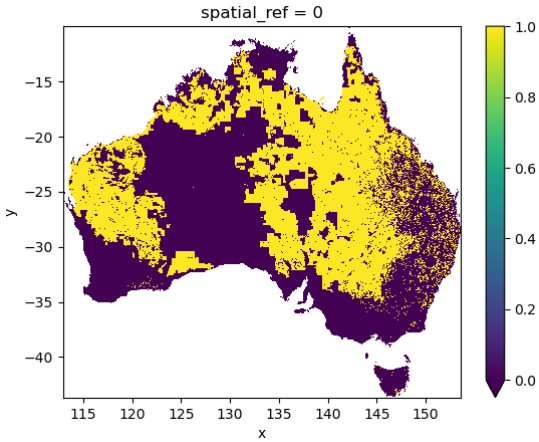
Figure 403 Boolean exclusion matrix for the class of Beef - modified land under dryland management in the year 2050	Figure 404 Boolean exclusion matrix for the class of Beef - modified land under irrigation land management in the year 2050
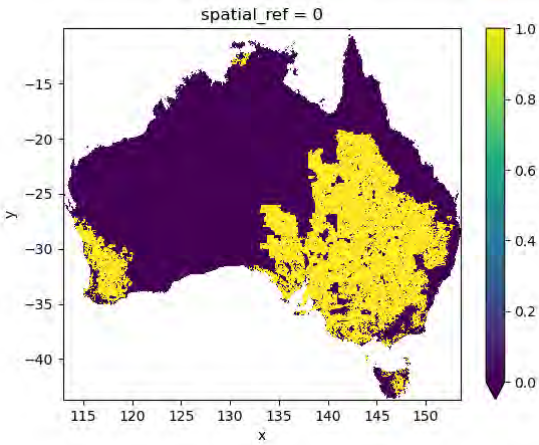	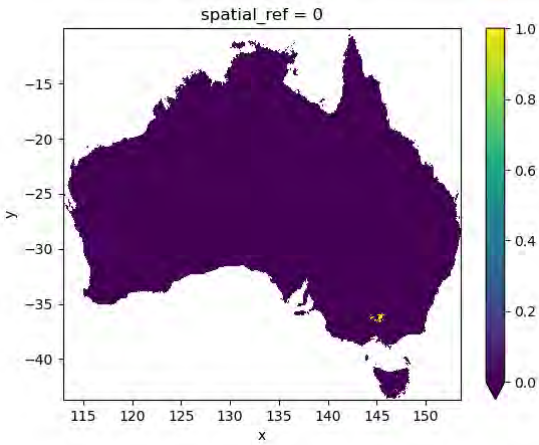
Figure 405 Boolean exclusion matrix for the class of Sheep - modified land under dryland management in the year 2050	Figure 406 Boolean exclusion matrix for the class of Sheep - modified land under irrigation land management in the year 2050

13.7. Establishment Cost for Agricultural Land Use

Lime 120 of file transition.py should be changed because it applied to both irrigation and dryland management system.

The initial establishment cost for agricultural lands $\mathbf{IEstCost}^{AG}(y)$, is defined as a zero-filled tensor of dimensions $N_c \times N_{lu}$:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 245
$\mathbf{IEstCost}^{AG} = 0_{N_c \times N_{lu}}$	

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.

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- $N_{lu} = 28$: Number of agricultural land-use categories

Regarding the shape of this tensor, it is denoted as $\mathbf{IEstCost}_{r\ell}^{AG}(y)$, where each element represents the establishment cost of transitioning a given cell r from its current land-use class ℓ_r to a new agricultural class ℓ_j in year y.

To update the values of $\mathbf{IEstCost}_{r\ell}^{AG}(y)$, the first step is to extract the land-use class of cell r from the land-use map $\mathbf{LUM}_r(y)$. Accordingly, the land-use label can be written as:

$\ell_r = \mathbf{LUM}_r(y)$	Equation 246

To confirm that cell r belongs to **agricultural land**, the value of $\mathbf{BLuLmM}_{mr\ell}$ must be extracted (see Equation 234). Then, at least one of the conditions in Equation 247 must be satisfied—either condition is sufficient, as both yield the same result.

$\ell_r \in \mathcal{L}_{\text{AgrLand}}$	Equation 247
$\mathbf{BLuLmM}_{mr\ell} = \text{True}$	

where,

- $\mathbf{BLuLmM}_{mr\ell}$ is the Boolean tensor representing the land-use and land management matrix (Equation 234)
- $\mathcal{L}_{\text{AgrLand}}$ is the set of all land used employed for agricultural purposes (Equation 12)

Then, the related transition costs of each cell r are taken either from $\mathbf{TCM}_r(y)$ in Equation 242 based on ℓ_r, or set to 0 otherwise.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists\ \ell_r, \ell_r = \mathbf{LUM}_r(y)$	Equation 248
$\mathbf{IEstCost}_{r\ell}^{AG}(y) = \begin{cases} \mathbf{TCM}_{\ell_r}(y) & \text{If} \quad (\ell_r \in \mathcal{L}_{\text{AgrLand}}) \wedge (\mathbf{BLuLmM}_{mr\ell} = \text{True}) \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{TCM}_r(y)$: Transition cost matrix (Equation 242)
- $\mathbf{BLuLmM}_{mr\ell}$: Boolean land-use and land management tensor (Equation 234)
- $\mathcal{L}_{\text{AgrLand}}$: Agricultural land-use classes (Equation 12)
- $\mathbf{LUM}_r(y)$: Land use map of year y (See Figure 371 and Figure 393)

The flowchart illustrating the initialization and update process for the establishment cost of non-irrigation lands is presented in Figure 407. It should be updated.

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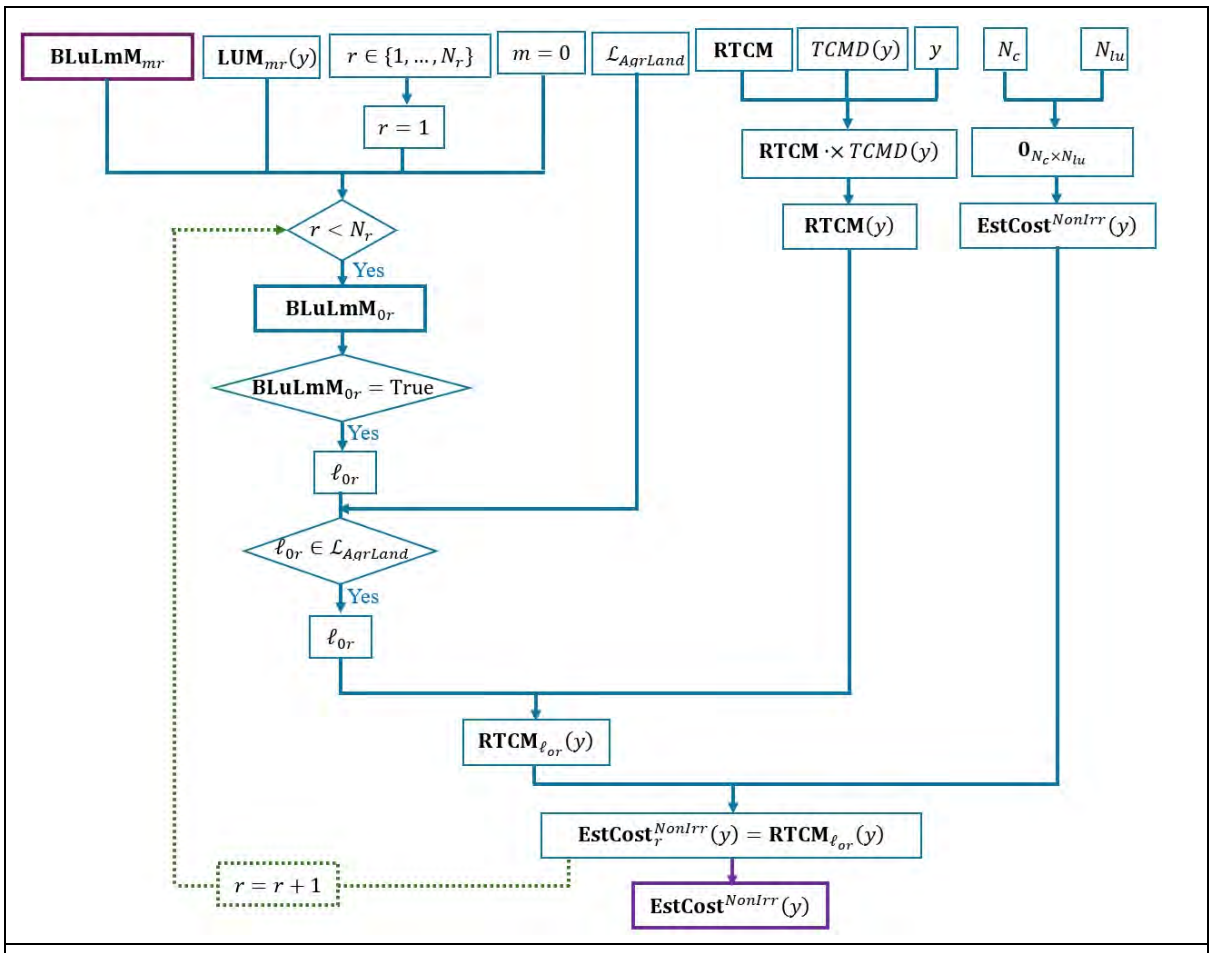

Figure 407 Establishment Cost of Non-Irrigation Lands It should be updated.

The updated establishment raw transition cost (Equation) of non-irrigation lands ($\mathbf{IEstCost}_{r\ell}^{AG}$) for the year 2050 was computed, and some of these costs are presented in Figure 408, Figure 410, Figure 412, Figure 414, Figure 416, and Figure 418.

13.8. Amortize Upfront Costs to Annualized Costs

The establishment cost can be amortized over time using the following payment formula:

$$PMT = \frac{PV \times DR \times (1 + DR)^{NP}}{(1 + DR)^{NP} - 1}$$	Equation 249

Where:

- PMT: Annual payment (amortized value)
- PV: Present value (initial cost, $\mathbf{IEstCost}^{AG}$)
- DR: Discount rate per period (LUTO 2.0 considered the value of 7% or 0.07)
- NP: Number of periods (LUTO 2.0 considered the value of 30 years)

Regarding Equation , PV is considered as $\mathbf{IEstCost}_{r\ell}^{AG}(y)$ Therefore, by substituting it into the formula, Equation 249 can be written as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 250

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$$\mathbf{PMT}^{AG} = \frac{\mathbf{IEstCost}_{r\ell}^{AG}(y) \times DR \times (1+DR)^{NP}}{(1+\mathrm{DR})^{\mathrm{NP}} - 1}$$	

Considering the LUTO 2.0 model, in which payments are assumed to be made at the beginning of each period, the amortization formula is adjusted accordingly:

$$\mathbf{PMT}_{begin}^{AG} = \mathbf{PMT}^{AG} \times \frac{1}{1+DR}$$	Equation 251

Substituting the general amortization formula (Equation 250) into this adjustment:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 252
$$\mathbf{PMT}_{begin}^{AG} = \frac{\mathbf{IEstCost}_{r\ell}^{AG}(y) \times DR \times (1+DR)^{NP}}{(1+DR)^{NP} - 1} \times \frac{1}{1+DR}$$	

For a given year y, this simplifies to:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 253
$$\mathbf{PMT}_{begin}^{AG}(y) = \frac{\mathbf{IEstCost}_{r\ell}^{AG}(y) \times DR \times (1+DR)^{NP-1}}{(1+DR)^{NP} - 1}$$	

For example, in the LUTO 2.0 model, with $DR = 0.07$ and $NP = 30$:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 254
$$\mathbf{PMT}_{begin}^{AG}(y) = \frac{\mathbf{IEstCost}_{r\ell}^{AG}(y) \times 0.07 \times (1+0.07)^{30-1}}{(1+0.07)^{30} - 1}$$	

Which can be simplified as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 255
$$\mathbf{PMT}_{begin}^{AG}(y) = \frac{\mathbf{IEstCost}_{r\ell}^{AG}(y) \times 0.07 \times (1+0.07)^{29}}{(1+0.07)^{30} - 1}$$	

This equation represents a tensor of equivalent annual payments (i.e., amortized values) of the initial establishment cost $\mathbf{IEstCost}^{AG}(y)$, distributed over 30 years at a 7% discount rate, under the assumption that payments are made at the beginning of each period.

13.9. Update the Value of $\mathbf{IEstCost}^{AG}$ Based on the Amortize Upfront Costs

To adjust the initial establishment cost $\mathbf{IEstCost}_{r\ell}^{AG}(y)$, previously computed in Equation , the model considers whether **amortized upfront costs** (denoted as $AmUpCost$) should be applied.

The update is defined as:

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$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	
$\mathbf{IEstCost}_{r\ell}^{AG}(y) = \begin{cases} -1 \times \mathbf{PMT}_{begin}^{AG}(y) & \text{If } AmUpCost = \text{True} \\ \mathbf{PMT}_{begin}^{AG}(y) & \text{If } AmUpCost = \text{False} \end{cases}$	Equation 256

Based on Equation 256,

- If the initial value of $AmUpCost$ is True, the updated $\mathbf{IEstCost}_{r\ell}^{AG}(y)$ represents the negative annual cash flow, reflecting the amortized cost over time.
- If $AmUpCost$ is False, the updated $\mathbf{IEstCost}_{r\ell}^{AG}(y)$ remains equal to the initial establishment cost, without applying amortization.

By default, LUTO 2.0 model assumes $AmUpCost = \text{False}$; thereby returning the unamortized initial cost $\mathbf{IEstCost}_{r\ell}^{AG}(y)$.

To convert the unit from \$/ha to \$/cell, the real area multiplier $\mathbf{RA}_r$ is applied as follows:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$		where,
$\mathbf{IEstCost}_{r\ell}^{AG}(y) = \mathbf{IEstCost}_{r\ell}^{AG}(y) \times \mathbf{RA}_r$	Equation 257	where,

- $\mathbf{RA}_r$: Real area multiplier for cell r (Figure 5)

The updated annualized establishment costs for non-irrigated lands in 2050, adjusted to AUD per cell, were computed using Equation 257. Examples of these results are illustrated in Figure 409, Figure 411, Figure 413, Figure 415, Figure 417, and Figure 419.

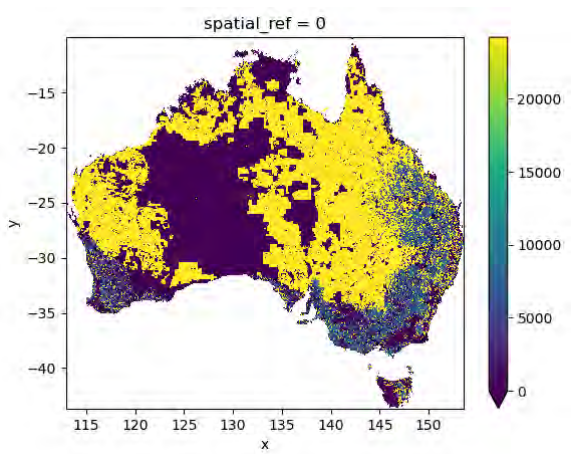

Figure 408 Non-irrigation-related raw transition costs for cells converted from land use in 2050 (Figure 393) to winter cereals under dryland management (AUD per ha)

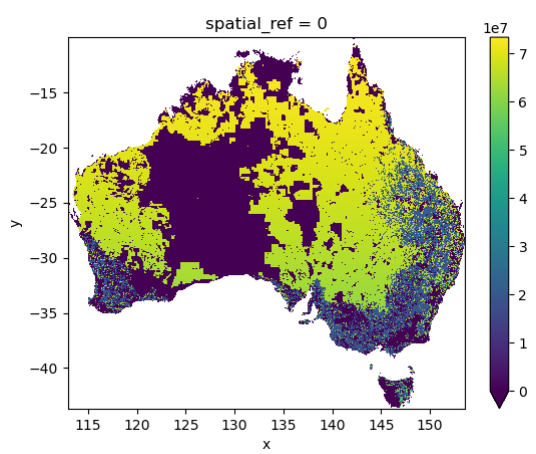

Figure 409 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) winter cereals under dryland management, adjusted to AUD per cell

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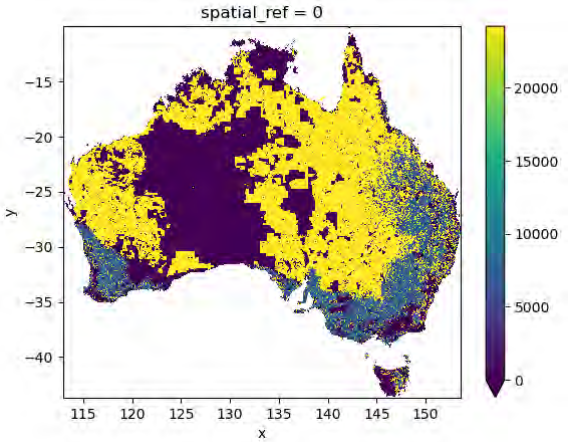

Figure 410 Non-irrigation-related raw transition for cells converted from land use in 2050 (Figure 393) to summer cereals under dryland management (AUD per ha)

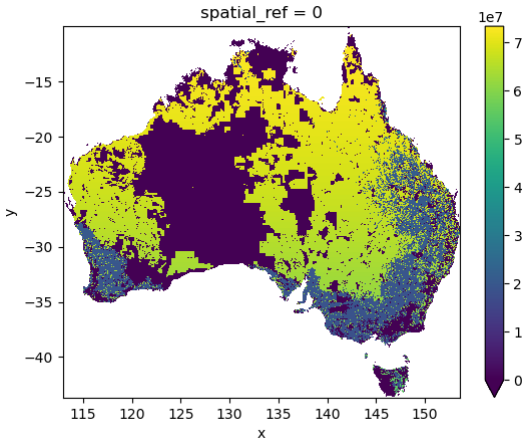

Figure 411 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to summer cereals under dryland management, adjusted to AUD per cell

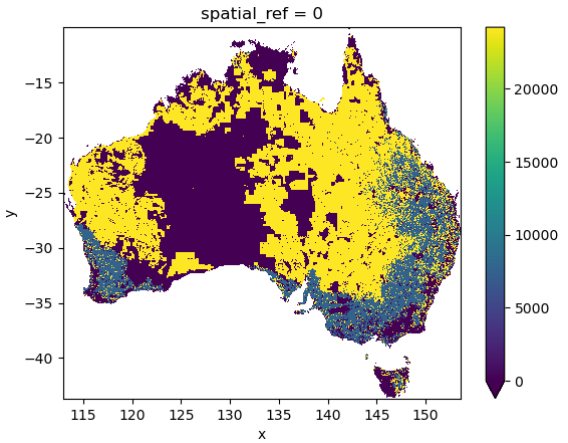

Figure 412 Non-irrigation-related raw transition costs for cells converted from land use in 2050 (Figure 393) to hay under dryland management (AUD per ha)

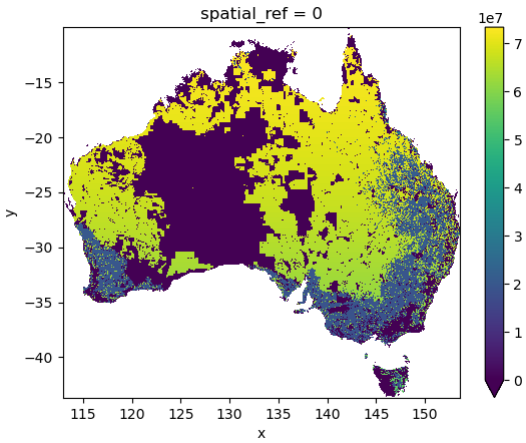

Figure 413 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to hay under dryland management, adjusted to AUD per cell

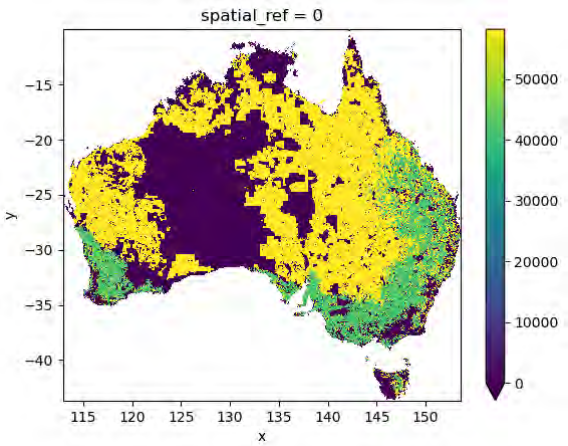

Figure 414 Non-irrigation-related raw transition costs for cells converted from land use in 2050 (Figure 393) to grapes under dryland management (AUD per ha)

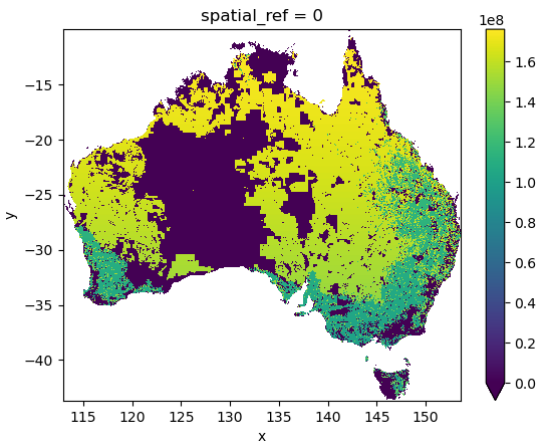

Figure 415 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to grapes under dryland management, adjusted to AUD per cell

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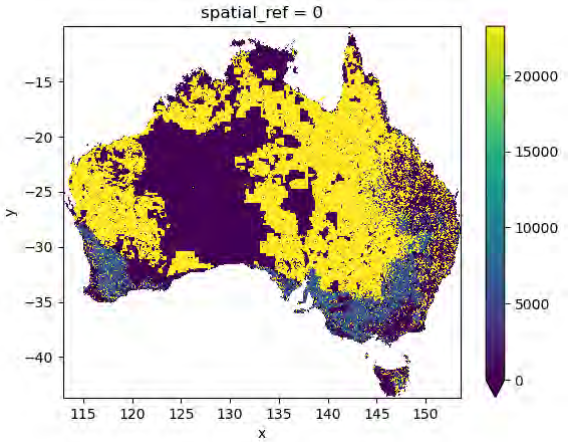

Figure 416 Non-irrigation-related raw transition costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under dryland management (AUD per ha)

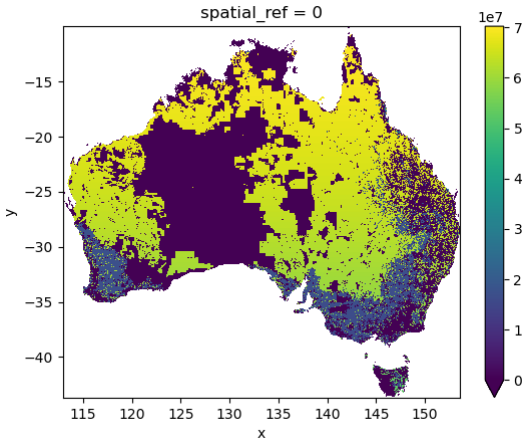

Figure 417 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under dryland management, adjusted to AUD per cell

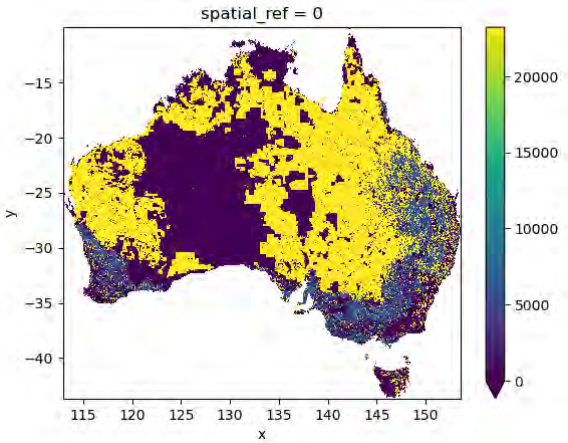

Figure 418 Non-irrigation-related raw transition costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under dryland management (AUD per ha)

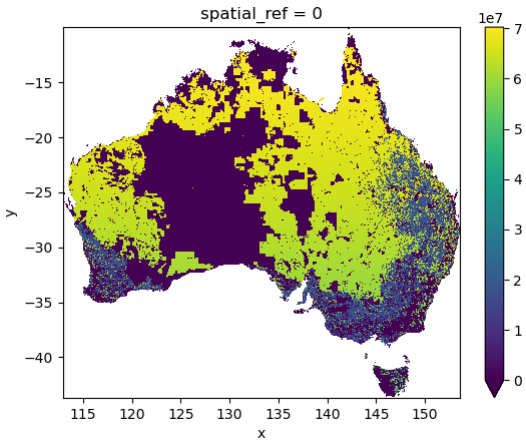

Figure 419 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under dryland management, adjusted to AUD per cell

13.10. Establishment Costs for All Agricultural Land Use and Land Management Systems (Including Amortized Upfront Costs)

To represent establishment costs for both ($\mathbf{IEstCost}_{r\ell}^{AG,Dry}$) and irrigation ($\mathbf{IEstCost}_{r\ell}^{AG,Irr}$) management systems, we initialize the following two tensors:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	
$\mathbf{IEstCost}_{r\ell}^{AG,Dry} = 0_{N_c \times N_{lu}}$	Equation 258
$\mathbf{IEstCost}_{r\ell}^{AG,Irr} = 0_{N_c \times N_{lu}}$	Equation 259

where,

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- N_c: Number of cells in the base-year land-use map$\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_{lu} = 28$: Number of agricultural land-use classes

The establishment cost for cells under dryland management is updated as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L} \exists \ell_r = \mathbf{LUM}_r(y)$	
$\mathbf{IEstCost}_{r\ell}^{AG,Dry}(y) = \begin{cases} \mathbf{IEstCost}_r^{AG}(y) & \text{If} \quad \mathbf{BLuLmM}_{0,r,\ell_r} = 0 \wedge \mathbf{AgCells}_{mr} = \text{True} \\ 0 & \text{Otherwise} \end{cases}$	Equation 260

Similarly, for irrigated lands, the establishment cost is updated as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L} \exists \ell_r = \mathbf{LUM}_r(y)$	
$\mathbf{IEstCost}_{r\ell}^{AG,Irr}(y) = \begin{cases} \mathbf{IEstCost}_r^{AG}(y) & \text{If} \quad \mathbf{BLuLmM}_{1,r,\ell_r} = 1 \wedge \mathbf{AgCells}_{mr} = \text{True} \\ 0 & \text{Otherwise} \end{cases}$	Equation 261

To generalize for both land management types, we initialize the combined establishment cost tensor:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 262
$\mathbf{EstCost}_{mr\ell}^{AG} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c: Number of cells in the base-year land-use map$\mathbf{LUM}^{\mathrm{BYear}}$
- $N_k = 2$: Number of agricultural management practices $m \in \mathcal{M}$
- $N_{lu} = 28$: Number of agricultural land-use classes

Then $\mathbf{EstCost}_{mr\ell}^{AG}$ is updated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 263
$\mathbf{EstCost}_{mr\ell}^{AG}(y) = \begin{cases} \mathbf{IEstCost}_{mr}^{AG,Dry}(y) & \text{If} \quad m = 0 \\ \mathbf{IEstCost}_{mr}^{AG,Irr}(y) & \text{If} \quad m = 1 \end{cases}$	

The process for initializing and updating the establishment cost across both land management types is illustrated in Figure 420 (It should be updated).

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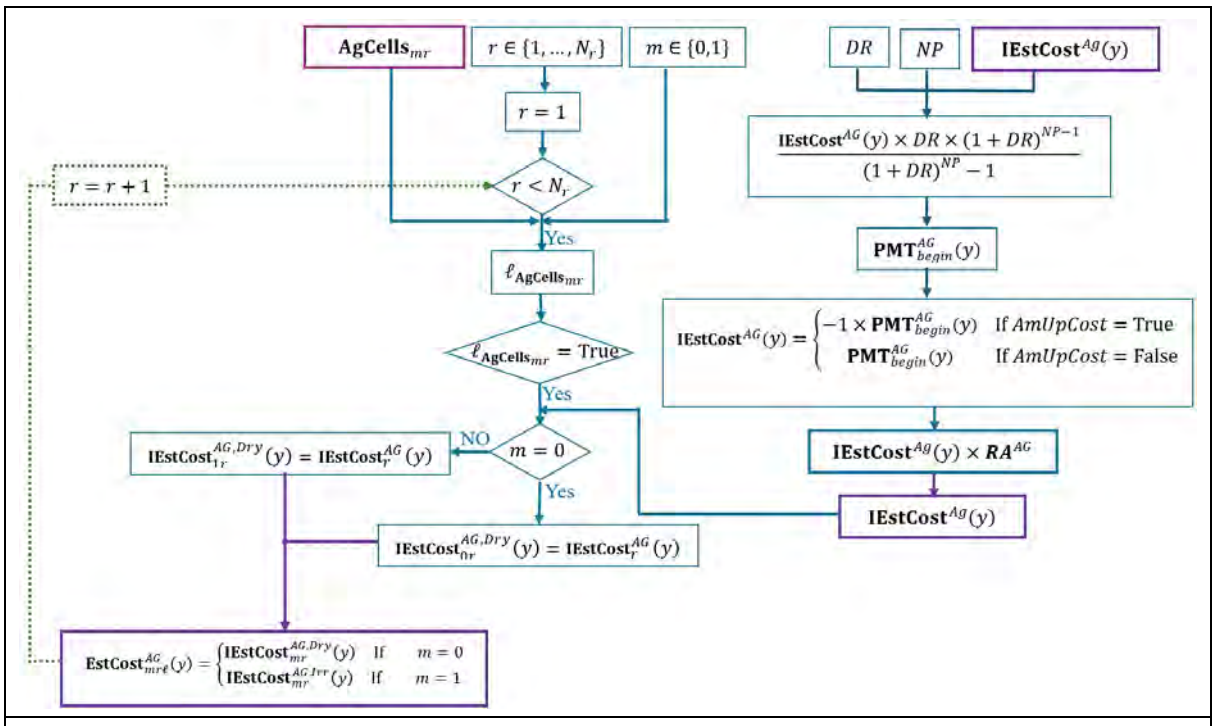

Figure 420 Establishment Costs for all agricultural land use and land management systems, including Amortize Upfront Costs (It should be updated)

13.11. Update Establishment Cost Using Exclusion Matrices

In the transition cost model, if a cell r retains its current land-use class ℓ_r, the associated transition cost is zero. Therefore, to accurately reflect this condition, the establishment cost matrix $\mathbf{EstCost}^{AG}_{mr\ell}(y)$ must be updated using the Boolean exclusion matrix $\mathbf{XCM}_{mr\ell}$ (Equation 244). Additionally, to exclude **non-agricultural cells**, the matrix $\mathbf{BLuLmM}^{\text{NOT}}_{mr\ell}$ is used (Equation 236), which negates the Boolean land-use and land management matrix to identify excluded cells.

Since $\mathbf{EstCost}^{AG}_{mr\ell}$, $\mathbf{XCM}_{mr\ell}$, and $\mathbf{BLuLmM}^{\text{NOT}}_{mr\ell}$ all share the same dimensions, they can be element-wise multiplied:

$\mathbf{EstCost}^{AG}_{mr\ell}(y) = \mathbf{EstCost}^{AG}_{mr\ell}(y) \times \mathbf{XCM}_{mr\ell}(y) \times \mathbf{BLuLmM}^{\text{NOT}}_{mr\ell}(y)$	Equation 264

This update ensures that:

- No cost is assigned to unchanged land uses.
- Non-agricultural land uses are excluded from the cost computations.

Figure 421-Figure 432 illustrate the annualised non-irrigation-related transition costs associated with land-use changes projected for the year 2050. These figures present the costs in AUD per cell, adjusted to reflect only those cells undergoing land-use transitions—costs for unchanged land uses are set to zero based on the Boolean exclusion matrix (Equation 264).

Figure 421, Figure 423, Figure 425, Figure 427, Figure 429, and Figure 431 display transition costs for cells that are converted from their 2050 land use (as shown in Figure 393) to the following classes under dryland management:

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- Winter cereals (Figure 395)
- Summer cereals (Figure 397)
- Hay (Figure 399)
- Grapes (Figure 401)
- Beef – modified land (Figure 403)
- Sheep – modified land (Figure 405)

In contrast, Figure 422, Figure 424, Figure 426, Figure 428, Figure 430, **and** Figure 432 show the corresponding transition costs under irrigation management, with unchanged land uses also set to zero based on the Boolean exclusion matrix: Winter cereals (Figure 396)

- Summer cereals (Figure 398)
- Hay (Figure 400)
- Grapes (Figure 402)
- Beef – modified land (Figure 404)
- Sheep – modified land (Figure 406)

Together, these figures provide insight into the economic implications of land-use transitions under both dryland and irrigated agricultural management systems in future scenarios.

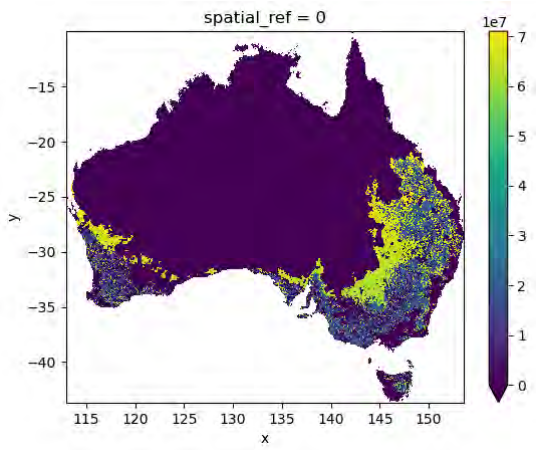

Figure 421 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to winter cereals under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 395).

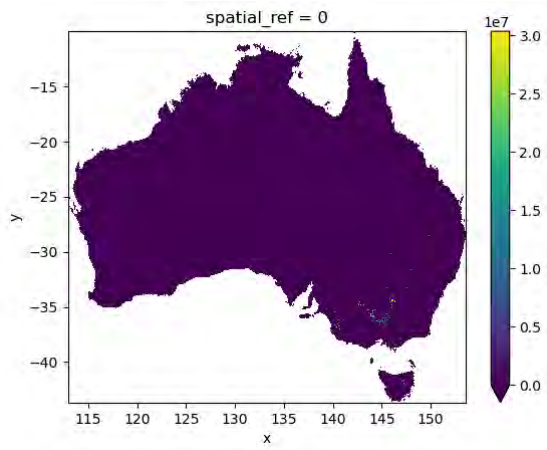

Figure 422 Annualised non-irrigation-related transition costs for cells converted from lanFigure 432d use in 2050 (Figure 393) to winter cereals under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 396).

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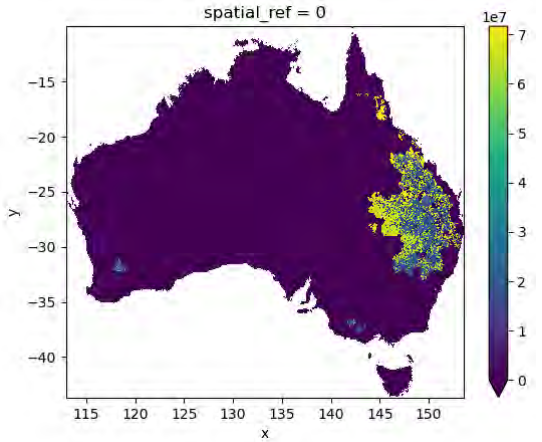


Figure 423 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to summer cereals under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 397).

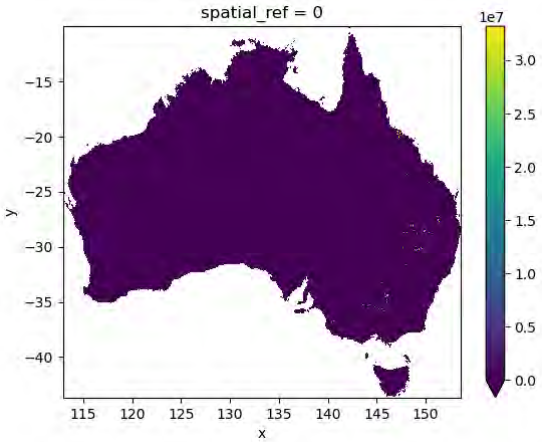


Figure 424 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to summer cereals under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 398).

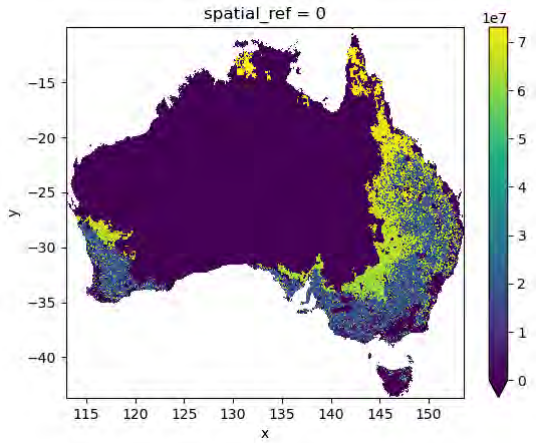


Figure 425 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to hay under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 399).

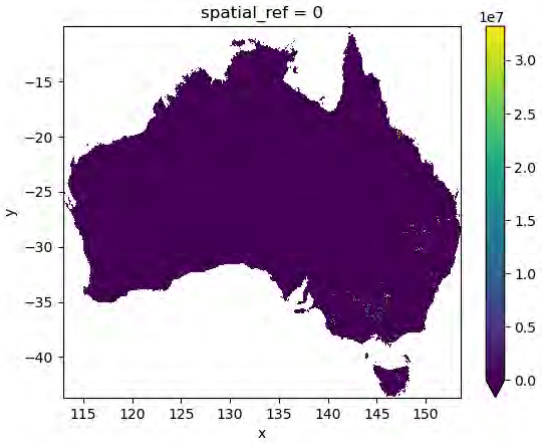
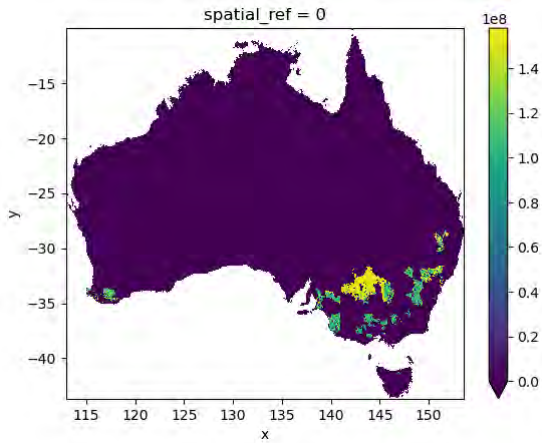


Figure 426 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to hay under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 400).



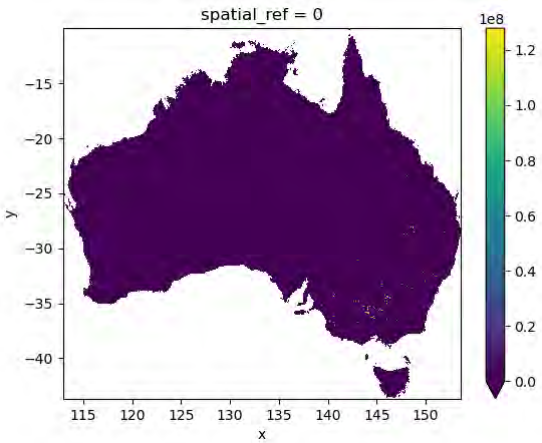


Figure 427 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to grapes under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 401).

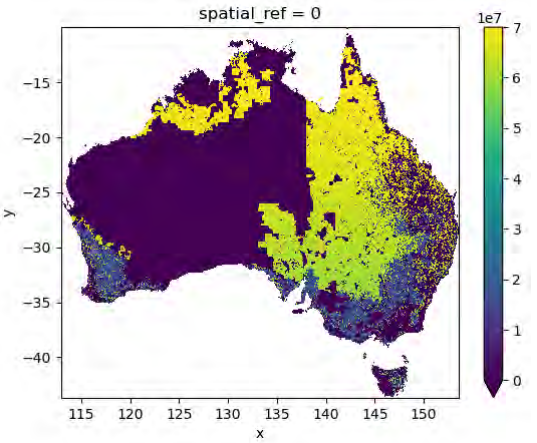


Figure 428 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to grapes under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 402).

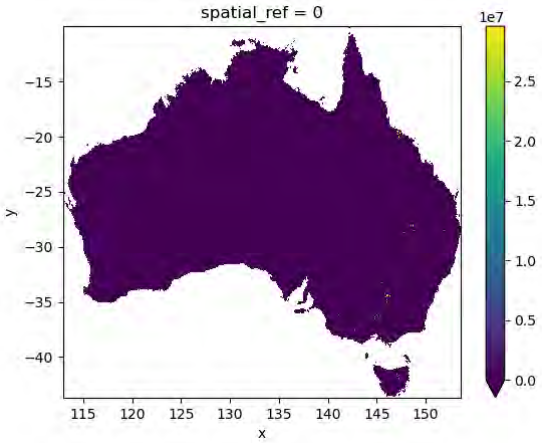


Figure 429 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 403).

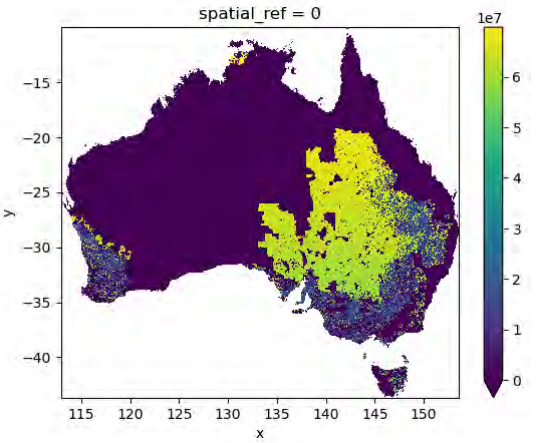


Figure 430 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 404).

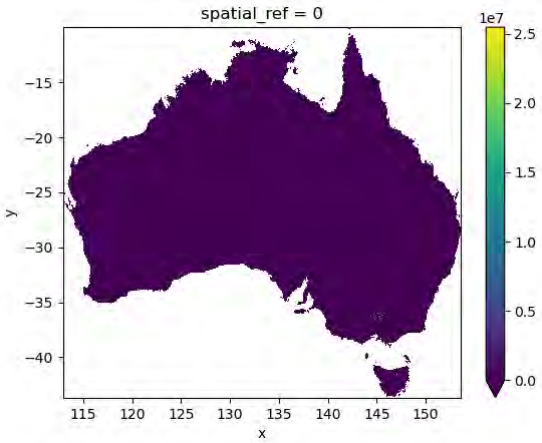


Figure 431 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 405).

Figure 432 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 406).

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13.12. Water License Cost

This section quantifies changes in water-related costs arising from land-use transitions, particularly when converting between dryland and irrigated agricultural systems. These changes include:

- Water license fees
- Infrastructure installation or removal
- Amortization of water-related costs

The resulting matrix, $\mathbf{WLC}_{mr\ell}(y)$, represents the annualized change in water-related costs per cell (AUD/cell) associated with specific land-use transitions.

13.12.1. The total water requirement matrix

The water requirements matrix $\mathbf{WReqM}_{mr\ell}^{AG,LS}$ (Equation 137), which stores the water demand values for land uses under both dryland and irrigation management systems, is introduced in Section 7.1. By applying the Boolean land-use and land management matrix $\mathbf{BLuLmM}_{mr\ell}$ (Equation 234), the total water requirement for each cell, denoted as $\mathbf{TWR}_{mr\ell}(y)$, can be computed as follows:

$$\mathbf{TWR}_r(y) = \sum_{\ell=1}^{N_{lu}} \sum_{1=1}^{N_k} \mathbf{WReqM}_{mr\ell}^{AG,LS}(y) \times \mathbf{BLuLmM}_{mr\ell}(y)$$	Equation 265

where,

- $\mathbf{WReqM}_{mr\ell}^{AG,LS}$: Water requirement for land use ℓ, management m, and cell r (Equation 137)
- $\mathbf{BLuLmM}_{mr\ell}(y)$: Boolean land-use and land management tensor (Equation 234),
- $N_k = 2$, Number of land management strategies $m \in \mathcal{M}$(dry/irrigation)
- $N_{lu} = 28$: Number of agricultural land-use classes

The computed $\mathbf{TWR}_r$ is illustrated in Figure 434.

13.12.2. Net water requirements

The net water requirement for each potential land-use type ℓ is calculated relative to the current land use:

$$\mathbf{NetWR}_{mr\ell}(y) = \mathbf{WReqM}_{mr\ell}^{AG,LS}(y) - \mathbf{TWR}_r(y)$$	Equation 266

where,

- $\mathbf{TWR}_r$ is the total water requirements (Equation 265)
- $\mathbf{WReqM}_{mr\ell}^{AG,LS}$ represents the water requirement for land use ℓ under land management strategy m for cell r (Equation 137)

The computed net water requirement matrix, $\mathbf{NetWR}_{mr\ell}$, is broadcast across all cells to evaluate how much additional or reduced water is required if a land-use change occurs. The results are illustrated in Figure 437-Figure 448. As shown in these figures, the net water requirements under dryland management are consistently

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zero or negative. This reflects the fact that dryland systems typically demand less water than the current land use, or may not require additional water at all.

In contrast, for irrigated land-use scenarios, the net water requirements can be positive, zero, or negative, depending on the specific crop type and environmental conditions. This variation arises due to the typically higher water demands of irrigated systems, which may exceed, match, or in rare cases fall below the water needs of the existing land use.

This comparison underscores the significant disparity in water requirements between dryland and irrigated agricultural practices, highlighting the importance of accounting for water availability and cost in land-use planning.

13.12.3. Water License Cost

Water licenses are typically required for irrigated agricultural activities (both crops and livestock), where users must purchase the right to access water for irrigation purposes. The cost associated with these rights is calculated based on the net change in water requirements resulting from land-use transitions.

The water license cost matrix, $\mathbf{WLC}_{mr\ell}(y)$, is computed as:

$\mathbf{WLC}_{mr\ell}(y) = \mathbf{NetWR}_{mr\ell}(y) \times \mathbf{WLP}_r \times WLCM(y) \times IWLC$	Equation 267

where,

- $\mathbf{WLP}_r$: Water license price per megalitre (ML) for cell r (Figure 433)
- $\mathbf{NetWR}_{mr\ell}(y)$: Net water requirement for land-use ℓ, land management m, and cell r (see Equation 266)
- $WLCM(y)$: Year-specific multiplier adjusting the water license cost (e.g., inflation, policy change) multiplier
- $IWLC$: Binary indicator (0 or 1) that enables or disables water license costs

As shown, $\mathbf{WLC}_{mr\ell}(y)$ is calculated by multiplying the net water requirement $\mathbf{NetWR}_{mr\ell}(y)$ by the water license price $\mathbf{WLP}_r$ (in AUD per megalitre). This value is further adjusted by the water license cost multiplier $WLCM(y)$ and the inclusion flag $IWLC$.

Accordingly, if the net water requirement increases—for example, due to a transition from dryland to irrigated land—the total cost rises to account for the additional water rights that must be acquired. This ensures that the model accurately reflects the economic implications of increased water use under irrigation scenarios.

13.12.4. Cost of Establishing Irrigation Infrastructure

When a land-use change involves converting dryland to irrigated agriculture, an additional infrastructure cost is incurred to establish irrigation systems. This cost is added to the water delta matrix for the relevant cells and calculated as:

$\mathbf{EstIrrInfr}_r(y) = \mathrm{Cost}_{\mathrm{EstIrrInfr}} \times ICM(y) \times \mathbf{RA}_r$	Equation 268

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Where:

- $\text{Cost}_{\text{EstIrrInfr}}$ indicates the cost for establishing irrigation infrastructure, which is considered to be $\text{Cost}_{\text{EstIrrInfr}} = 10000$ AUD/ha (as per LUTO 2.0)
- $ICM(y)$: Inflation/deflation multiplier for year y.
- $\mathbf{RA}_r$: Real area of cell r (see Figure 5)

The computed costs of establishing irrigation infrastructure are illustrated in Figure 435.

To update the water license cost matrix for dryland transitions ($\mathbf{BLuLmM}_{0,r,\ell} = \text{True}$) is:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \ell \in \mathcal{L}$	Equation 269
$\mathbf{WLC}_{1,r,\ell}(y) = \begin{cases} \mathbf{WLC}_{1,r,\ell}(y) + \mathbf{EstIrrInfr}_r & \text{If} \quad \mathbf{BLuLmM}_{0,r,\ell} = \text{True} \\ \mathbf{WLC}_{1,r,\ell}(y) & \text{otherwise} \end{cases}$	

13.12.5. Cost of Removing Irrigation Infrastructure (Irrigated to Dryland)

Conversely, when a cell's land use changes from irrigated to dryland, a cost is incurred for removing the existing irrigation infrastructure. This removal cost is added to the water license cost matrix as part of the water delta accounting.

The removal cost for each cell r is calculated using:

$\mathbf{RemIrrInfr}_r = \text{Cost}_{\text{RemIrrInfr}}(y) \times ICM(y) \times \mathbf{RA}_r$	Equation 270

where,

- $\text{Cost}_{\text{RemIrrInfr}}$: Represents the cost of removing irrigation infrastructure, set to $\text{Cost}_{\text{EstIrrInfr}} = 5000\ \$/ha$ in LUTO 2.0 model.
- $ICM(y)$: Stands for the Inflation/Cost Multiplier in year y, used to adjust irrigation-related costs for economic changes over time.
- $\mathbf{RA}_r$: The real area of cell r, used to convert costs from per hectare to per cell (see Figure 5)

The computed cost of removing irrigation infrastructure is illustrated in Figure 436.

To update the water license cost matrix for irrigation transitions ($\mathbf{BLuLmM}_{1,r,\ell} = \text{True}$) is:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \mathcal{L}$	Equation 271
$\mathbf{WLC}_{0,r,\ell}(y) = \begin{cases} \mathbf{WLC}_{0,r,\ell}(y) + \mathbf{RemIrrInfr}_r & \text{If} \quad \mathbf{BLuLmM}_{1,r,\ell} = \text{True} \\ \mathbf{WLC}_{0,r,\ell}(y) & \text{otherwise} \end{cases}$	

13.12.6. Updated Water License Cost

After computing the following components:

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- $\mathbf{WLC}_{mr\ell}(y)$ — the initial water license cost matrix (Equation 267),
- $\mathbf{WLC}_{1,r,\ell}(y)$ — the cost adjustment for dryland to irrigated transitions (Equation 269),
- $\mathbf{WLC}_{0,r,\ell}(y)$ — the cost adjustment for irrigated to dryland transitions (Equation 271),

the updated water license cost matrix $\mathbf{WLC}_{mr\ell}(y)$ must be finalized by selecting the appropriate value based on the land management condition of each cell. This is done using the Boolean land-use and land management matrix:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 272
$\mathbf{WLC}_{mr\ell}(y) = \begin{cases} \mathbf{WLC}_{0,r,\ell}(y) & \text{If} \quad \mathbf{BLuLmM}_{1,r,\ell} = \text{True} \\ \mathbf{WLC}_{1,r,\ell}(y) & \text{If} \quad \mathbf{BLuLmM}_{0,r,\ell} = \text{True} \end{cases}$	

This ensures that the final $\mathbf{WLC}_{mr\ell}(y)$ reflects the correct water licensing cost adjustments for each cell, depending on whether irrigation infrastructure is being established or removed.

13.13. Amortization of Water License Costs

To convert total water license costs into equivalent annual payments, the following amortization formula is used:

$\mathbf{WLC}_{begin}(y) = \dfrac{\mathbf{WLC}_{mr\ell}(y) \times DR \times (1+DR)^{NP-1}}{(1+DR)^{NP} - 1}$	Equation 273

Here,

- $\mathbf{WLC}_{mr\ell}$: Total water licence cost (Equation 272)
- $DR = 0.07$: Discount rate per period (LUTO 2.0 considered the value of 7% or 0.07)
- $NP = 30$: Number of payment periods (LUTO 2.0 considered the value of 30 years)

This equation represents a tensor of equivalent annual payments—that is, the amortized value of the water license cost$\mathbf{WLC}_{mr\ell}(y)$—calculated over a 30-year period at a 7% discount rate, under the assumption that payments are made at the beginning of each period.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	
$\mathbf{WLC}_{mr\ell}(y) = \begin{cases} -1 \times \mathbf{WLC}_{begin}(y) & \text{If } AmUpCost = \text{True} \\ \mathbf{WLC}_{begin}(y) & \text{If } AmUpCost = \text{False} \end{cases}$	Equation 274

To update the value of $\mathbf{WLC}_{mr\ell}(y)$, which was initially computed using Equation 272, the binary flag $AmUpCost$ (Amortize Upfront Costs) must be taken into account.

According to Equation 274:

- If $AmUpCost =$ True, the updated $\mathbf{WLC}_{mr\ell}(y)$ represents the negative annualized cash flow, reflecting the amortized cost over time.
- If $AmUpCost =$ False, the value of $\mathbf{WLC}_{mr\ell}(y)$ remains equal to the initial, non-amortized cost.

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By default, the LUTO 2.0 model assumes $AmUpCost = \text{False}$, meaning that the model returns the full upfront water license cost without amortization unless specified otherwise.

13.14. Update Water Licence Cost with Exclusion Matrices

In cases where a cell r retains the same land management class m_r, the water license cost should be zero. To ensure this, the water license cost matrix $\mathbf{WLC}_{mr\ell}(y)$ must be updated using the exclusion matrix $\mathbf{XCM}_{mr\ell}$ (as defined in Equation 244).

Additionally, for cells that are not assigned to agricultural land use (i.e., $\ell \in \{1, \dots, 28\}$), the transition cost is controlled by the negated Boolean Land-Use and Land Management Matrix $\mathbf{BLuLmM}^{\text{NOT}}_{mr\ell}$, defined in Equation 236.

Since all three matrices—$\mathbf{WLC}_{mr\ell}(y)$, $\mathbf{XCM}_{mr\ell}(y)$, and $\mathbf{BLuLmM}^{\text{NOT}}_{mr\ell}(y)$—share the same dimensions, their values can be updated through element-wise multiplication:

$$\mathbf{WLC}_{mr\ell}(y) = \mathbf{WLC}_{mr\ell}(y) \times \mathbf{XCM}_{mr\ell}(y) \times \mathbf{BLuLmM}^{\text{NOT}}_{mr\ell}(y)$$	Equation 275

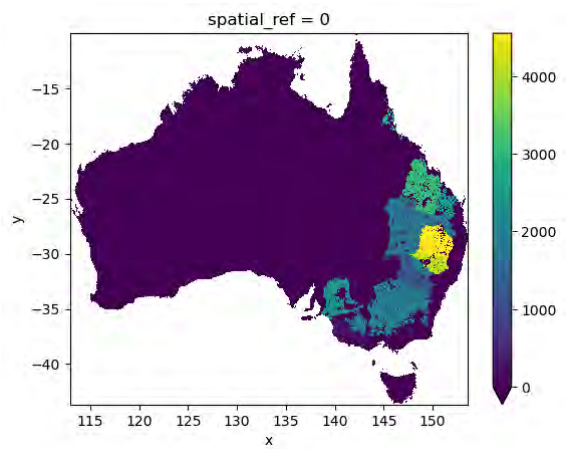

Figure 433 Water Licence Price

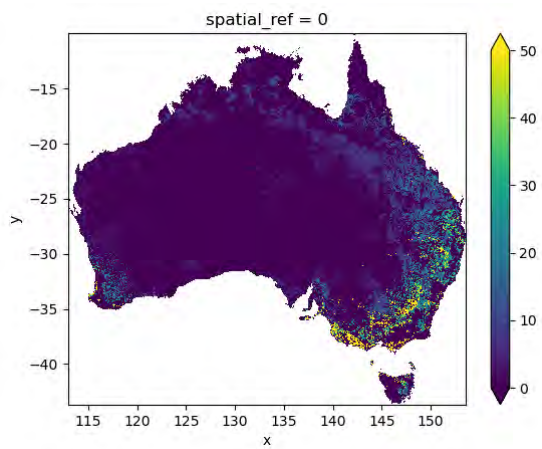

Figure 434 The summation of total water requirements of current land-use and land management

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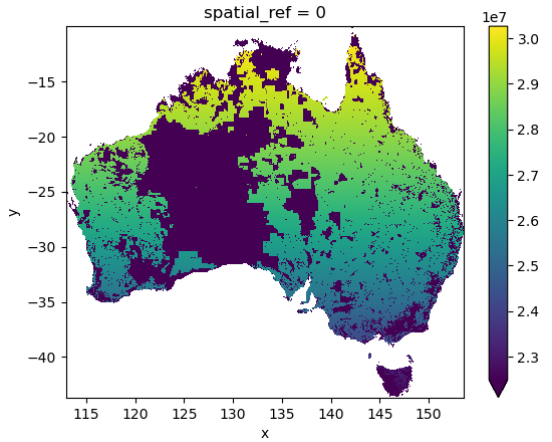

Figure 435 Cost of establishing irrigation infrastructure

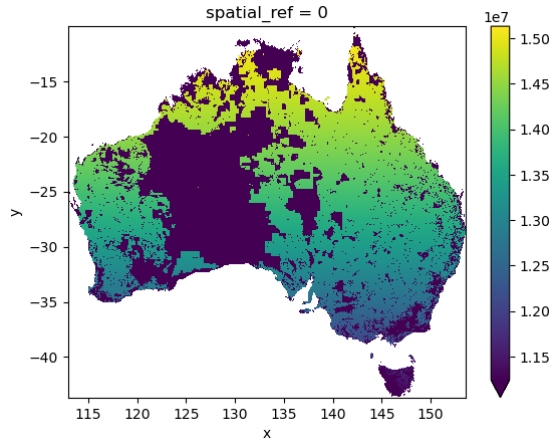

Figure 436 Cost of removing irrigation infrastructure

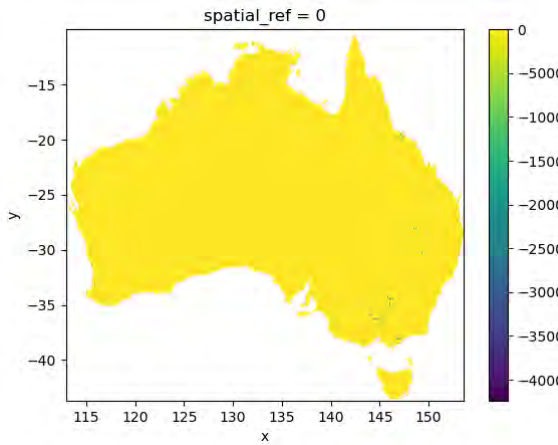

Figure 437 Net water requirements calculated as the difference in water requirements between current land-use and winter cereals under dryland management system

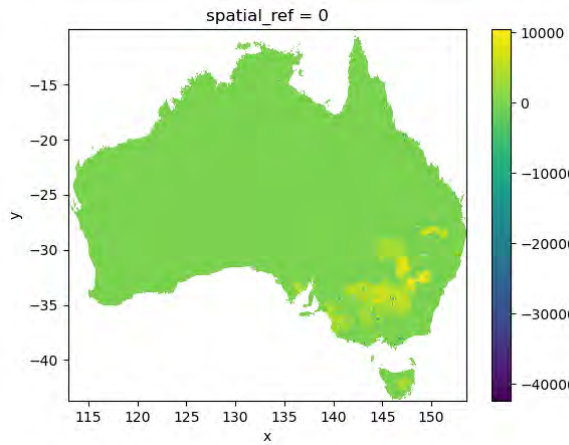

Figure 438 Net water requirements calculated as the difference in water requirements between current land-use and winter cereals under irrigation land management system

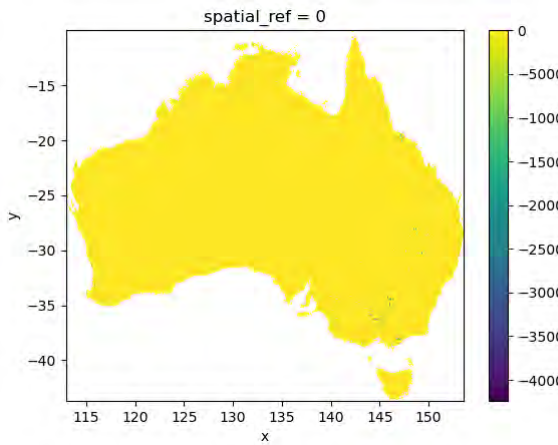

Figure 439 Net water requirements calculated as the difference in water requirements between current land-use and summer cereals under dryland management system

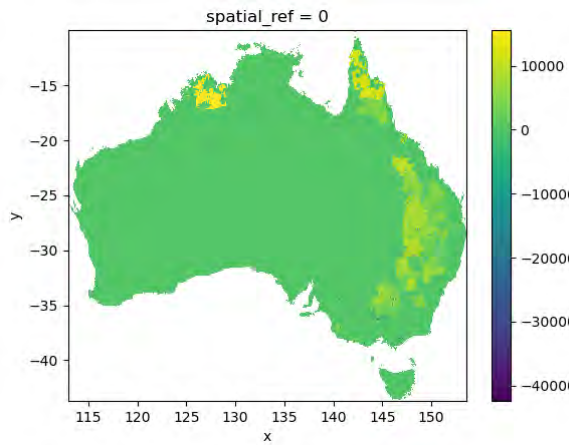

Figure 440 Net water requirements calculated as the difference in water requirements between current land-use and summer cereals under irrigation land management system

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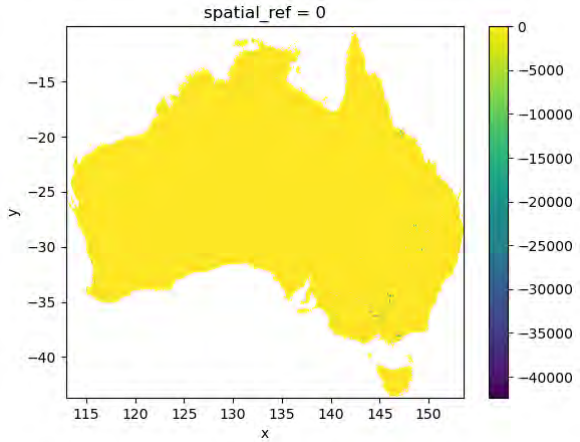

Figure 441 Net water requirements calculated as the difference in water requirements between current land-use and hay under dryland management system

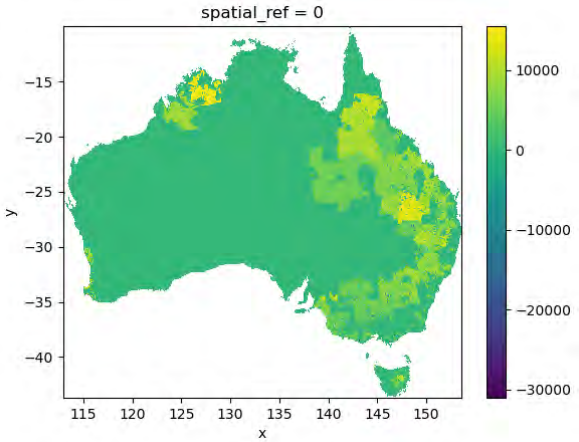

Figure 442 Net water requirements calculated as the difference in water requirements between current land-use and hay under irrigation land management system

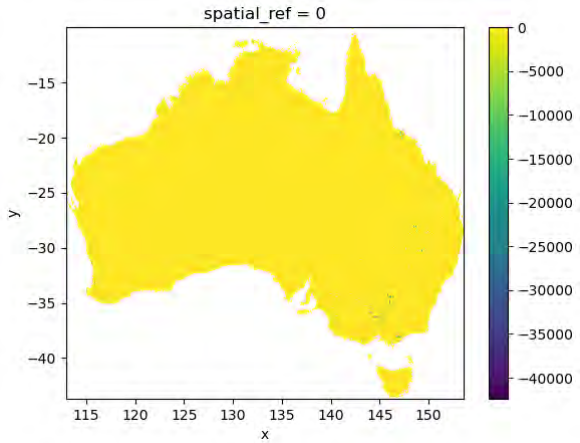

Figure 443 Net water requirements calculated as the difference in water requirements between current land-use and grapes under dryland management system

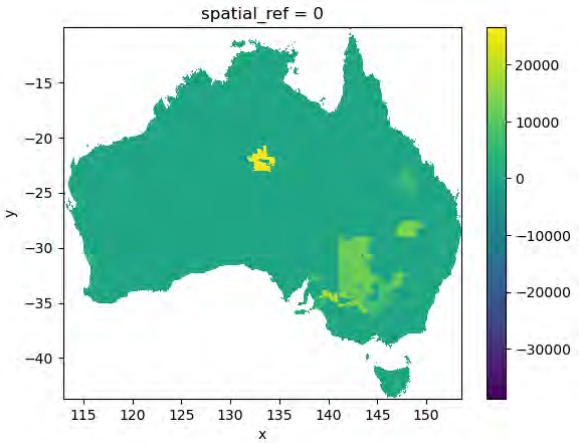

Figure 444 Net water requirements calculated as the difference in water requirements between current land-use and grapes under irrigation land management system

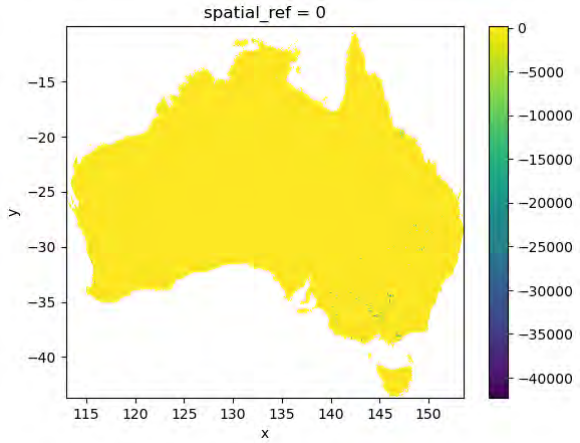

Figure 445 Net water requirements calculated as the difference in water requirements between current land-use and beef-modified land under dryland management system

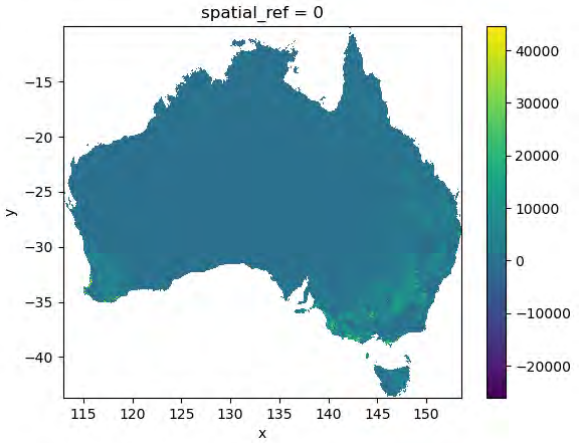

Figure 446 Net water requirements calculated as the difference in water requirements between current land-use and beef-modified land under irrigation land management system

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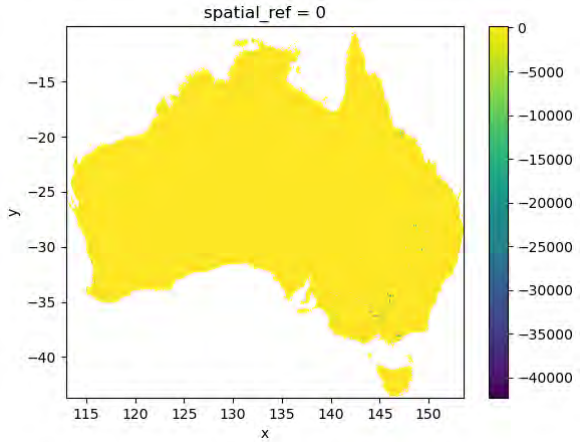

Figure 447 Net water requirements calculated as the difference in water requirements between current land-use and sheep-modified land under dryland management system

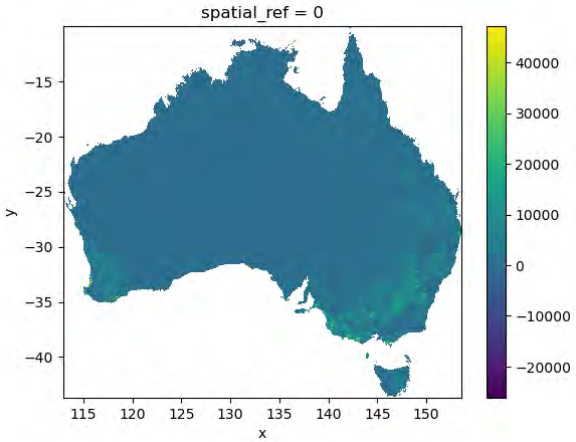

Figure 448 Net water requirements calculated as the difference in water requirements between current land-use and sheep-modified land under irrigation land management system

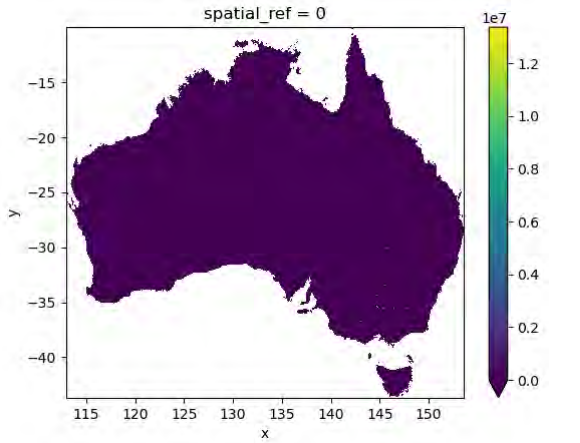

Figure 449 Annualised water licence costs for cells converted from land use in 2050 (Figure 393) to winter cereals under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 395).

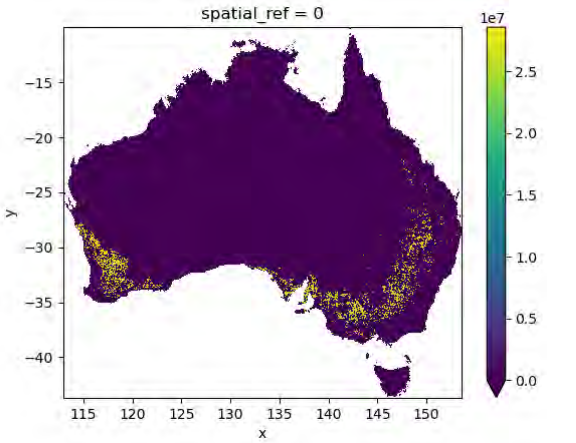

Figure 450 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to winter cereals under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 396).

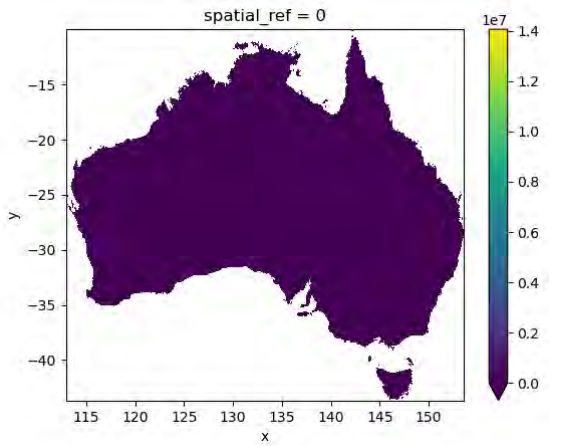

Figure 451 Annualised water licence costs for cells converted from land use in 2050 (Figure 393) to

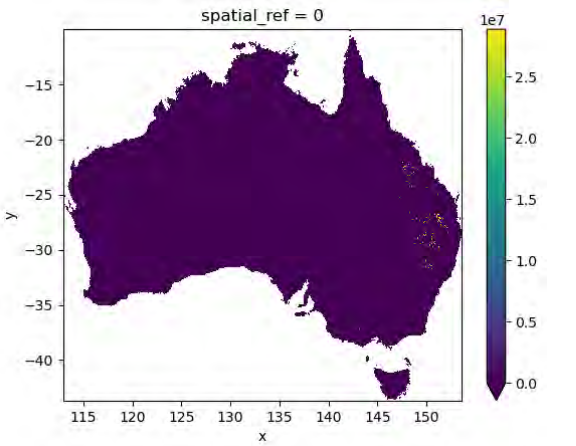

Figure 452 Annualised non-irrigation-related transition costs for cells converted from land use in

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summer cereals under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 397).	2050 (Figure 393) to summer cereals under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 398).
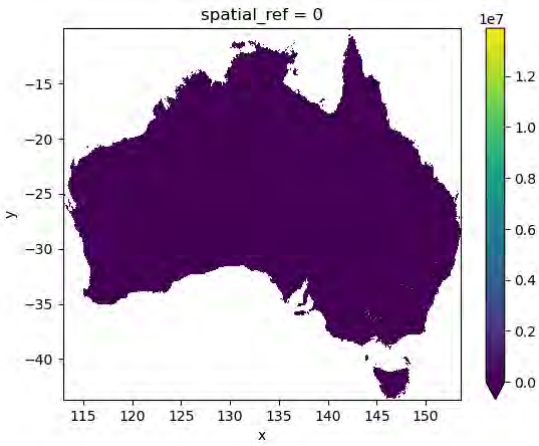	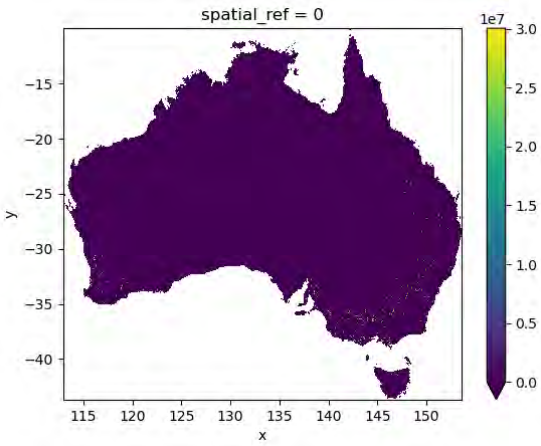
Figure 453 Annualised water licence costs for cells converted from land use in 2050 (Figure 393) to hay under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 399).	Figure 454 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to hay under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 400).
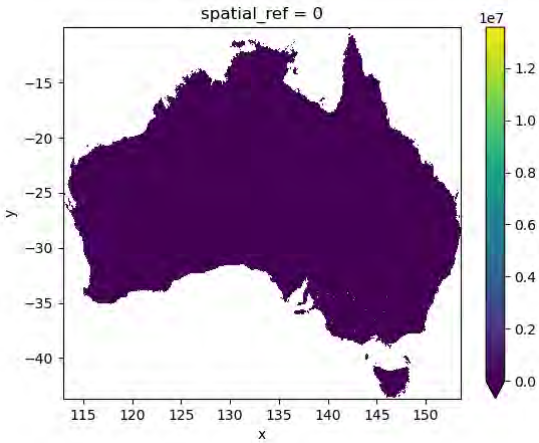	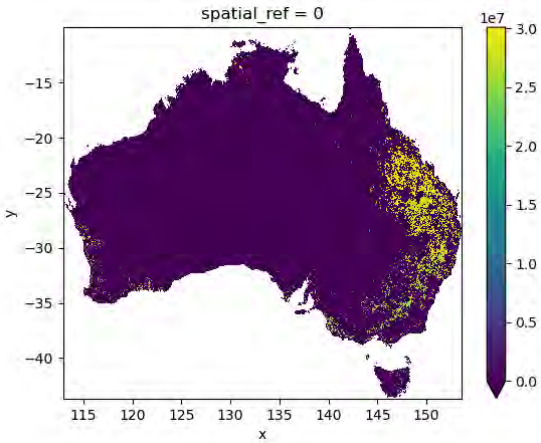
Figure 455 Annualised water licence costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 403).	Figure 456 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 404).

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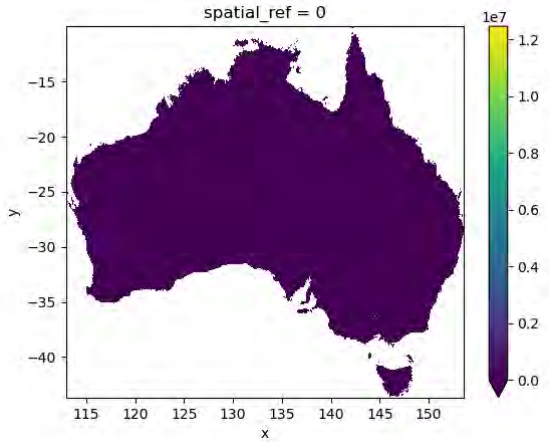

Figure 457 Annualised water licence costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under dryland management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix ((Figure 405).

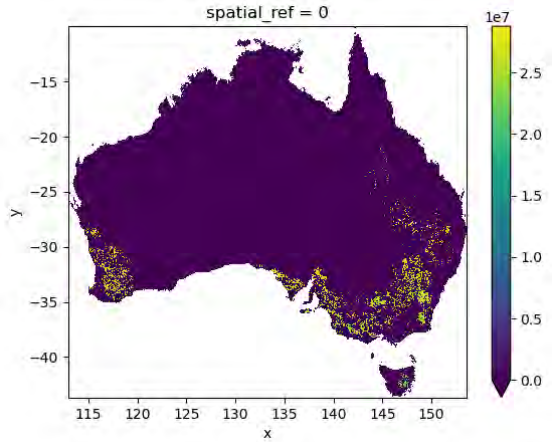

Figure 458 Annualised non-irrigation-related transition costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under irrigation land management, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 406).

The flowchart illustrating the initialization and update process for the establishment cost of non-irrigation lands is presented in Figure 459. (Should be updated).

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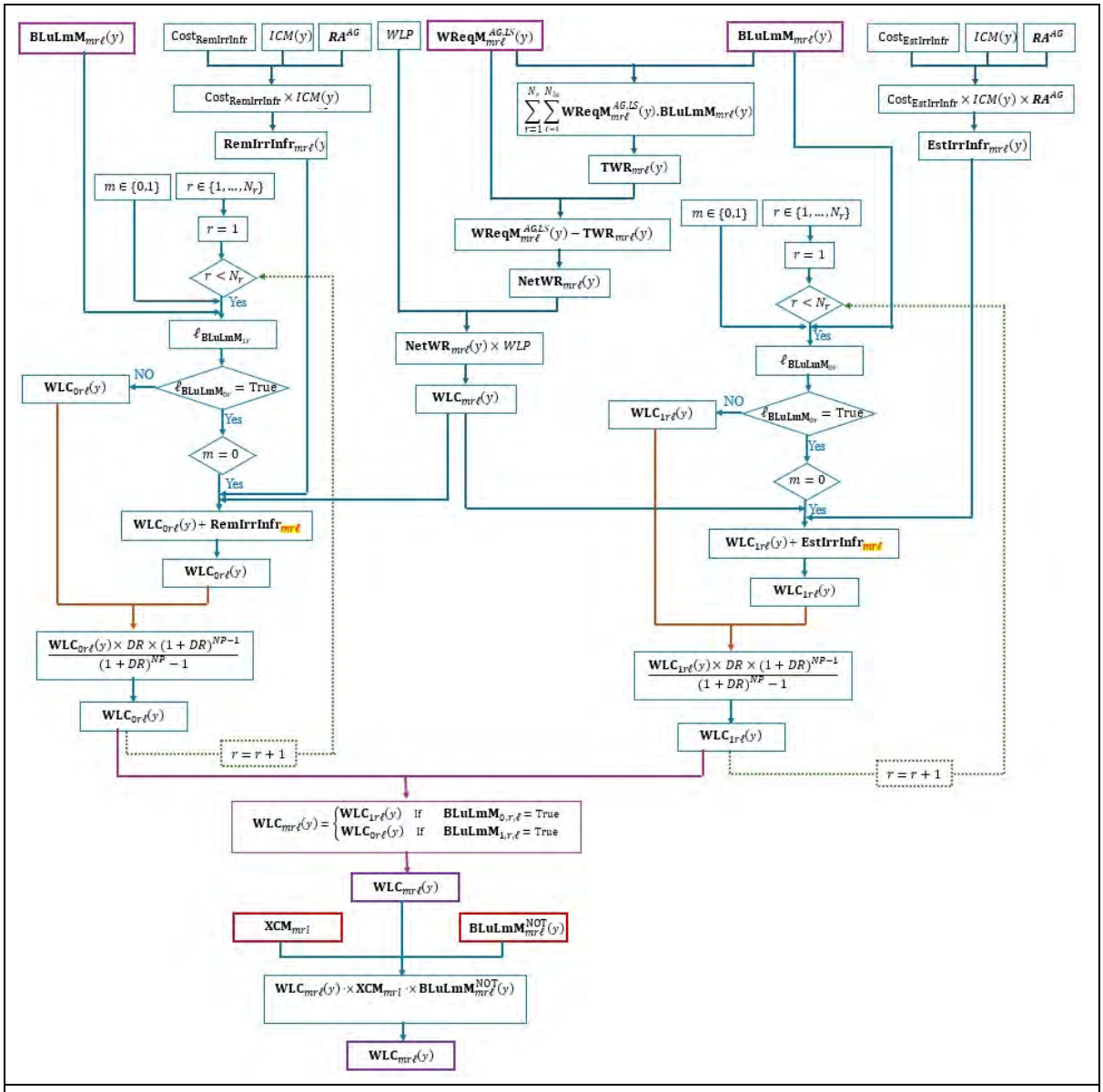

Figure 459 Water license cost for all agricultural land use and land management systems (Should be updated).

13.15. Carbon Costs of Transitioning Natural Land to Modified Land

As defined in Equation 93, $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$ represents the carbon emission penalty incurred when land transitions from a natural land use class ℓ_i to a modified land use class ℓ_j. The greenhouse gas emission cost associated with this transition, denoted as $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y)$, is calculated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 276
$\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y) = \mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}(y) \times CO2Price(y)$	

where,

- $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$ is the carbon emission penalty for the transition from natural land use class ℓ_i to modified land use class ℓ_j (see Equation 93)

- $CO2Price(y)$ is the market price of CO_2 in year y, measured in AUD per Tonne of CO_2 (refer to Figure 349)

13.16. Update the Value of $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}$ Based on Amortize Upfront Costs

To distribute the emission cost over time, the amortized annual value is computed using:

$$\mathbf{GHGEP}_{begin}^{TNL2ML}(y) = \frac{\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y) \times DR \times (1+DR)^{NP-1}}{(1+DR)^{NP}-1}$$	Equation 277

Here,

- $DR = 0.07$: Discount rate per year (LUTO 2.0 considered the value of 7% or 0.07)
- $NP = 30$: Amortization period (LUTO 2.0 considered the value of 30 years)
- $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y)$: Greenhouse gas emission cost associated with the transition of land-use (ℓ) cell r from natural land to modified land (Equation 276)

The following equation represents a tensor of the equivalent annual payment (i.e., amortized value) of the greenhouse gas emission cost $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y)$, calculated over 30 years at a 7% discount rate, assuming payments are made at the beginning of each period:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	
$$\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y) = \begin{cases} -1 \times \mathbf{GHGEP}_{begin}^{TNL2ML}(y) & \text{If } AmUpCost = \text{True} \\ \mathbf{GHGEP}_{begin}^{TNL2ML}(y) & \text{If } AmUpCost = \text{False} \end{cases}$$	Equation 278

To update the value of $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y)$, initially computed using Equation 276, the binary parameter Amortize Upfront Costs ($AmUpCost$) must be taken into account.

According to Equation 278,

- If the initial value of $AmUpCost$ is True ($AmUpCost = \text{True}$), the updated $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y)$ reflects the negative annualized cash flow, representing the amortized greenhouse gas emission cost over the investment horizon.
- If the initial value of $AmUpCost$ is False ($AmUpCost = \text{False}$), the updated $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y)$ remains equal to the initial unamortized cost, applied in full.

As default, the LUTO 2.0 model sets $AmUpCost = \text{False}$; thereby applying the full emission cost $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y)$ without any amortization.

13.17. Update $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}$ with Exclude Matrices

The greenhouse gas emission cost associated with the transition of land-use (ℓ) cell r from natural land to modified land, denoted as $\mathbf{GHGEP}_{mr\ell}^{TNL2ML}(y)$, should be updated to reflect only eligible transitions. Specifically, if the land management type m_r of a given cell remains unchanged, the emission cost is considered zero.

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To account for this, the exclusion matrix $\mathbf{XCM}_{mr\ell}$ (see Equation 244) is used to exclude unchanged or restricted transitions. Additionally, the Boolean matrix $\mathbf{BLuLmM}^{\mathrm{NOT}}_{mr\ell}$ (from Equation 236) is used to eliminate non-agricultural land-use transitions.

$\mathbf{GHGEP}^{TNL2ML}_{mr\ell}$, $\mathbf{XCM}_{mr\ell}$, and $\mathbf{BLuLmM}^{\mathrm{NOT}}_{mr\ell}$ are tensors of the same size, they can be element-wise multiplied to obtain the final updated greenhouse gas emission cost:

$\mathbf{GHGEP}^{TNL2ML}_{mr\ell}(y) = \mathbf{GHGEP}^{TNL2ML}_{mr\ell}(y) \times \mathbf{XCM}_{mr\ell} \times \mathbf{BLuLmM}^{\mathrm{NOT}}_{mr\ell}(y)$	Equation 279

The flowchart illustrating the initialization and update of $\mathbf{GHGEP}^{TNL2ML}_{mr\ell}$ is provided in Figure 460. (Should be updated).

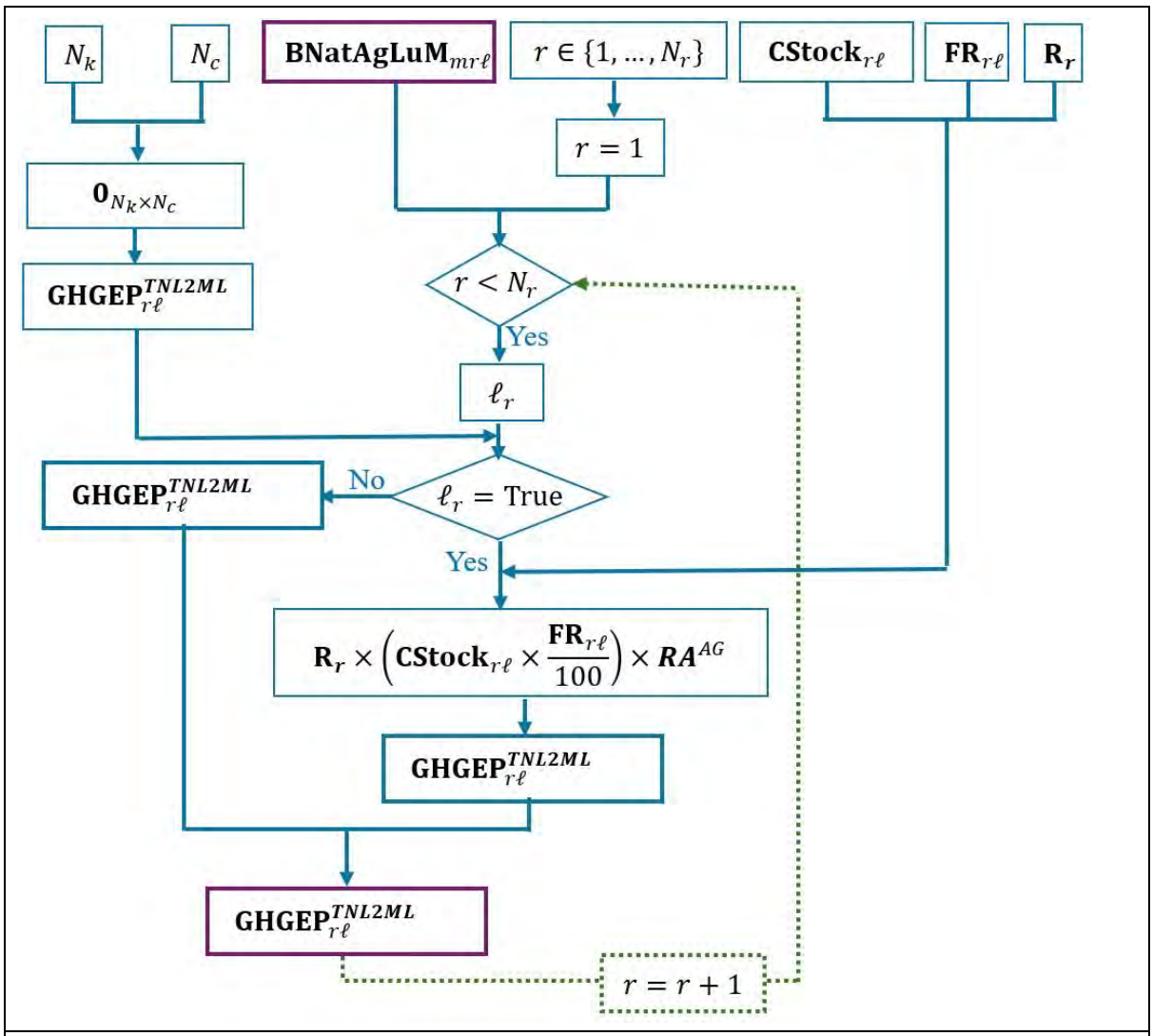

Figure 460 Carbon Costs of Transitioning Natural Land to Modified Land

13.18. The total costs

In the LUTO 2.0 model, the total costs associated with land-use transitions can be represented in two distinct ways, depending on the model configuration: either as separate cost components or as a unified cumulative value.

When costs are returned separately, each component is retained as an individual matrix:

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- Establishment cost $\mathbf{EstCost}^{AG}_{mr\ell}(y)$
- Water license cost $\mathbf{WLC}_{mr\ell}(y)$
- Greenhouse gas (GHG) emissions cost $\mathbf{GHGEP}^{TNL2ML}_{mr\ell}$

Alternatively, when the model is configured to return a single aggregated value, these components are summed to calculate the total transition cost matrix $\mathbf{TotTranMatC}^{AG}_{mr\ell}$, representing the cumulative financial impact of a land-use transition:

$\mathbf{TotTranMatC}^{AG}_{mr\ell}(y) = \mathbf{EstCost}^{AG}_{mr\ell}(y) + \mathbf{WLC}_{mr\ell}(y) + \mathbf{GHGEP}^{TNL2ML}_{mr\ell}(y)$	Equation 280

The computed $\mathbf{TotTranMatC}^{AG}_{mr\ell}(y)$ values for various land-use transitions are visualized in Figure 461-Figure 470.

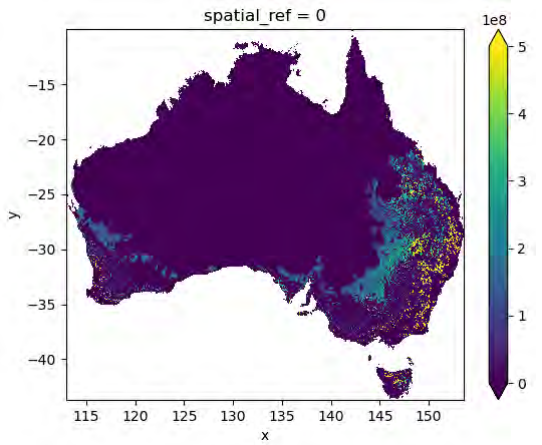


Figure 461 Total annualised costs for cells converted from land use in 2050 (Figure 393) to winter cereals under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 397).

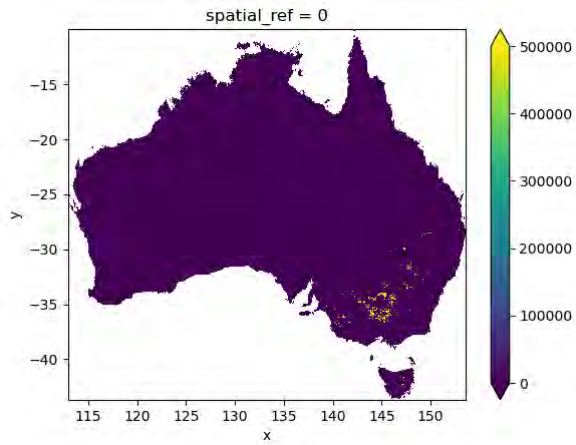
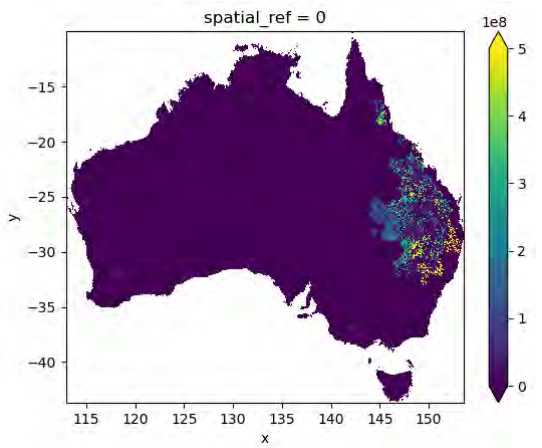


Figure 462 Total annualised costs for cells converted from land use in 2050 (Figure 393) to winter cereals under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 398)



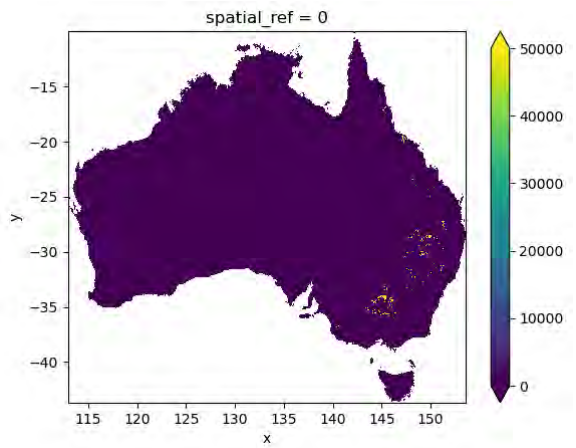


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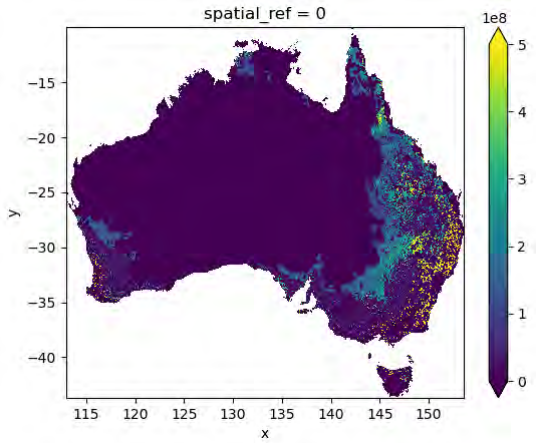
Figure 463 Total annualised costs for cells converted from land use in 2050 (Figure 393) to summer cereals under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 399).

Figure 464 Total annualised costs for cells converted from land use in 2050 (Figure 393) to summer cereals under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 400).



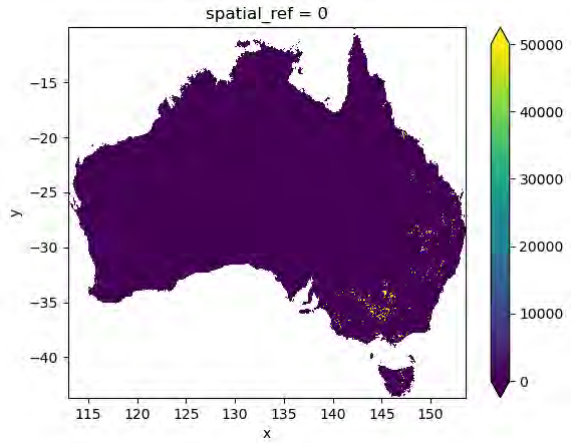
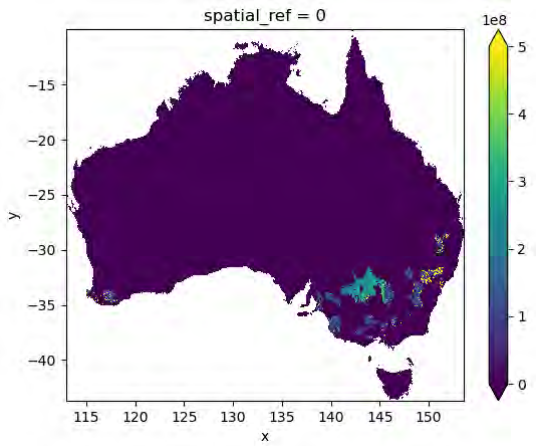


Figure 465 Total annualised costs for cells converted from land use in 2050 (Figure 393) to hay under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 401).

Figure 466 Total annualised costs for cells converted from land use in 2050 (Figure 393) to hay under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 402).



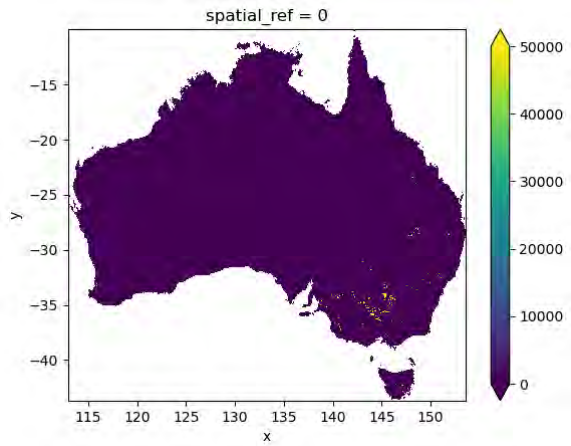


Figure 467 Total annualised costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 403).

Figure 468 Total annualised costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 404).

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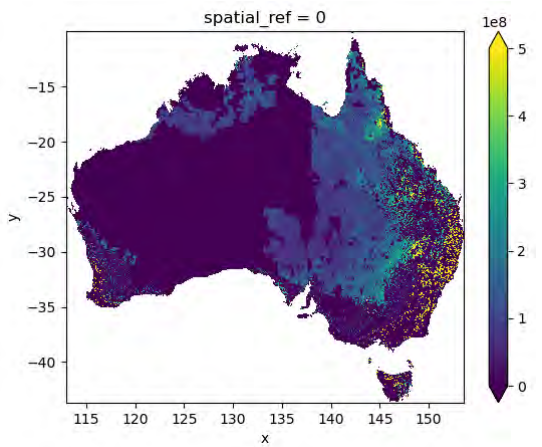

Figure 469 Total annualised costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 405).

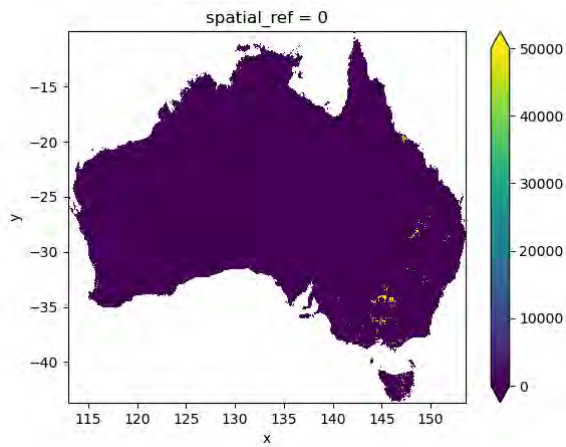

Figure 470 Total annualised costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under dry land management system, adjusted to AUD per cell, with costs set to 0 for unchanged land uses using the Boolean exclusion matrix (Figure 406).

The flowchart of initializing and updating the establishment cost of non-irrigation lands is illustrated in Figure 471. It should be updated

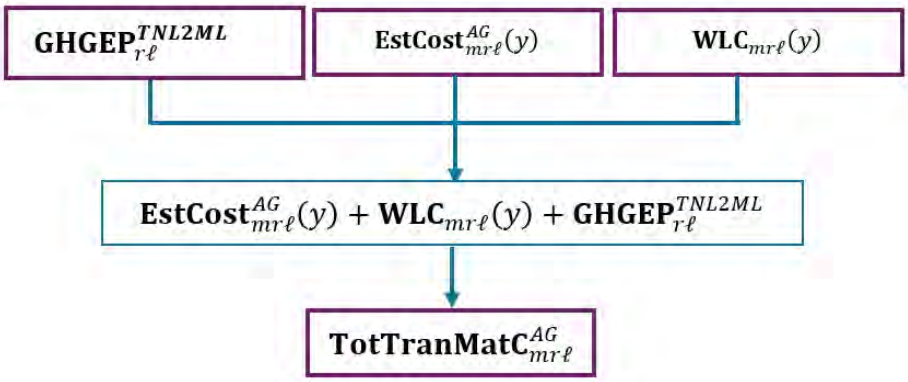

Figure 471 The total costs associated with land-use transitions(It should be updated)

14. Impacts of Agricultural Management Practices on the Transition Costs of Agricultural Land uses

In ecological modeling, it is essential to evaluate the potential effects of various land management practices on the transition costs associated with agricultural land uses. The list of agricultural management practices applicable to different land use types is outlined in Equation 22.

In the LUTO 2.0 model, it is assumed that these agricultural management practices do not influence the transition costs of agricultural land uses. As a result, the following transition cost matrices are defined as zero matrices:

- $\mathbf{TranMatC}_{mr\ell}^{\text{AspTaxifor}}$
- $\mathbf{TranMatC}_{mr\ell}^{\text{PrecAgric}}$
- $\mathbf{TranMatC}_{mr\ell}^{\text{EcolGrazing}}$

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- $\mathbf{TranMatC}_{mr\ell}^{\text{SavBurn}}$
- $\mathbf{TranMatC}_{mr\ell}^{\text{AgTech EI}}$

As defined in Equation 281-Equation 285.

14.1. Asparagopsis Taxiformis Effects on Transition Cost

Let $\mathbf{TranMatC}_{mr\ell}^{\text{AspTaxifor}}$ denote the updated transition cost matrix incorporating the integration of Asparagopsis taxiformis into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Asparagopsis taxiformis})$	Equation 281
$\mathbf{TranMatC}_{mr\ell}^{\text{AspTaxifor}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AspTaxifor}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (see Equation 21); hence $N_k = 2$.
- $N_{lu}^{\text{AspTaxifor}} = 6$, since Asparagopsis taxiformis affects beef, sheep, and dairy production across both natural and modified land (see Equation 25).

14.2. Precision Agriculture Effects on Transition Cost

Let $\mathbf{TranMatC}_{mr\ell}^{\text{PrecAgric}}$ denote the updated transition cost matrix resulting from the integration of Precision Agriculture into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Precision Agriculture})$	Equation 282
$\mathbf{TranMatC}_{mr\ell}^{\text{PrecAgric}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{PrecAgric}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); so $N_k = 2$.
- $N_{lu}^{\text{PrecAgric}} = 20$, since Precision Agriculture affects 20 land use classes (see Equation 27).

14.3. Ecological Grazing Effects on Transition Cost

Let $\mathbf{TranMatC}_{mr\ell}^{\text{EcolGrazing}}$ be the updated transition cost matrix by integrating Ecological Grazing into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Ecological Grazing})$	Equation 283
$\mathbf{TranMatC}_{mr\ell}^{\text{EcolGrazing}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{EcolGrazing}}\right)}$	

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where,

- N_c is the number of cells in land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); so $N_k = 2$.
- $N_{lu}^{\text{EcolGrazing}} = 3$, because Ecological Grazing practice affects beef, sheep, and dairy production on modified land (Equation 29).

14.4. Savanna Burning Effects on Transition Cost

Let $\mathbf{TranMatC}_{mr\ell}^{\text{SavBurn}}$ denote the updated transition cost matrix resulting from the implementation of Savanna Burning within agricultural land management.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{Savanna Burning})$	Equation 284
$\mathbf{TranMatC}_{mr\ell}^{\text{SavBurn}} = 0_{(N_k \times N_c \times N_{lu}^{\text{SavBurn}})}$	

where,

- N_c is the number of cells in the base land-use map $\mathbf{LUM}^{\text{BYear}}$,
- N_k is the number of agricultural management practices $m \in \mathcal{M}$ (Equation 21); hence $N_k = 2$,
- $N_{lu}^{\text{SavBurn}} = 4$, since Savana Burning practice affects beef, sheep, and dairy production across natural land as well as unallocated natural land (Equation 31).

14.5. AgTech EI Effects on Transition Cost

Let $\mathbf{TranMatC}_{mr\ell}^{\text{AgTech EI}}$ represent the updated transition cost matrix after integrating AgTech EI into agricultural land management strategies.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \phi(\text{AgTech EI})$	Equation 285
$\mathbf{TranMatC}_{mr\ell}^{\text{AgTech EI}} = 0_{\left(N_k \times N_c \times N_{lu}^{\text{AgTech EI}}\right)}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$,
- $N_k = 2$ is the number of agricultural management practices $m \in \mathcal{M}$ (see Equation 21),
- $N_{lu}^{\text{AgTech EI}} = 20$, since AgTech EI practice affects 20 land use classes (see Equation 33).

14.6. Computation of Lower Bound Agricultural Management Matrices for Base Year Optimization

This section computes the lower bound matrices $\mathbf{LB}_{mr\ell}^{\text{AGMP}}$ for agricultural management practices during the base year optimization process. It is initialize as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 286

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$\mathbf{LB}_{mr\ell}^{\text{AGMP}} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the base year land-use map $\mathbf{LUM}^{\text{BYear}}$,
- $N_k = 2$ is the number of agricultural management practices $m \in \mathcal{M}$,
- $N_{lu} = 28$ is the number of agricultural land-use categories; hence.

Case 1:

If the base year matches the calibration year **or** the base year is not listed in the non-agricultural data variables, the lower bound matrix remains initialized as a zero tensor per Equation 286.

Case 2:

If the base year different from the calibration year, the lower bound matrix for each $\ell \in \phi(\text{Agricultural Practice})$ (Equation 35) is computed based on decision variables:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(\text{Agricultural Practice})$	Equation 287
$\mathbf{LB}_{mr\ell}^{\text{AGMP}} = \frac{\lfloor \mathbf{D}_{mr\ell}^{AgManag}(y) \times 10^d \rfloor}{10^d}$	

where,

agricultural management decision variables

- $\mathbf{D}_{mr\ell}^{AgManag}(y)$, $\ell \in \mathcal{K}$ is the agricultural management decision variable associated with each practice (see Equation 22)
- d is the number of decimal places used for rounding as defined by the model setting ($d = \mathbf{6}$)
- $\lfloor . \rfloor$ is the floor function applied element-wise to the matrix

14.7. Agricultural Management Practices Effects on the Transition Cost of Agricultural Land Uses

Define the variable $\mathbf{TranMatC}^{\text{AGMP}}$, which represents a dictionary of agricultural management practice effects on transition costs, mapping each key k to the corresponding value $\mathbf{TranMatC}_{mr\ell}^{k}$, as:

$\mathbf{TranMatC}^{\text{AGMP}} = \left\{ k \rightarrowtail \mathbf{TranMatC}_{mr\ell}^{k}(y) \mid r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}, \mathbf{TranMatC}_{mr\ell}^{k}(y) \in \mathbb{R}^{N_k \times N_c \times N_{lu}^k} \right\}$	Equation 288

where,

- $\mathcal{K}$: The set of agricultural management practices applicable to land-use types (as defined in Equation 22)
- $k \in \mathcal{K}$: A specific agricultural management practice.

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- N_c: Total number of cells in the base year land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_k = 2$: Number of land management types $m \in \mathcal{M}$ (dryland and irrigation) as per Equation 21.
- N_{lu}^k: Number of land use types affected by each agricultural management practices $\mathcal{K}$ (see Equation 24-Equation 32)
- $\mathbb{R}$: Domain of real numbers.
- $\mathbf{TranMatC}_{mr\ell}^k(y)$**:** Transition Cost Matrix by integrating k-th agricultural management practice in year y.

Regarding the agricultural management practices, $\mathcal{K}$ is the set that lists all agricultural management practices applicable to different land use types (as defined in Equation 22). According to Equation 23, a mapping rule ϕ exists, which relates each element from the set of agricultural management practices $\mathcal{K}$ (the domain) to relevant or applicable land uses from the set $\mathcal{L}$ (defined in Equation 1). The specific land uses associated with each agricultural management practice are outlined in Equation 24-Equation 32.

Using this framework, the initialized transition cost dictionary $\mathbf{TranMatC}^{\text{AGMP}}$ (defined in Equation 288) is updated as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists k, k \in \mathcal{K}$	Equation 289
$\mathbf{TranMatC}^{\text{AGMP}}(y) = \begin{cases} k \rightarrowtail \mathbf{TranMatC}_{mr\ell}^{\text{AspTaxifor}}(y) & if \quad k \in \phi(\text{Asparagopsis taxiformis}) \\ k \rightarrowtail \mathbf{TranMatC}_{mr\ell}^{\text{PrecAgric}}(y) & if \quad k \in \phi(\text{Precision Agriculture}) \\ k \rightarrowtail \mathbf{TranMatC}_{mr\ell}^{\text{EcolGrazing}}(y) & if \quad k \in \phi(\text{Ecological Grazing}) \\ k \rightarrowtail \mathbf{TranMatC}_{mr\ell}^{\text{SavBurn}}(y) & if \quad k \in \phi(\text{Savanna Burning}) \\ k \rightarrowtail \mathbf{TranMatC}_{mr\ell}^{\text{AgTech EI}}(y) & if \quad k \in \phi(\text{AgTech EI}) \end{cases}$	

where,

- $\mathcal{K}$: Set of agricultural management practices applicable to different land use types (Equation 22)
- k: Agricultural management practice type.
- $\mathbf{TranMatC}_{mr\ell}^{\text{AspTaxifor}}(y)$: Transition Cost Matrix with Asparagopsis taxiformis integrating into agricultural land management strategies (Equation 281).
- $\mathbf{TranMatC}_{mr\ell}^{\text{PrecAgric}}(y)$: Transition Cost Matrix with Precision agriculture integrating into agricultural land management strategies (Equation 282).
- $\mathbf{TranMatC}_{mr\ell}^{\text{EcolGrazing}}(y)$: Transition Cost Matrix with Ecological Grazing integrating into agricultural land management strategies (Equation 283).
- $\mathbf{TranMatC}_{mr\ell}^{\text{SavBurn}}(y)$: Transition Cost Matrix with Savanna Burning integrating into agricultural land management strategies (Equation 284).
- $\mathbf{TranMatC}_{mr\ell}^{\text{AgTech EI}}(y)$: Transition Cost Matrix with AgTech EI integrating into agricultural land management strategies (Equation 285).
- $\phi(\text{Asparagopsis taxiformis})$ refers to the Asparagopsis taxiformis practice, which primarily affects livestock on natural and modified land (Equation 25).
- $\phi(\text{Precision Agriculture})$ refers to the Precision Agriculture practice, which is primarily applied to cropping, intensive cropping, and horticulture (Equation 27).
- $\phi(\text{Ecological Grazing})$ refers to the Ecological Grazing practice, which is primarily applied to livestock on modified land (Equation 29).
- $\phi(\text{Savanna Burning})$ refers to the Savanna Burning practice, which is primarily related to livestock on natural land, as well as unallocated natural land (Equation 31).

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- $\phi(\text{AgTech EI})$ refers to the AgTech EI practice, which primarily affects cropping, intensive cropping, and horticulture (Equation 33).

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15. Non-Agricultural Land Use Cost

15.1. The Cost of Environmental Plantings

This section computes the cost of environmental plantings is computed for each cell r in the model. This cost accounts for both the annual maintenance cost and the ecosystem service benefit, adjusted by the actual land area allocated to environmental planting. The cost of environmental plantings for each cell ($\mathbf{EPC}_r^{NonAG}(y)$) is calculated as follows:

$\mathbf{EPC}_r^{NonAG}(y) = \left[\left(AMC_{EnvPlanting}^{NonAg} \times MCM(y)\right) - AESB_{EnvPlanting}^{NonAg}\right] \times \mathbf{RA}_r$	Equation 290

where,

- $\mathbf{EPC}_r^{NonAG}(y)$ is the total environmental planting cost for cell r in year y.
- $AMC_{EnvPlanting}^{NonAg}$ is the annual maintenance cost per hectare for environmental plantings. In LUTO 2.0, this is initialized to 100 AUD/ha, $AMC_{EnvPlanting}^{NonAg} = 100$
- $MCM(y)$ is the maintenance cost multiplier for year y.
- $AESB_{EnvPlanting}^{NonAg}$ is the annual ecosystem service benefit per hectare from environmental plantings. This is initialized to 0 in LUTO 2.0., $AESB_{EnvPlanting}^{NonAg} = 0$
- $\mathbf{RA}_r$ is the real area of cell r, as defined in Figure 5.

The computed environmental planting costs for the year 2050 are shown in Figure 473, and the flowchart representing this computation is shown in Figure 472.

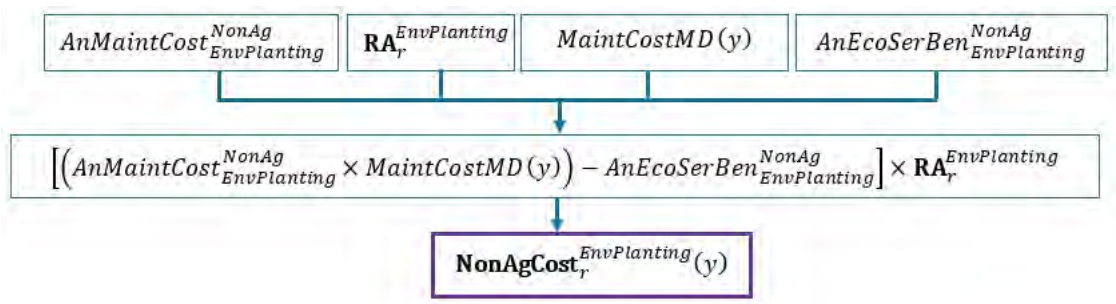

Figure 472 The Cost of environmental plantings Flowchart

15.2. The Cost of riparian plantings

This section outlines the method for calculating the cost of riparian plantings for each cell r in the model $\mathbf{RPC}_r^{NonAG}(y)$. The cost structure mirrors that used for environmental plantings, incorporating both maintenance costs and ecosystem service benefits, and is adjusted by the actual area allocated to riparian planting. The cost for each cell is calculated as:

$\mathbf{RPC}_r^{NonAG}(y) = \left[\left(AMC_{RipPlant}^{NonAg} \times MCM(y)\right) - AESB_{RipPlant}^{NonAg}\right] \times \mathbf{RA}_r$	Equation 291

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where,

- $\mathbf{EPC}_r^{NonAG}(y)$) is the total riparian planting cost for cell r in year y.
- $AMC_{RipPlant}^{NonAg}$ is the annual maintenance cost per hectare for riparian plantings. In LUTO 2.0, this is initialized to **100 AUD/ha**, $AMC_{RipPlant}^{NonAg} = 100$
- $MCM(y)$ is the maintenance cost multiplier for year y.
- $AESB_{RipPlant}^{NonAg}$ is the annual ecosystem service benefit per hectare of riparian plantings. This is initialized to **0** in LUTO 2.0., $AESB_{RipPlant}^{NonAg} = 0$
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed cost of riparian plantings for the year 2050 is shown in Figure 474, and the corresponding computation flowchart is shown in Figure 475.

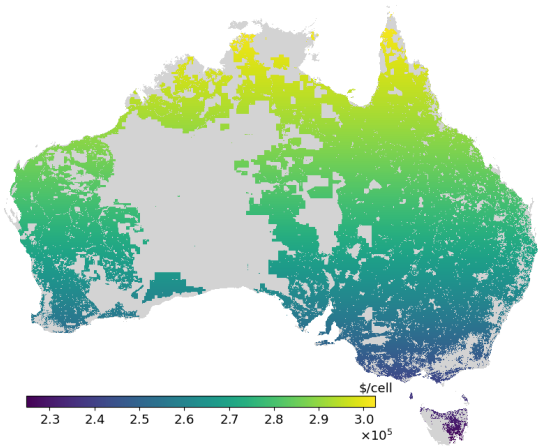

Figure 473 The cost of environmental plantings for year 2050

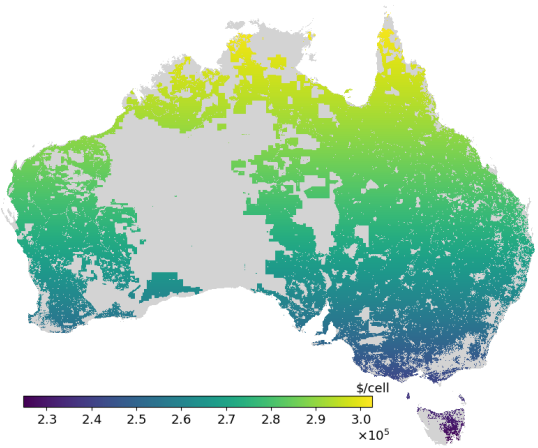

Figure 474 The cost of riparian plantings for year 2050

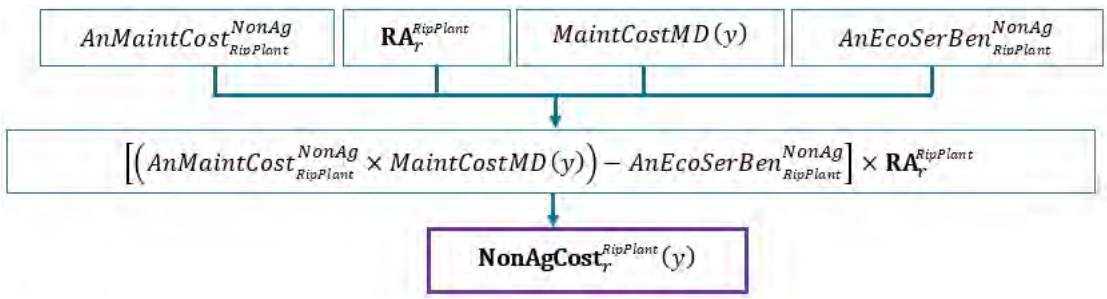

Figure 475 The Cost of riparian plantings Flowchart

15.3. The Cost of Agroforestry plantings (base)

This section describes the computation of costs associated with base agroforestry plantings for each cell r in the model. The calculation incorporates both maintenance costs and ecosystem service benefits, adjusted for the actual area of land allocated to agroforestry. The cost per cell ($\mathbf{BAFPC}_r^{NonAG}(y)$) is determined using the following equation:

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$\mathbf{BAFPC}_r^{NonAG}(y) = \left[\left(AMC_{AgFor}^{NonAg} \times MCM(y)\right) - AESB_{AgFor}^{NonAg}\right] \times \mathbf{RA}_r$	Equation 292

where,

- $\mathbf{BAFPC}_r^{NonAG}(y)$ is the total cost of base agroforestry plantings for cell r in year y.
- AMC_{AgFor}^{NonAg} is the annual maintenance cost per hectare for base agroforestry plantings, initialized to **100 AUD/ha** in LUTO 2.0., $AMC_{AgFor}^{NonAg} = 100$.
- $MCM(y)$ is the maintenance cost multiplier for year y.
- $AESB_{AgFor}^{NonAg}$ is the annual ecosystem service benefit per hectare of agroforestry plantings (base), initialized to **0** in LUTO 2.0., $AESB_{AgFor}^{NonAg} = 0$.
- $\mathbf{RA}_r$ is the real area of cell r, as defined in Figure 5.

The computed cost of base agroforestry plantings for year 2050 is shown in Figure 477, with the corresponding flowchart illustrated in Figure 476.

15.4. The Cost of Sheep-Agroforestry

This section calculates the cost of sheep-agroforestry plantings for each cell r by combining the base agroforestry planting costs with the livestock production costs associated with sheep farming. The cost is adjusted based on the portion of land dedicated to agroforestry within each cell. The equation used is:

$\mathbf{AFPC}_r^{Sheep,NonAG}(y) = \left(\mathbf{BAFPC}_r^{NonAG}(y) \times \mathbf{XCM}_r^{AgFor}\right) + \left[\mathbf{Cost}_r^{Sheep}(y) \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right]$	Equation 293

where,

- $\mathbf{AFPC}_r^{Sheep,NonAG}(y)$: Cost of sheep-agroforestry plantings for cell r in year y.
- $\mathbf{BAFPC}_r^{NonAG}(y)$: Base agroforestry planting cost (Equation 292 and Figure 477)
- $\mathbf{Cost}_r^{Sheep}(y)$: Sheep farming cost under modified land with dryland management (Equation 294, Figure 478).
- $\mathbf{XCM}_r^{AgFor}$: Exclusion matrix representing the proportion of land used for agroforestry (Equation 295 and Figure 479)

The computed cost of sheep-agroforestry plantings $\mathbf{AFPC}_r^{Sheep,NonAG}$ for year 2050 is illustrated in Figure 481.

For each cell r under dryland management ($m = 0$), the cost of sheep production is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}$	Equation 294
$\mathbf{Cost}_r^{Sheep}(y) = \begin{cases} \mathbf{TLPC}_{mr\ell}^{LS}(y) & \text{If} \quad m = 0 \wedge \ell = \text{Sheep} - \text{modified land} \\ 0 & \text{Otherwise} \end{cases}$	

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where,

- $\mathbf{TLPC}_{mr\ell}^{LS}(y)$: Total livestock production cost for sheep in year y (Equation 53)
- $\mathcal{L}_{\text{Sheep, modified}}$ is a set that contains $\text{Sheep} - \text{modified land}$ (Equation 6)

As LUTO 2.0 allows agroforestry cells to support both sheep and beef farming, the exclusion matrix $\mathbf{XCM}_r^{AgFor}(y)$ identifies cells assigned to either agroforestry class:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}$	Equation 295
$\mathbf{XCM}_r^{AgFor}(y) = \begin{cases} \mathbf{XCM}_{mr\ell}(y) & \text{If} \quad m = 0 \wedge \ell = \text{Sheep Agroforestry} \\ \mathbf{XCM}_{mr\ell}(y) & \text{If} \quad m = 0 \wedge \ell = \text{Beef Agroforestry} \\ 0 & \text{otherwise} \end{cases}$	

where,

- $\mathbf{XCM}_{mr\ell}(y)$ is the Boolean Exclusion Matrix for a given year (Equation 244)
- $\text{Sheep Agroforestry}$, $\text{Sheep Agroforestry} \in \mathcal{L}_{\text{NonAgrLand}}$ (Equation 13)
- Beef Agroforestry, $\text{Beef Agroforestry} \in \mathcal{L}_{\text{NonAgrLand}}$ (Equation 13)

Since agroforestry systems involve a combination of planted tree rows and open pasture space, it is essential to quantify the proportion of land within each cell that is actually used for agroforestry. This Agroforestry Proportion (denoted as AgrFor_{Prop}) reflects the share of land dedicated to agroforestry rows relative to the total cell area. Calculating this proportion is crucial for accurately modeling land allocation and assessing the cost-effectiveness and efficiency of agroforestry land use strategies.

$\text{AgFor}_{Prop} = \dfrac{\text{AgFor}_{RW}}{\text{AgFor}_{RW} + \text{AgFor}_{RS}}$	Equation 296

where,

AgFor_{RW} is the Agroforestry row width, a constant parameter in LUTO 2.0, set as $\text{AgFor}_{RW} = 20$

AgFor_{RS} is the Agroforestry row spacing, a constant parameter in LUTO 2.0, set as $\text{AgFor}_{RS} = 40$

Hence, the Agroforestry proportion is:

$\text{AgFor}_{Prop} = \dfrac{20}{20 + 40} = 0.333$	Equation 297

The values of the exclusion matrix $\mathbf{XCM}_r^{AgFor}$ (Equation 295) are updated based on the land-use class and computed Agroforestry Proportion AgFor_{Prop} (from Equation 297) as: follows

$\mathbf{XCM}_r^{AgFor} = \mathbf{XCM}_r^{AgFor} \times \text{AgrFor}_{Prop}$	Equation 298

The computed $\mathbf{XCM}_r^{AgFor}$ is illustrated in Figure 479.

15.5. The Cost of Beef-Agroforestry

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This section calculates the cost of beef-agroforestry plantings by adjusting the base agroforestry cost and the specific costs related to beef farming. The equation is:

$$\mathbf{AFPC}_r^{Beef,NonAG}(y) = \left(\mathbf{BAFPC}_r^{NonAG}(y) \times \mathbf{XCM}_r^{AgFor}\right) + \left[\mathbf{Cost}_r^{Beef}(y) \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right]$$	Equation 299

where,

- $\mathbf{AFPC}_r^{Beef,NonAG}(y)$ is the cost of beef-agroforestry for cell r in year y.
- $\mathbf{BAFPC}_r^{NonAG}(y)$ is the cost of agroforestry plantings (base) for each cell (Equation 292 and Figure 477)
- $\mathbf{Cost}_r^{Beef}(y)$ is the cost associated with beef farming in modified land under fry land management system, calculated by Equation 294 (Figure 478).
- $\mathbf{XCM}_r^{AgFor}$ is the exclusion matrix representing the proportion of land used for agroforestry (Equation 295 and Figure 479) (I have to double check that which equations Equation 295 or **Error! Reference source not found.** should be used)

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}$	Equation 300
$$\mathbf{Cost}_r^{Beef}(y) = \begin{cases} \mathbf{TLPC}_{mr\ell}^{LS}(y) & \text{If} \quad m = 0 \wedge \ell = \text{Beef} - \text{modified land} \\ 0 & \text{Otherwise} \end{cases}$$	

where,

- $\mathbf{TLPC}_{mr\ell}^{LS}(y)$ is the total livestock production cost for each livestock type ℓ for year y (Equation 53)
- $\mathcal{L}_{\text{Beef, modified}}$ is a set that contains $\text{Beef} - \text{modified land}$ (Equation 5)

The computed cost of beef-agroforestry plantings $\mathbf{AFPC}_r^{Beef,NonAG}$ for year 2050 is illustrated in Figure 482.

Deakin University CRICOS Provider Code: 00113B

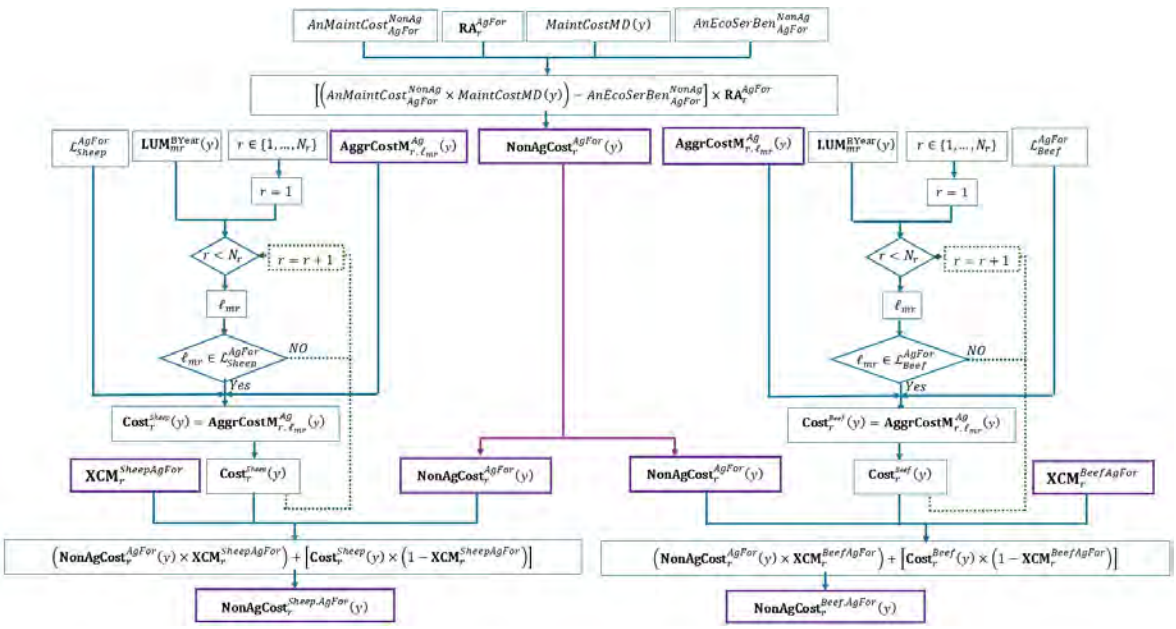

Figure 476 The Cost of carbon plantings Belt (Sheep and Beef and Base) flowchart

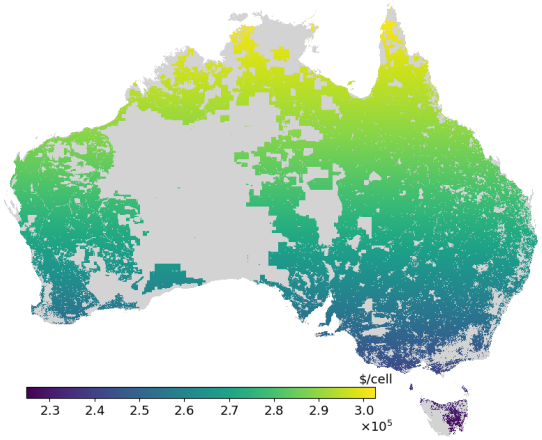

Figure 477 The cost of agroforestry plantings (base) for year 2050

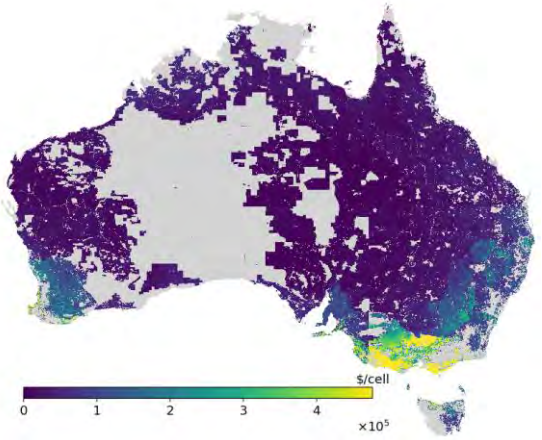

Figure 478 The sheep modified land cost for year 2050

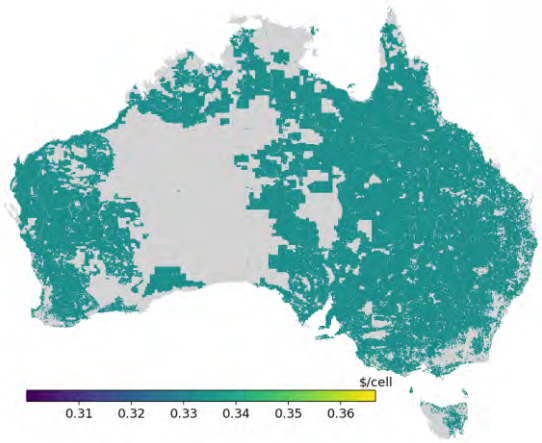

Figure 479 The exclusion matrix representing the proportion of land used for agroforestry for year 2050

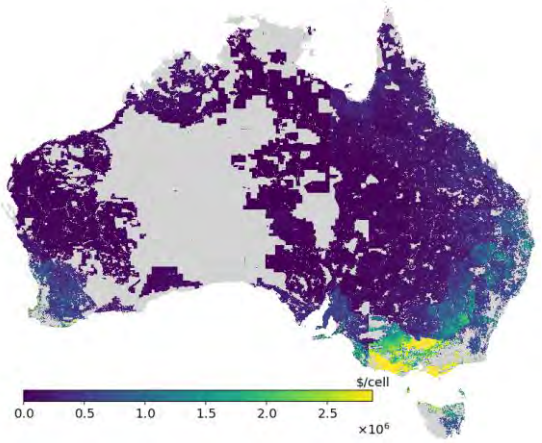

Figure 480 The beef modified land cost for year 2050

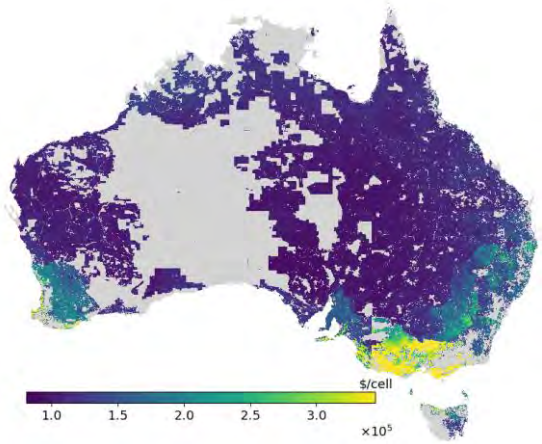

Figure 481 The sheep-agroforestry cost for year 2050

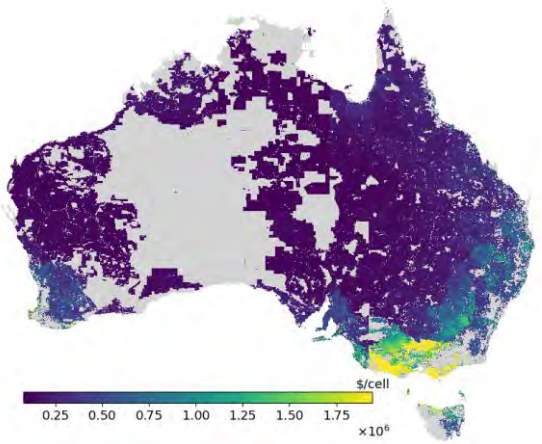

Figure 482 The beef-agroforestry cost for year 2050

15.6. **The Cost of carbon plantings (Block arrangement)**

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This section computes the cost of carbon plantings for the block arrangement ($\mathbf{CPBlockC}_r^{NonAG}$) for each cell r. This cost includes both the maintenance cost and any ecosystem service benefits, adjusted by the actual area of land used for these plantings. The equation for calculating this cost is:

$\mathbf{CPBlockC}_r^{NonAG}(y) = \left[\left(AMC_{CPBlock}^{NonAg} \times MCM(y)\right) - AESB_{CPBlock}^{NonAg}\right] \times \mathbf{RA}_r$	Equation 301

where,

- $\mathbf{CPBlockC}_r^{NonAG}(y)$ is the total cost of carbon plantings for the block arrangement for cell r in year y.
- $AMC_{CPBlock}^{NonAg}$ represents the annual maintenance cost per hectare for carbon plantings for the block arrangement, initialized to 100 in LUTO 2.0. ($AMC_{CPBlock}^{NonAg} = 100$).
- $MCM(y)$ represents the maintenance cost multiplier for each year (y).
- $AESB_{CPBlock}^{NonAg}$ represents annual ecosystem service benefit per hectare of carbon plantings for the block arrangement, initialized to 0 in LUTO 2.0.($AESB_{CPBlock}^{NonAg} = 0$).
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed cost of beef-agroforestry plantings $\mathbf{CPBlockC}_r^{NonAG}$ for the year 2050 is illustrated in Figure 483, and the process is outlined in the flowchart in Figure 484.

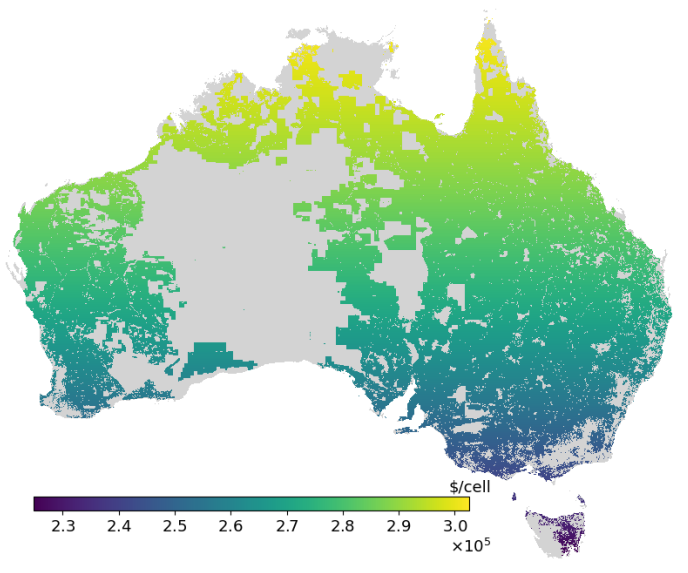

Figure 483 The cost of carbon plantings for the block arrangement for year 2050

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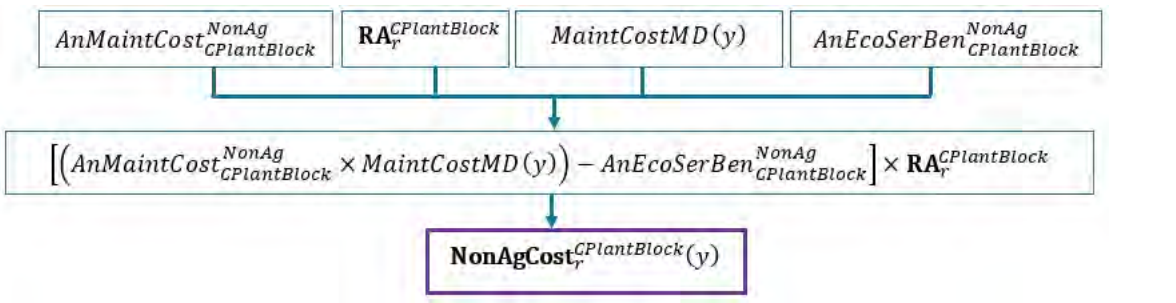

Figure 484 The Cost of carbon plantings (Block) flowchart

15.7. The Base Cost of Carbon Plantings (Belt arrangement)

This section calculates the cost of the base carbon plantings for the belt arrangement ($\mathbf{CPBeltC}_r^{NonAG}$) for each cell r using the following equation:

$\mathbf{BCPBeltC}_r^{NonAG}(y) = \left[\left(AMC_{CPBelt}^{NonAg} \times MCM(y)\right) - AESB_{CPBelt}^{NonAg}\right] \times \mathbf{RA}_r$	Equation 302

where,

- $\mathbf{BCPBeltC}_r^{NonAG}(y)$ is the total base cost of carbon plantings for the belt arrangement for cell r in year y.
- AMC_{CPBelt}^{NonAg} is the annual maintenance cost per hectare for carbon plantings in the belt arrangement, initialized to 100 in LUTO 2.0 ($AMC_{CPBelt}^{NonAg} = 100$).
- $MCM(y)$ is the maintenance cost multiplier for year (y).
- $AESB_{CPBelt}^{NonAg}$ is the annual ecosystem service benefit per hectare for the belt arrangement, initialized to 0 in LUTO 2.0. ($AESB_{CPBelt}^{NonAg} = 0$).
- $\mathbf{RA}_r$ is the real area (Figure 5).

The computed cost of the base carbon plantings for the belt arrangement for year 2050 is shown in Figure 486, and the associated flowchart is presented in Figure 485.

15.8. The Cost of Sheep-Carbon Plantings (Belt arrangement)

This function calculates the of sheep-carbon plantings for the belt arrangement by adjusting the base belt planting cost $\mathbf{BCPBeltC}_r^{NonAG}(y)$ incorporating the specific costs related to sheep farming $\mathbf{Cost}_r^{Sheep}$. The equation is:

$\mathbf{CPBeltC}_r^{Sheep,NonAG}(y) = (\mathbf{BCPBeltC}_r^{NonAG}(y) \times \mathbf{XCM}_r^{CPBelt}) + \left[\mathbf{Cost}_r^{Sheep}(y) \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$	Equation 303

where,

- $\mathbf{CPBeltC}_r^{Sheep,NonAG}(y)$ is the cost of sheep-carbon plantings for the belt arrangement for cell r in year y.
- $\mathbf{BCPBeltC}_r^{NonAG}(y)$ is the total base cost of carbon plantings for the belt arrangement for each cell from Equation 302 (see Figure 486).

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- $\mathbf{Cost}_r^{Sheep}(y)$ is the cost of sheep farming under dryland management (see Equation 294, Figure 478).
- $\mathbf{XCM}_r^{CPBelt}$ is the exclusion matrix representing the proportion of land used for carbon plantings (see Equation 304 and Figure 487)

As per LUTO 2.0, carbon planting cells in the belt arrangement can be used for both sheep and beef farming. Thus, the exclusion matrix $\mathbf{XCM}_r^{CPBelt}(y)$ reflects cells shared by both uses:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}$	Equation 304
$\mathbf{XCM}_r^{CPBelt}(y) = \begin{cases} \mathbf{XCM}_{mr\ell}(y) & \text{If} \quad m = 0 \wedge \ell = \text{Sheep Carbon Plantings} \\ \mathbf{XCM}_{mr\ell}(y) & \text{If} \quad m = 0 \wedge \ell = \text{Beef Carbon Plantings} \\ \mathbf{0} & \text{otherwise} \end{cases}$	

where,

- $\mathbf{XCM}_{mr\ell}(y)$ is the Boolean Exclusion Matrix for a given year (Equation 244)
- Sheep Carbon Plantings $\in \mathcal{L}_{\text{NonAgrLand}}$ (Equation 13)
- Beef Carbon Plantings $\in \mathcal{L}_{\text{NonAgrLand}}$ (Equation 13)

As the portion of land occupied by belt planting within a given cell, this proportion (CPBelt_{Prop}) should be computed, as it allows us to quantify the area utilized for the carbon plantings in the belt arrangement versus open space within the belt planting system. This ratio is critical for understanding land allocation and the overall efficiency of land use in belt planting.

The proportion of Carbon Planting for the belt arrangement is computed as:

$\text{CPBelt}_{Prop} = \dfrac{\text{CPBelt}_{RW}}{\text{CPBelt}_{RW} + \text{CPBelt}_{RS}}$	Equation 305

where,

- CPBelt_{RW} is the Agroforestry row width, a constant parameter in LUTO 2.0, set as $\text{CPBelt}_{RW} = 20$
- CPBelt_{RS} is the Agroforestry row spacing, a constant parameter in LUTO 2.0, set as $\text{CPBelt}_{RS} = 40$

Hence, the carbon plantings belt proportion is:

$\text{CPBelt}_{Prop} = \dfrac{20}{20 + 40} = 0.333$	Equation 306

The values of $\mathbf{XCM}_r^{CPBelt}$ are updated based on the land-use class and the computed CPBelt_{Prop} from Equation 305 as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\text{BYear}}$	Equation 307
$\mathbf{XCM}_r^{CPBelt}(y) = \mathbf{XCM}_r^{CPBelt}(y) \times \text{CPlantBelt}_{Prop}$	

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The exclusion matrix representing the proportion of land used for the base carbon plantings for the belt arrangement for year 2050 is illustrated in Figure 487, and the computed cost of sheep-agroforestry plantings $\mathbf{CPBeltC}_r^{Sheep,NonAG}$ for year 2050 is illustrated in Figure 481.

15.9. The Cost of Beef-Carbon Plantings (Belt arrangement)

This section calculates the cost of beef- carbon plantings for the belt arrangement by adjusting the base carbon plantings cost $\mathbf{BCPBeltC}_r^{NonAG}(y)$ and incorporating the specific costs related to beef farming $\mathbf{Cost}_r^{Beef}$. The equation is:

$$\mathbf{CPBeltC}_r^{Beef,NonAG}(y) = (\mathbf{BCPBeltC}_r^{NonAG}(y) \times \mathbf{XCM}_r^{CPBelt}) + \left[\mathbf{Cost}_r^{Beef}(y) \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$$	Equation 308

where,

- $\mathbf{CPBeltC}_r^{Beef,NonAG}(y)$ is the cost of beef-carbon plantings for the belt arrangement for cell r in year y.
- $\mathbf{BCPBeltC}_r^{NonAG}(y)$ is the total base cost of carbon plantings for the belt arrangement for each cell (Equation 302 and Figure 486)
- $\mathbf{Cost}_r^{Beef}(y)$ is the cost associated with beef farming in modified land under dryland management, calculated by Equation 300 (Figure 480).
- $\mathbf{XCM}_r^{CPBelt}$ is the exclusion matrix representing the proportion of land used for carbon plantings for the belt arrangement (Equation 304 and Figure 479)

The computed cost of beef-agroforestry plantings $\mathbf{CPBeltC}_r^{Beef,NonAG}$ for year 2050 is illustrated in Figure 489.

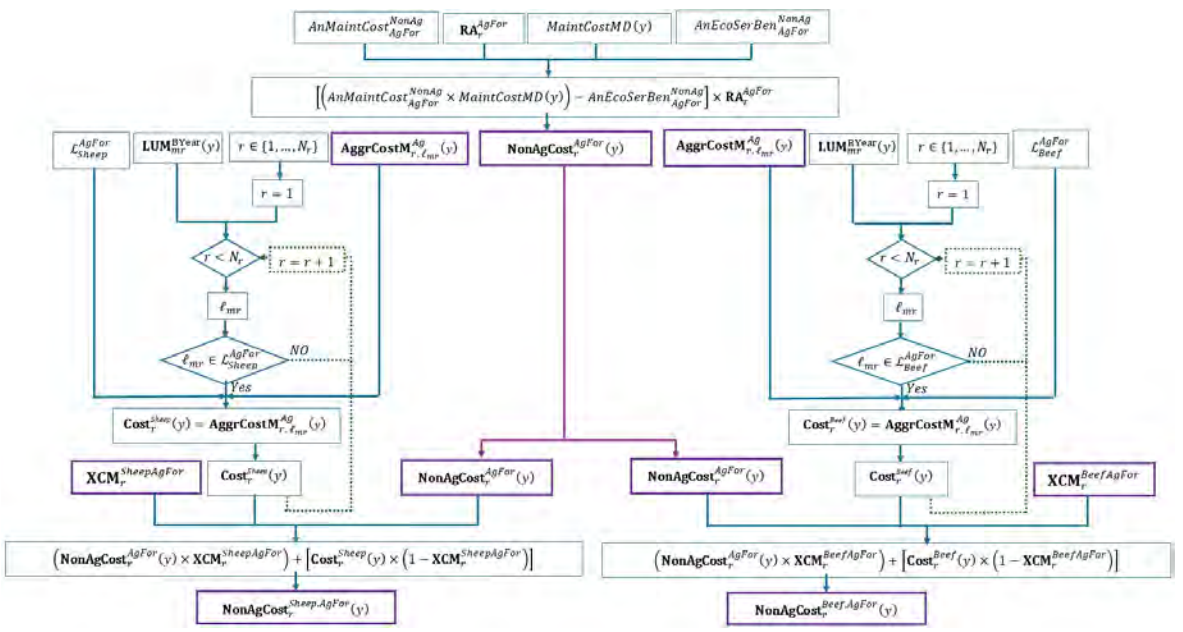

Figure 485 The Cost of carbon plantings belt (sheep, beef, and base) flowchart

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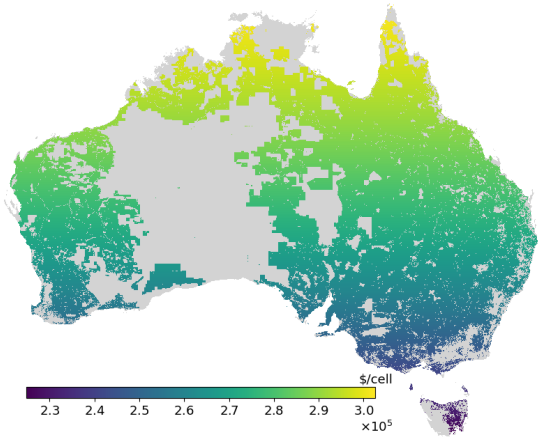

Figure 486 The cost of the base carbon plantings for the belt arrangement for year 2050

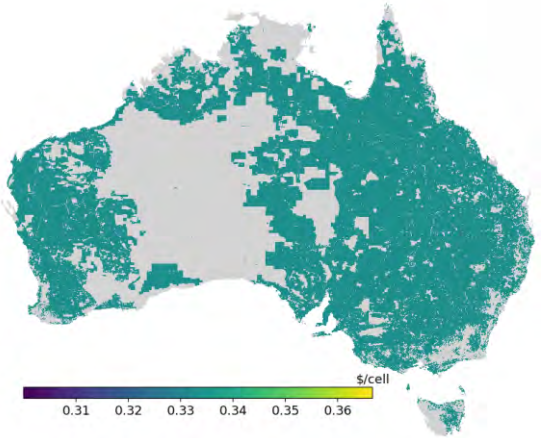

Figure 487 The exclusion matrix representing the proportion of land used for the base carbon plantings for the belt arrangement for year 2050

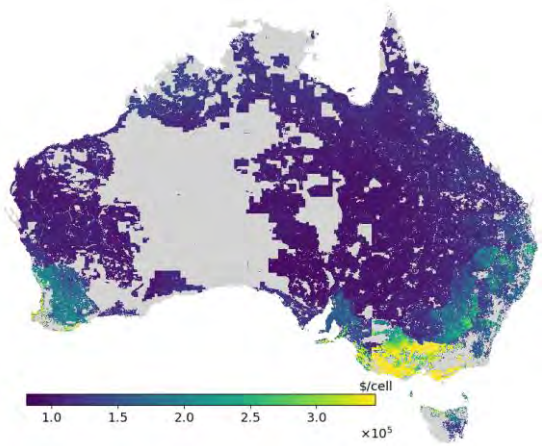

Figure 488 The sheep-carbon plantings for the belt arrangement cost for year 2050

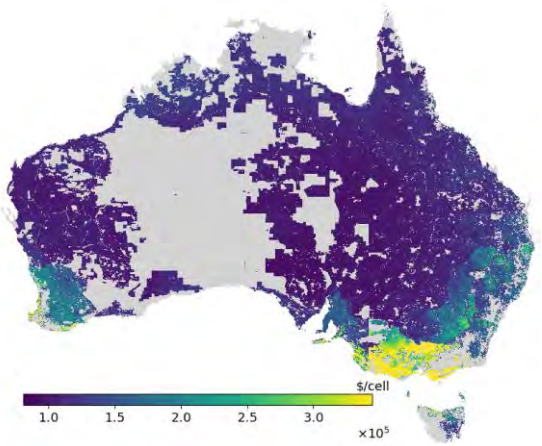

Figure 489 The beef-carbon plantings for the belt arrangement cost for year 2050

15.10. Cost of Bioenergy with carbon capture and storage (BECCS)

This section calculates the cost of bioenergy with carbon capture and storage (BECCS) $\mathbf{BECCSC}_r^{NonAG}$ for each cell r using the following equation:

$\mathbf{BECCSC}_r^{NonAG}(y) = \mathbf{Cost}_r^{BECCS} \times BECCSCM(y) \times \mathbf{RA}_r$	Equation 309

where,

- $\mathbf{BECCSC}_r^{NonAG}(y)$ is the cost of BECCS for cell r in year y (AUD/Cell).
- $\mathbf{Cost}_r^{BECCS}$ is the cost of BECCS for cell r (AUD/ha) (Figure 490).
- $BECCSCM(y)$ is the BECCS cost multiplier.
- $\mathbf{RA}_r$ represents the real area (Figure 5).

The computed cost of bioenergy with carbon capture and storage (BECCS) $\mathbf{BECCSC}_r^{NonAG}$ for year 2050 is illustrated in Figure 491, and the flowchart is presented in Figure 492.

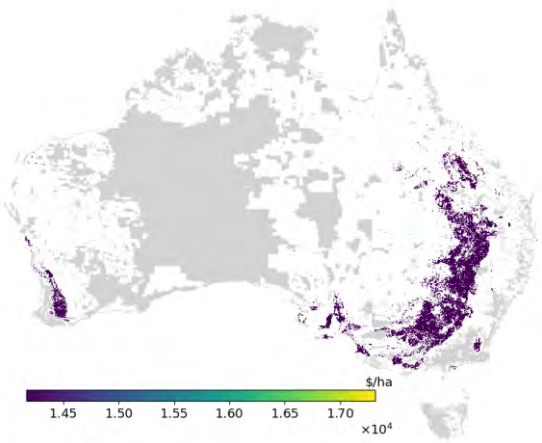

Figure 490 The cost of bioenergy with carbon capture and storage (AUD/ha)

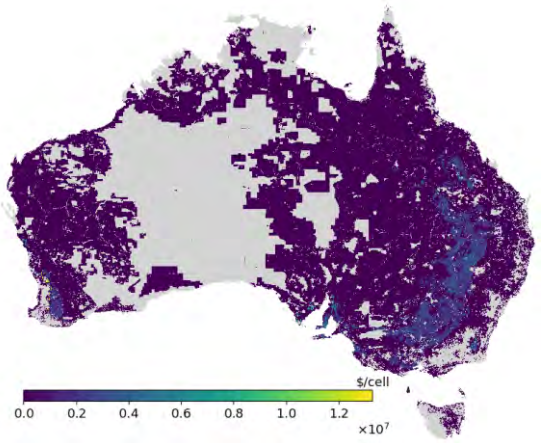

Figure 491 The cost of bioenergy with carbon capture and storage (BECCS) for year 2050 (AUD/Cell)

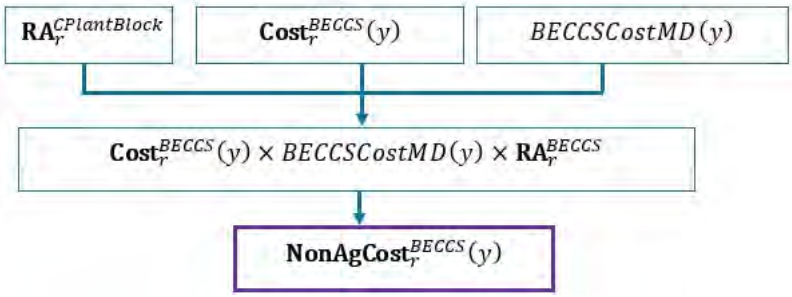

Figure 492 Cost of Bioenergy with carbon capture and storage (BECCS) flowchart

15.11. The Cost Matrix of all Non-Agricultural Land Use:

This section aggregates the costs of all non-agricultural land uses into a single matrix. The overall cost matrix is constructed by concatenating the individual cost vectors for each land use in the non-agricultural land-use set $\mathcal{L}_{\text{NonAgrLand}}$, as defined in Equation 13. The equation is:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 310
$\mathbf{NACM}_{r\ell}^{NonAg}(y) = \text{concatenate}\left(\begin{matrix}\mathbf{EPC}_r^{NonAG}(y), \mathbf{RPC}_r^{NonAG}(y), \mathbf{AFPC}_r^{Sheep,NonAG}(y), \\ \mathbf{AFPC}_r^{Beef,NonAG}(y), \mathbf{CPBlockC}_r^{NonAG}(y), \mathbf{CPBeltC}_r^{Sheep,NonAG}(y), \\ \mathbf{CPBeltC}_r^{Beef,NonAG}(y), \mathbf{BECCSC}_r^{NonAG}(y)\end{matrix}\right)$	

where,

- $\mathbf{NACM}_{r\ell}^{NonAg}(y)$ is the aggregated cost matrix for all non-agricultural land uses in cell r for year y.
- $\mathcal{L}_{\text{NonAgrLand}}$ is a set the represents the classes of non-agricultural land uses (Equation 13)

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Economics/Non Agricultural/ghg.py

16. The Greenhous Gas (GHG) Emissions of Non-Agricultural Land Use

16.1. Greenhouse Gas Emissions for Environmental Plantings (Block)

This section computes the greenhouse gas (GHG) emissions for environmental plantings. The GHG emissions are based on carbon sequestration data, adjusted for factors such as fire risk and the risk of reversal. The flowchart of the method is presented in Figure 500.

16.1.1. Fire Risk Adjustment

The CO2 sequestration is adjusted by the fire risk and risk of reversal. The required parameters are defined as:

$$\mathbf{FRSAF}_r = \frac{\mathbf{FR}_r^{Level}}{100} \times (1 - RRB_r)$$	Equation 311

where,

- $\mathbf{FRSAF}_r$ is the Fire Risk Sequestration Adjustment Factor
- $\mathbf{FR}_r^{Level}$ represents the fire risk level (Figure 495-Figure 497, and Table 12).
- RRB_r represents the risk of reversal buffer under based on project duration (25 to 100 Years)

These parameters can be defined as follows:

16.1.2. Fire Risk

$FR_r^{Level}(y)$ is a value representing the impact of fire on carbon sequestration, selected based on risk scenarios. The value depends on the percentile of modelled fire impacts:

Table 12 The fire risk values based on impact scenarios

Fire risk Level	low	med	high
Percentile of modelled fire impacts	5th	50th	95th
$\mathbf{FR}_r^{Level}$	80.3967	89.2485	93.2735
Map	Figure 495	Figure 496	Figure 497

In LUTO 2.0, the default level is 'med' ($Level = \text{med}$).

16.1.3. Risk of Reversal

RRB_r represents a buffer accounting for the potential reversal or loss of sequestered carbon. Typical values for RRB_r range from 0.05 (100-years projects) to 0.25 (25-years projects). In LUTO 2.0, the default value for RRB_r is 0.05.

16.1.4. Average Annual GHG Sequestration for Environmental Plantings (Block) Adjusted for Fire and Reversal Risk

This section describes the calculation of average annual greenhouse gas (GHG) sequestration for environmental plantings (block), considering fire risk $\mathbf{FR}_r^{Level}$ and the risk of reversal RRB_r. The sequestration values are adjusted by multiplying the aboveground carbon sequestration (measured in tonnes of CO_2 per hectare per year) by the fire risk factor $\mathbf{FR}_r^{Level}$ (as a percentage) and the risk of reversal buffer RRB_r, which reflects potential carbon losses over time due to project termination or other disturbances. The calculation also incorporates belowground carbon sequestration, which remains unaffected by these risks.

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The final adjusted value provides a more realistic estimate of long-term carbon storage potential for environmental plantings.

$\mathbf{AGHG}_r^{EnvPlanting} = \left(\mathbf{AGC}_r^{EnvPlanting} \times \mathbf{FRSAF}_r\right) + \mathbf{BGC}_r^{EnvPlanting}$	Equation 312

where,

- $\mathbf{AGC}_r^{EnvPlanting}$ represents the average annual aboveground CO2 sequestration per hectare (Figure 493)
- $\mathbf{BGC}_r^{EnvPlanting}$ represents the average annual belowground CO2 sequestration per hectare (Figure 494)
- $\mathbf{FRSAF}_r$ represents the Fire Risk Sequestration Adjustment Factor (Equation 311)
- $\mathbf{AGHG}_r^{EnvPlanting}$ represents the average annual greenhouse gas (GHG) sequestration for environmental plantings (block) (Figure 498)

16.1.5. Final GHG Emissions Calculation of Environmental Plantings per Cell

Combining the above equations, the total GHG emissions for environmental plantings ($\mathbf{GHGE}_{r,\,\ell_{mr}}^{EnvPlanting}(y)$) can be expressed as:

$\mathbf{GHGE}_r^{EnvPlanting} = -\left(\mathbf{AGHG}_r^{EnvPlanting} \times \mathbf{RA}_r\right)$	Equation 313

- $\mathbf{AGHG}_r^{EnvPlanting}$ represents the average annual greenhouse gas (GHG) sequestration for environmental plantings (block) (Equation 311)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{GHGE}_r^{EnvPlanting}$ represents the total GHG emissions for environmental plantings (block) (Figure 499)

This equation calculates the net greenhouse gas emissions, considering both aboveground and belowground carbon sequestration, adjusted for fire risk and the potential reversal of carbon sequestration.

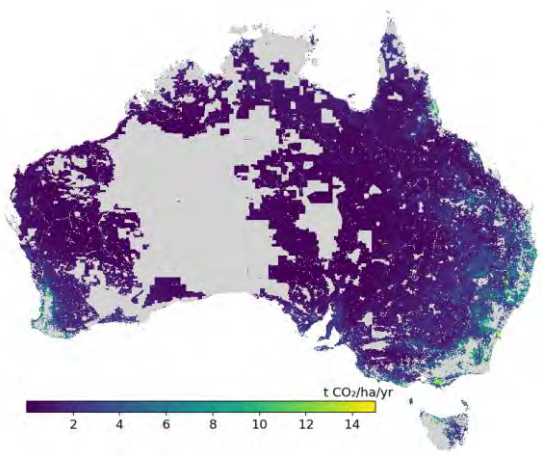	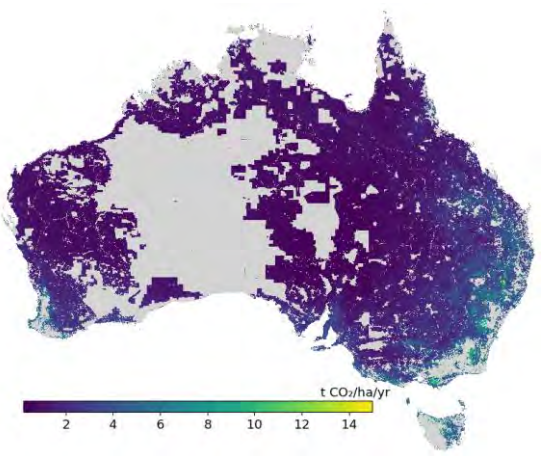
Figure 493 The average annual above-ground CO2 sequestration per hectare for environmental plantings (block)	Figure 494 The average annual below-ground CO2 sequestration per hectare for environmental plantings (block)

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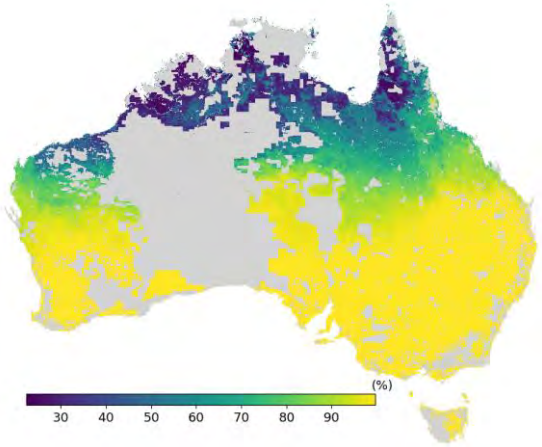

Figure 495 Low fire risk (5th percentile reduction)

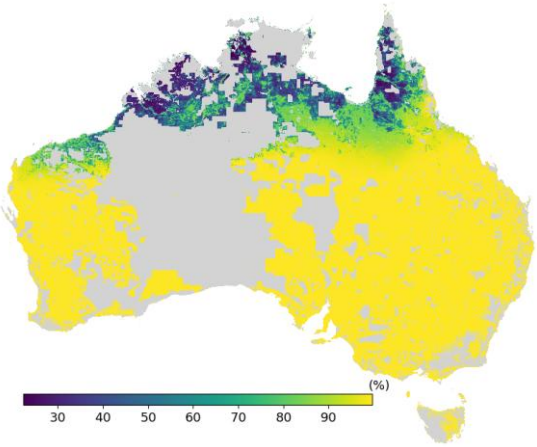

Figure 496 Medium fire risk (50th percentile reduction)

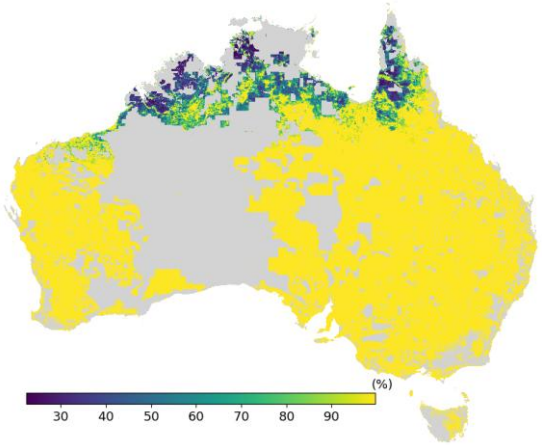

Figure 497 High fire risk (95th percentile reduction)

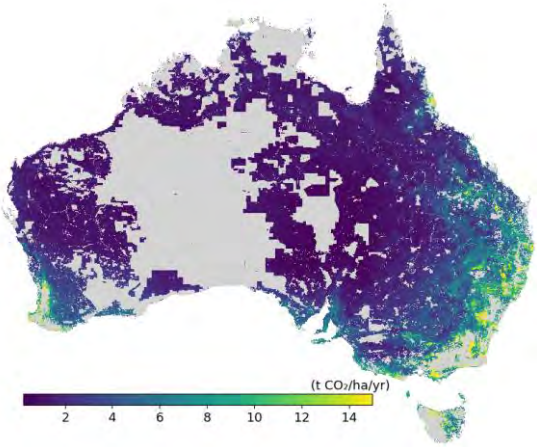

Figure 498 The average annual GHG sequestration for environmental plantings (block) per cell

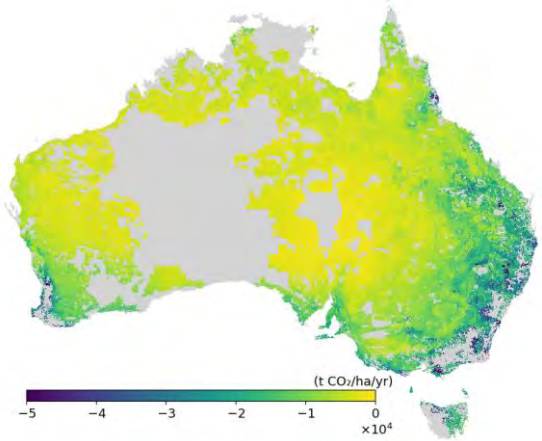

Figure 499 The total GHG emissions for environmental plantings (block) per cell

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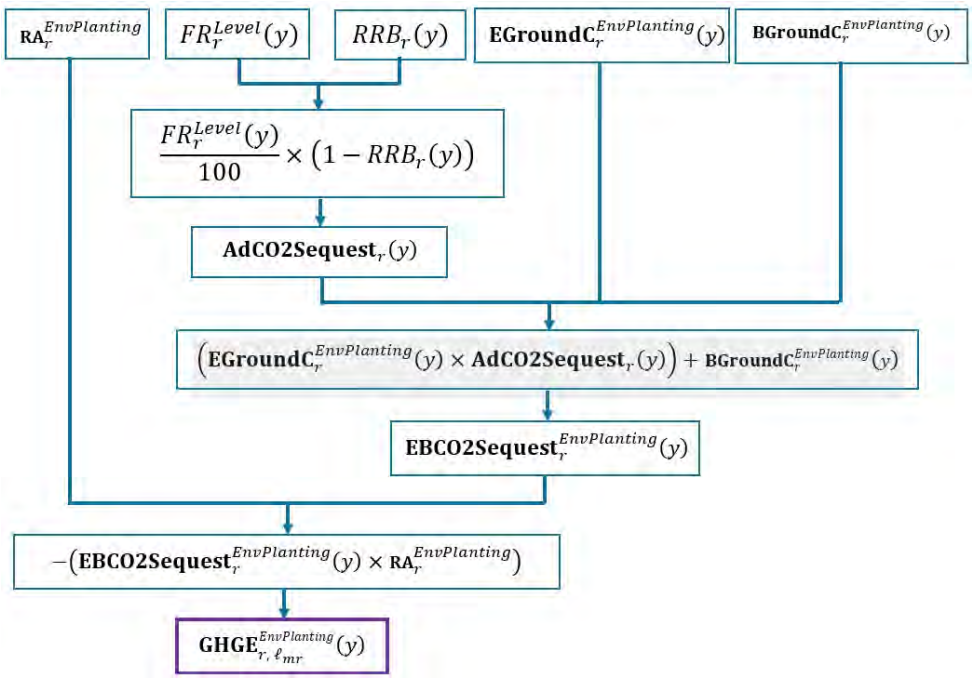

Figure 500 Greenhouse gas emissions of environmental plantings

16.2. Greenhouse Gas Emissions for Riparian Plantings

This section computes the greenhouse gas (GHG) emissions for riparian plantings. The GHG emissions are based on carbon sequestration data, adjusted for factors such as fire risk and the risk of reversal. The flowchart of the method is presented in Figure 505.

16.2.1. Average Annual GHG Sequestration for Riparian Plantings Adjusted for Fire and Reversal Risk

To compute the average annual greenhouse gas (GHG) sequestration for riparian plantings while accounting for the fire risk sequestration adjustment factor $\mathbf{FRSAF}_r$ (Equation 311), other parameters such as the aboveground carbon sequestration $\mathbf{AGC}_r^{RipPlant}$ and belowground carbon sequestration $\mathbf{BGC}_r^{RipPlant}$ are required. $\mathbf{AGHG}_r^{RipPlant}$ is computed as:

$\mathbf{AGHG}_r^{RipPlant} = (\mathbf{AGC}_r^{RipPlant} \times \mathbf{FRSAF}_r) + \mathbf{BGC}_r^{RipPlant}$	Equation 314

where,

- $\mathbf{AGC}_r^{RipPlant}$ represents the average annual aboveground CO2 sequestration per hectare for riparian plantings (Figure 501)
- $\mathbf{BGC}_r^{RipPlant}$ represents the average annual belowground CO2 sequestration per hectare for riparian plantings (Figure 502)
- $\mathbf{FRSAF}_r$ represents the Fire Risk Sequestration Adjustment Factor (Equation 311)
- $\mathbf{AGHG}_r^{RipPlant}$ represents the average annual greenhouse gas (GHG) sequestration for riparian plantings (Figure 503)

16.2.2. Final GHG Emissions Calculation of riparian Plantings per Cell

Combining the above equations, the total GHG emissions for riparian plantings $\mathbf{GHGE}_r^{RipPlant}$ can be expressed as:

$$\mathbf{GHGE}_r^{RipPlant} = -\left(\mathbf{AGHG}_r^{RipPlant} \times \mathbf{RA}_r\right)$$	Equation 315

where,

- $\mathbf{AGHG}_r^{RipPlant}$ represents the average annual greenhouse gas (GHG) sequestration for riparian plantings (Equation 314)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{GHGE}_r^{RipPlant}$ represents the total GHG emissions for riparian plantings (Figure 504)

This equation calculates the net greenhouse gas emissions, considering both aboveground and belowground carbon sequestration, adjusted for fire risk and the potential reversal of carbon sequestration.

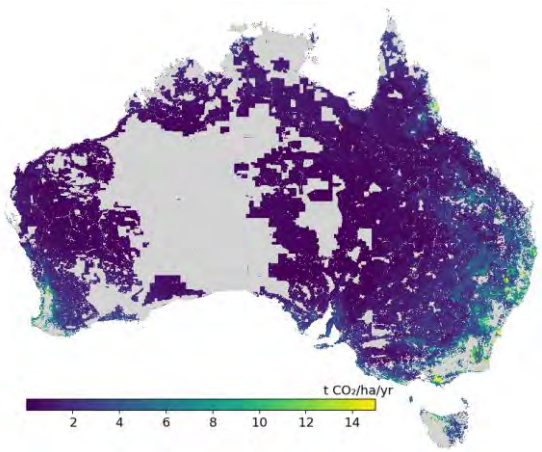

Figure 501 The average annual above-ground CO2 sequestration per hectare for riparian plantings

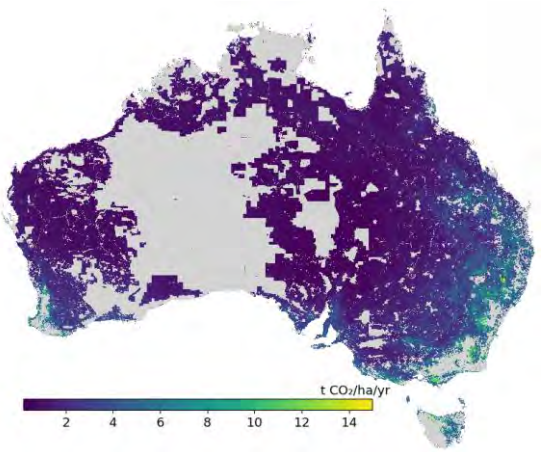

Figure 502 The average annual below-ground CO2 sequestration per hectare for environmental plantings (block)

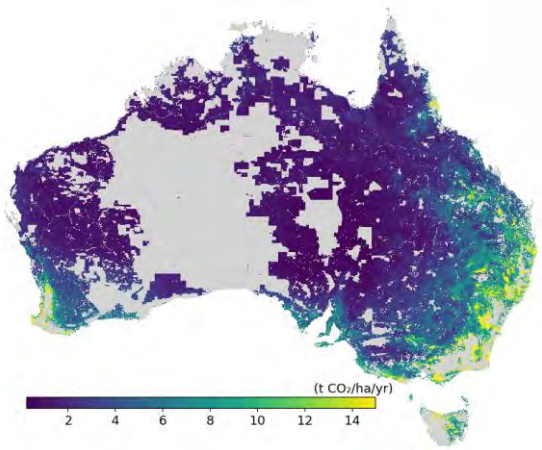

Figure 503 The average annual GHG sequestration for riparian plantings

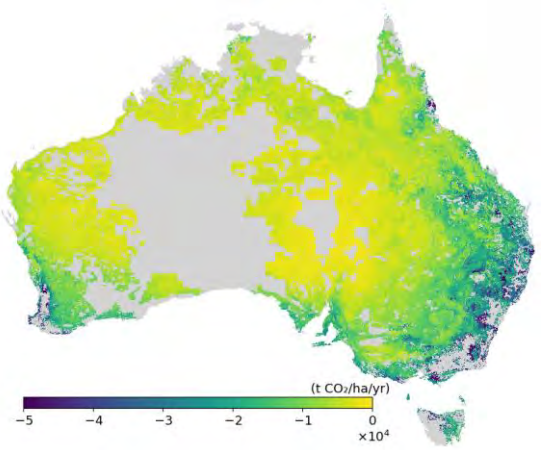

Figure 504 The total GHG emissions for riparian plantings per cell

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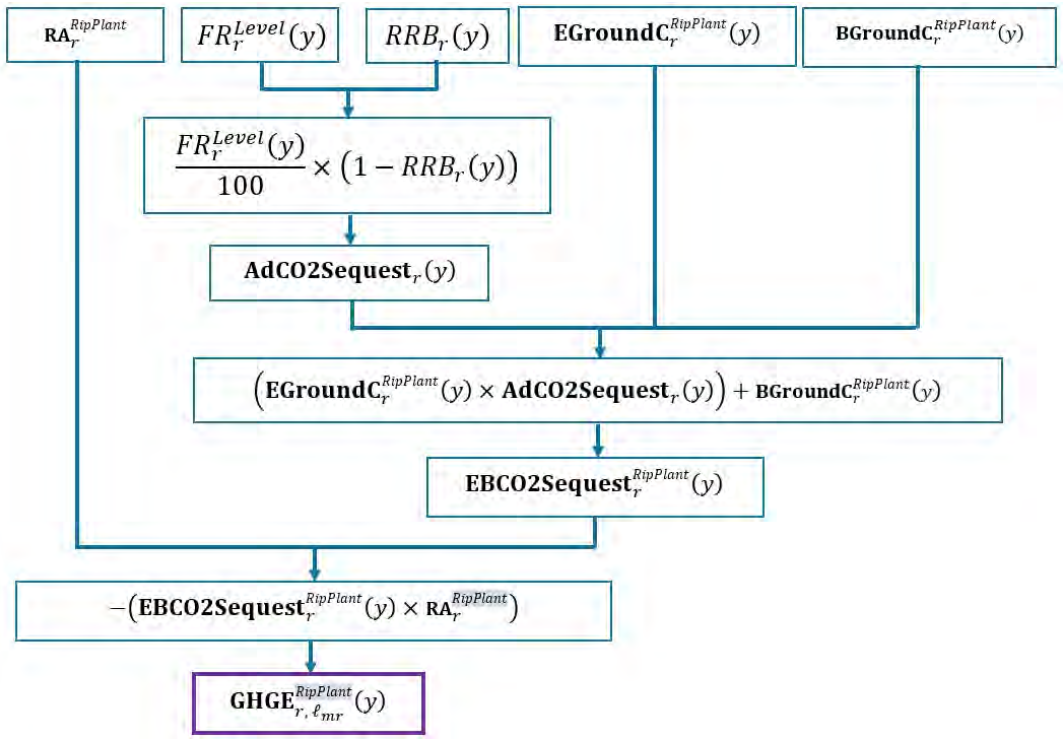

Figure 505 Greenhouse gas emissions for riparian plantings

16.3. Greenhouse Gas Emissions for Agroforestry Base

This section computes the greenhouse gas (GHG) emissions for the agroforestry (base). The GHG emissions are based on carbon sequestration data, adjusted for factors such as fire risk and the risk of reversal. The flowchart of the method is presented in Figure 510.

16.3.1. Average Annual GHG Sequestration for the Base Agroforestry Adjusted for Fire and Reversal Risk

To compute the average annual greenhouse gas (GHG) sequestration for the base agroforestry while accounting for the fire risk sequestration adjustment factor $\mathbf{FRSAF}_r$ (Equation 311), other parameters such as the aboveground carbon sequestration $\mathbf{AGC}_r^{AgrFor}$ and the belowground carbon sequestration $\mathbf{BGC}_r^{AgrFor}$ are required. $\mathbf{AGHG}_r^{AgrFor}$ is computed as:

$\mathbf{AGHG}_r^{AgrFor} = (\mathbf{AGC}_r^{AgrFor} \times \mathbf{FRSAF}_r) + \mathbf{BGC}_r^{AgrFor}$	Equation 316

where,

- $\mathbf{AGC}_r^{AgrFor}$ represents the average annual aboveground CO2 sequestration per hectare for the base agroforestry (Figure 506)
- $\mathbf{BGC}_r^{AgrFor}$ represents the average annual belowground CO2 sequestration per hectare for the base agroforestry (Figure 507)

- $\mathbf{FRSAF}_r$ represents the Fire Risk Sequestration Adjustment Factor (Equation 311)
- $\mathbf{AGHG}_r^{AgrFor}$ represents the average annual greenhouse gas (GHG) sequestration for the base agroforestry (Figure 508)

16.3.2. Final GHG Emissions Calculation for the Base Agroforestry per Cell

Combining the above equations, the total GHG emissions for the base agroforestry ($\mathbf{GHGE}_r^{Base,AgrFor}$) can be expressed as:

$\mathbf{GHGE}_r^{Base,AgrFor} = -\left(\mathbf{AGHG}_r^{AgrFor} \times \mathbf{RA}_r\right)$	Equation 317

- $\mathbf{AGHG}_r^{AgrFor}$ represents the average annual greenhouse gas (GHG) sequestration for the base agroforestry (Equation 316, Figure 508)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{GHGE}_r^{Base,AgrFor}$ represents the total GHG emissions for the base agroforestry (Figure 509)

This equation calculates the net greenhouse gas emissions, considering both aboveground and belowground carbon sequestration, adjusted for fire risk and the potential reversal of carbon sequestration.

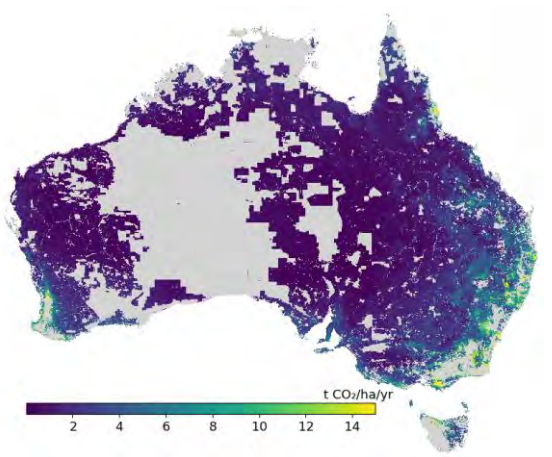

Figure 506 The average annual above-ground CO2 sequestration per hectare for the base agroforestry

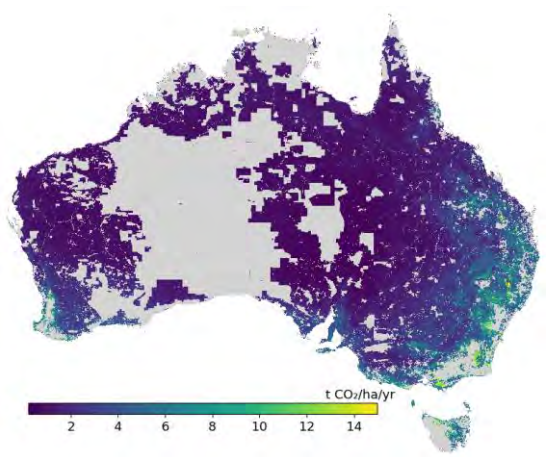

Figure 507 The average annual below-ground CO2 sequestration per hectare for the base agroforestry

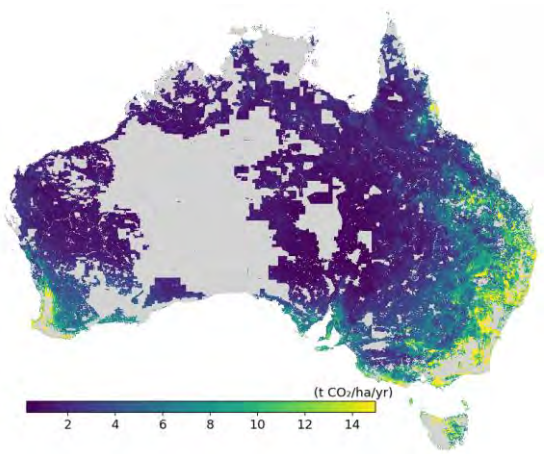

Figure 508 The average annual GHG sequestration for the base agroforestry

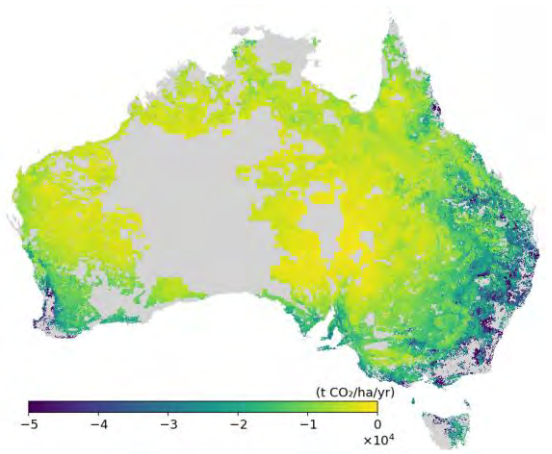

Figure 509 The total GHG emissions for the base agroforestry per cell

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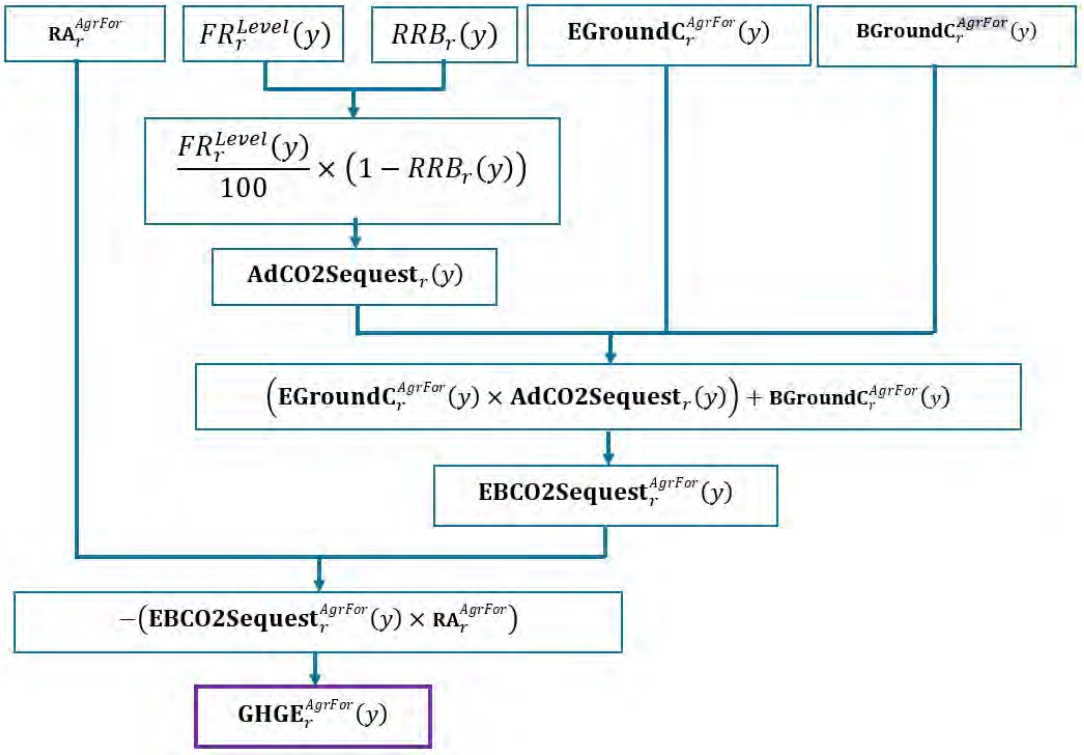

Figure 510 Greenhouse gas emissions for the base Agroforestry

16.4. The Greenhouse Gas Emissions for Sheep-Agroforestry

This section computes the total GHG emissions for a combination of sheep farming and agroforestry by adjusting the total GHG emissions for the base agroforestry $\mathbf{GHGE}_r^{Base,AgrFor}$ (Equation 317) and the specific GHG emissions related to sheep farming. The equation is:

$\mathbf{GHGE}_r^{Sheep,AgrFor} = (\mathbf{GHGE}_r^{Base,AgrFor} \times \mathbf{XCM}_r^{AgFor}) + [\mathbf{GHGE}_r^{Sheep} \times (1 - \mathbf{XCM}_r^{AgFor})]$	Equation 318

where,

- $\mathbf{GHGE}_r^{Sheep,AgrFor}$ is the total GHG emissions for sheep–agroforestry plantings for cell r
- $\mathbf{GHGE}_r^{Base,AgrFor}$ is the total GHG emissions for the base agroforestry for cell r (Equation 317, Figure 509)
- $\mathbf{GHGE}_r^{Sheep}$ is the GHG emissions associated with sheep farming in modified land under a dryland management system, calculated by Equation 319 (Figure 511).
- $\mathbf{XCM}_r^{AgFor}$ is the exclusion matrix representing the proportion of land used for agroforestry (Equation 295 and Figure 479)

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}$	Equation 319

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$\mathbf{GHGE}_r^{Sheep} = \begin{cases} \mathbf{GHGE}_{r\ell}^{LS} & \text{If} \quad m = 0 \ \wedge \ \ell = \text{Sheep} - \text{modified land} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{GHGE}_{r\ell}^{LS}$ is the GHG Emission of Livestock farming for each livestock type ℓ (Equation 87)
- $\mathcal{L}_{\text{Sheep, modified}}$ is a set that contains Sheep $-$ modified land (Equation 6)

The computed GHG emissions for sheep-agroforestry plantings $\mathbf{GHGE}_r^{Sheep,AgrFor}$ for year 2050 is illustrated in Figure 512.

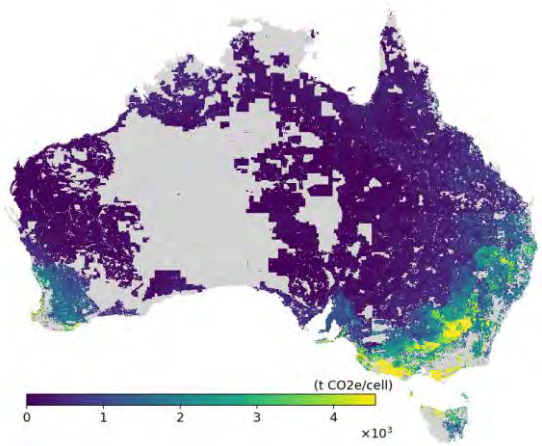

Figure 511 The total GHG emissions from sheep-modified land under Dry land management system

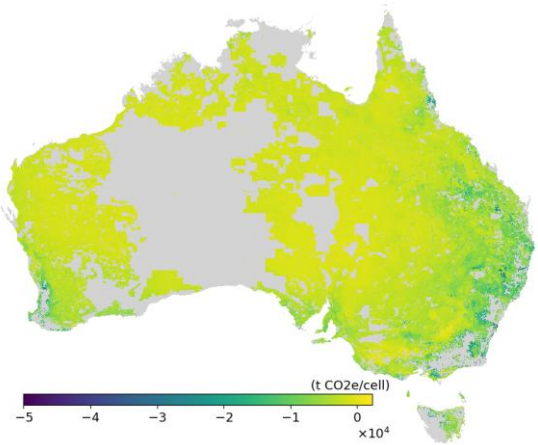

Figure 512 The total GHG emissions from sheep-agroforestry under Dry land management system

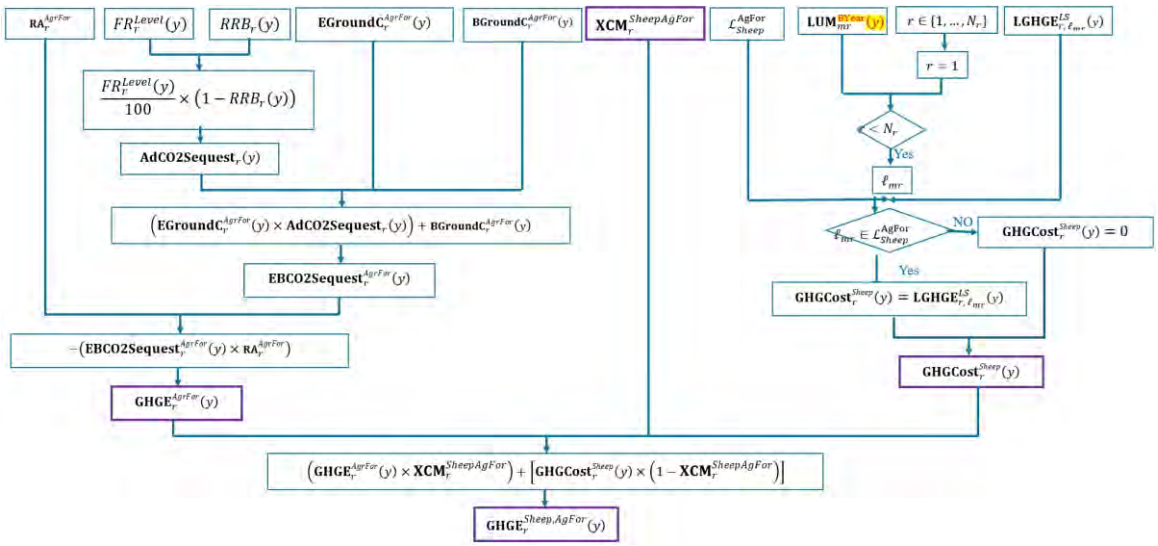

Figure 513 Greenhouse gas emissions for Sheep-Agroforestry

16.5. The Greenhouse Gas Emissions for Beef-Agroforestry

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This section computes the total GHG emissions for a combination of beef farming and agroforestry by adjusting the total GHG emissions for the base agroforestry $\mathbf{GHGE}_r^{AgrFor}$ (Equation 317) and the specific GHG emissions related to beef farming. The equation is:

$$\mathbf{GHGE}_r^{Beef,AgrFor} = \left(\mathbf{GHGE}_r^{Base,AgrFor} \times \mathbf{XCM}_r^{AgFor}\right) + \left[\mathbf{GHGE}_r^{Beef} \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right]$$	Equation 320

where,

- $\mathbf{GHGE}_r^{Beef,AgrFor}$ is the GHG emissions for beef-agroforestry plantings for cell r
- $\mathbf{GHGE}_r^{Base,AgrFor}$ is the total GHG emissions for the base agroforestry for cell r (Equation 317, Figure 509)
- $\mathbf{GHGE}_r^{Beef}$ is the GHG emissions associated with beef farming in modified land under dryland management system, calculated by Equation 321 (Figure 514).
- $\mathbf{XCM}_r^{AgFor}$ is the exclusion matrix representing the proportion of land used for agroforestry (Equation 295 and Figure 479)

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}$	Equation 321
$$\mathbf{GHGE}_r^{Beef} = \begin{cases} \mathbf{GHGE}_{r\ell}^{LS} & \text{If} \quad m = 0 \wedge \ell = \text{Beef} - \text{modified land} \\ 0 & \text{Otherwise} \end{cases}$$	

where,

- $\mathbf{GHGE}_{r\ell}^{LS}$ is the GHG Emission of Livestock farming for each livestock type ℓ (Equation 87)
- $\mathcal{L}_{\text{Beef, modified}}$ is a set that contains Beef $-$ modified land (Equation 5)

The computed GHG emissions for beef–agroforestry plantings $\mathbf{GHGE}_r^{Beef,AgrFor}$ for year 2050 are illustrated in Figure 515. The flowchart of the GHG emissions computation method is shown in Figure 516.

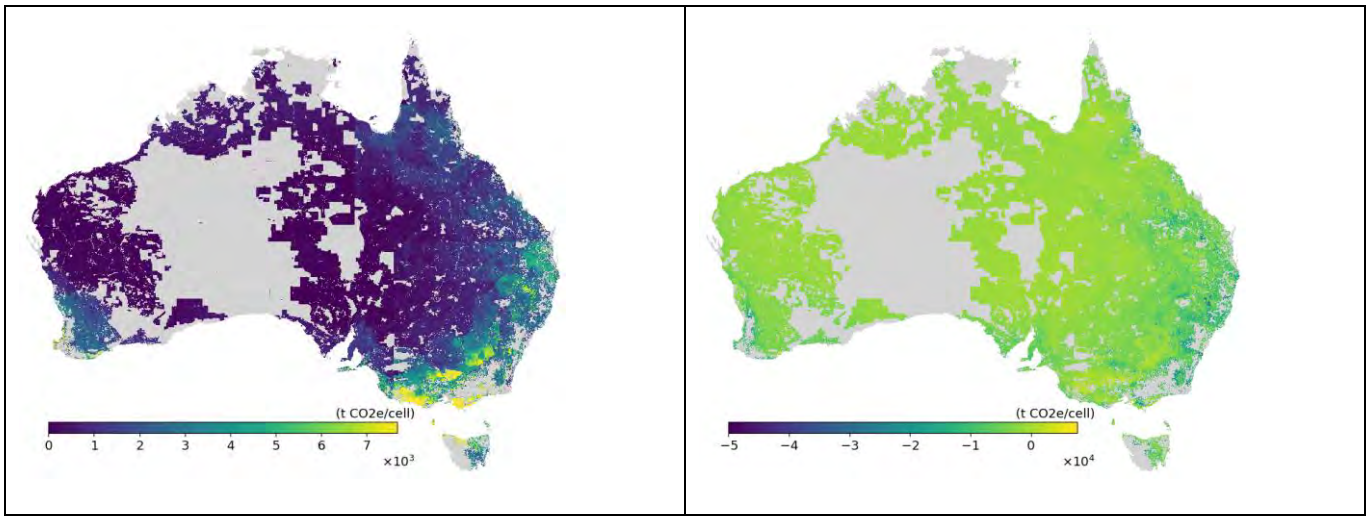

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Figure 514 The total GHG emissions from beef-modified land under dryland management system	Figure 515 The total GHG emissions beef-agroforestry under dryland management system

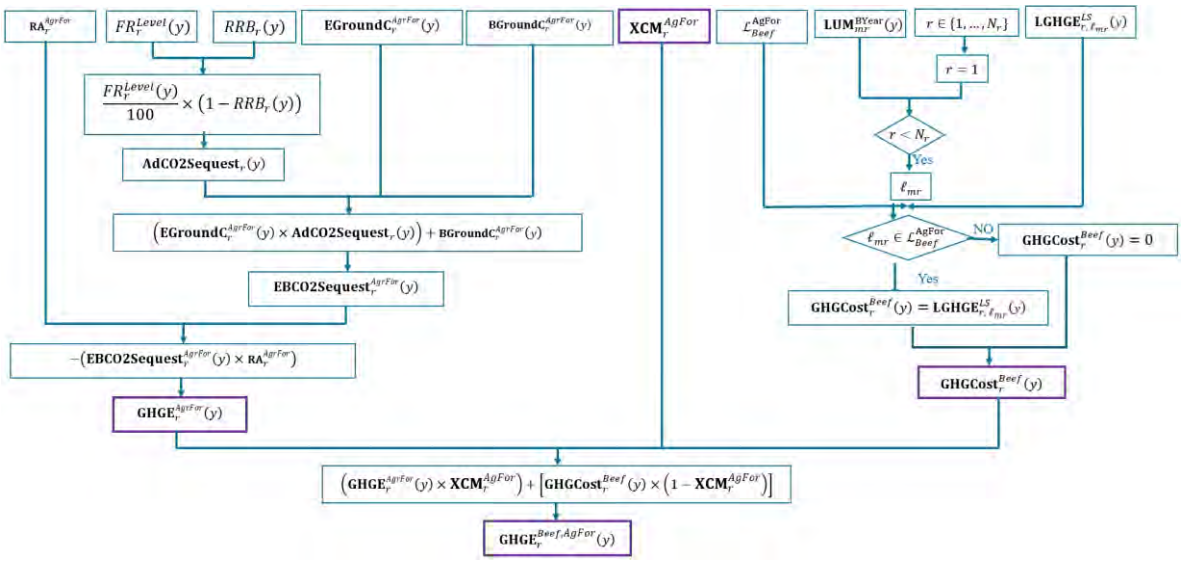

Figure 516 Greenhouse gas emissions for Beef-Agroforestry

16.6. Greenhouse Gas Emissions for Carbon Plantings (Block)

16.6.1. Average Annual GHG Sequestration for Carbon Plantings (Block) Adjusted for Fire and Reversal Risk

To compute the average annual greenhouse gas (GHG) sequestration for the carbon plantings (Block), while accounting for the fire risk sequestration adjustment factor $\mathbf{FRSAF}_r$ (Equation 311), other parameters such as the aboveground carbon sequestration $\mathbf{AGC}_r^{CPBlock}$ and the belowground carbon sequestration $\mathbf{BGC}_r^{CPBlock}$ are required. $\mathbf{AGHG}_r^{CPBlock}$ is computed as:

$\mathbf{AGHG}_r^{CPBlock} = (\mathbf{AGC}_r^{CPBlock} \times \mathbf{FRSAF}_r) + \mathbf{BGC}_r^{CPBlock}$	Equation 322

where,

- $\mathbf{AGC}_r^{CPBlock}$ represents the average annual aboveground CO2 sequestration per hectare for the carbon plantings (Block) (Figure 517)
- $\mathbf{BGC}_r^{CPBlock}$ represents the average annual belowground CO2 sequestration per hectare for the carbon plantings (Block) (Figure 518)
- $\mathbf{FRSAF}_r$ represents the Fire Risk Sequestration Adjustment Factor (Equation 311)
- $\mathbf{AGHG}_r^{CPBlock}$ represents the average annual greenhouse gas (GHG) sequestration for the carbon plantings (Block) (Figure 519)

16.6.2. Final GHG Emissions Calculation for the Carbon Plantings (Block) per Cell

Combining the above equations, the total GHG emissions for the carbon plantings (Block) ($\mathbf{GHGE}_r^{CPBlock}$) can be expressed as:

$\mathbf{GHGE}_r^{CPBlock} = -(\mathbf{AGHG}_r^{CPBlock} \times \mathbf{RA}_r)$	Equation 323

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where,

- $\mathbf{AGHG}_r^{CPBlock}$ represents the average annual greenhouse gas (GHG) sequestration for the carbon plantings (Block) (Equation 322,Figure 524)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{GHGE}_r^{CPBlock}$ represents the total GHG emissions for the carbon plantings (Block) (Figure 520)

This equation calculates the net greenhouse gas emissions, considering both aboveground and belowground carbon sequestration, adjusted for fire risk and the potential reversal of carbon sequestration. The flowchart of computing $\mathbf{GHGE}_r^{CPBlock}$ is illustrated in Figure 521.

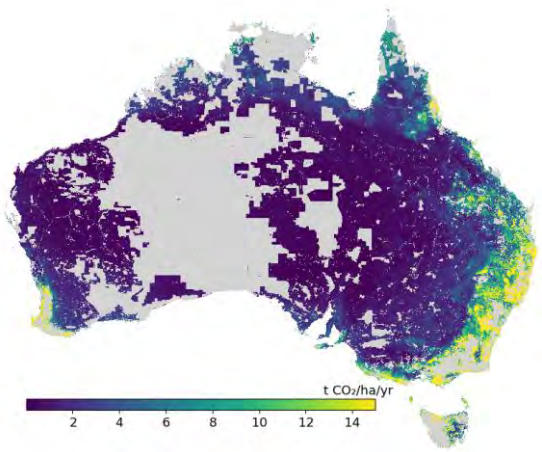

Figure 517 The average annual above-ground CO2 sequestration per hectare for carbon plantings (Block)

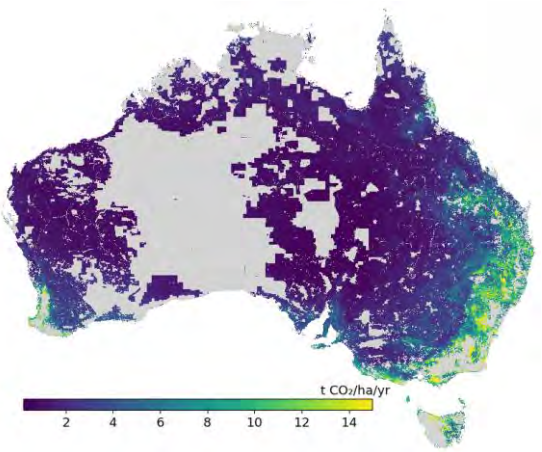

Figure 518 The average annual below-ground CO2 sequestration per hectare for carbon plantings (Block)

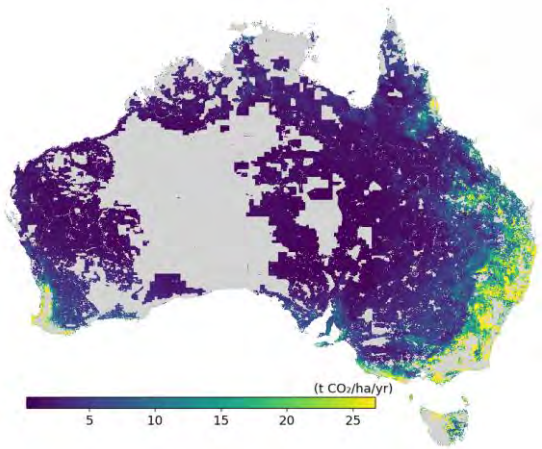

Figure 519 Average Annual GHG Sequestration for Carbon Plantings (Block) Adjusted for Fire and Reversal Risk for year 2050

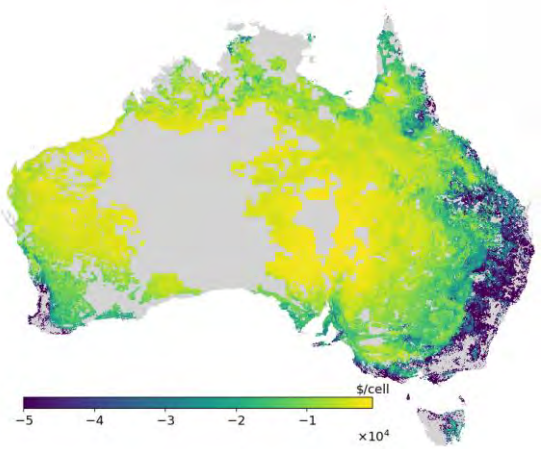

Figure 520 The total GHG emissions for carbon plantings (Block) for year 2050

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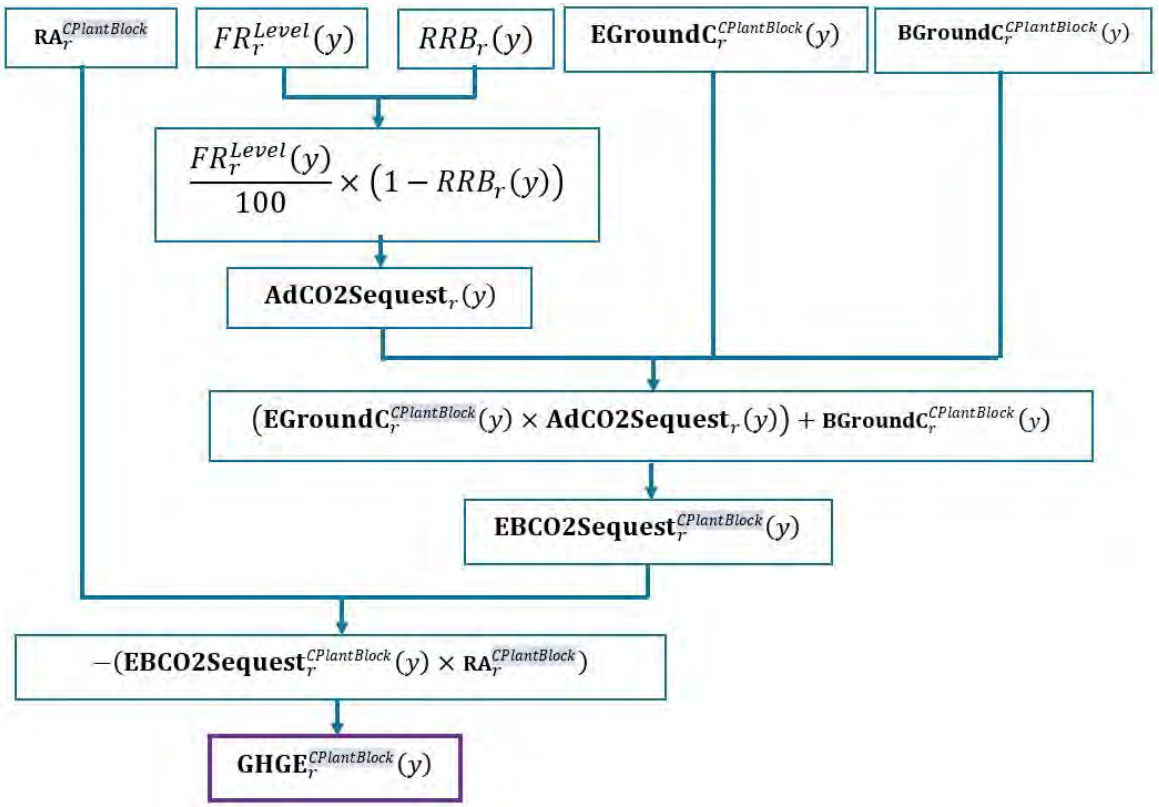

Figure 521 Greenhouse gas emissions for Carbon Plantings (Belt)

16.7. Greenhouse Gas Emissions for Carbon Plantings (Belt)

16.7.1. Average Annual GHG Sequestration for Carbon Plantings (Belt) Adjusted for Fire and Reversal Risk

To compute the average annual greenhouse gas (GHG) sequestration for the carbon plantings (Belt), while accounting for the fire risk sequestration adjustment factor $\mathbf{FRSAF}_r$ (Equation 311), other parameters such as the aboveground carbon sequestration $\mathbf{AGC}_r^{CPBelt}$ and the belowground carbon sequestration $\mathbf{BGC}_r^{CPBelt}$ are required. $\mathbf{AGHG}_r^{CPBelt}$ is computed as:

$\mathbf{AGHG}_r^{CPBelt} = (\mathbf{AGC}_r^{CPBelt} \times \mathbf{FRSAF}_r) + \mathbf{BGC}_r^{CPBelt}$	Equation 324

where,

- $\mathbf{AGC}_r^{CPBelt}$ represents the average annual aboveground CO2 sequestration per hectare for the carbon plantings (Belt) (Figure 522)
- $\mathbf{BGC}_r^{CPBelt}$ represents the average annual belowground CO2 sequestration per hectare for the carbon plantings (Belt) (Figure 523)
- $\mathbf{FRSAF}_r$ represents the Fire Risk Sequestration Adjustment Factor (Equation 311)
- $\mathbf{AGHG}_r^{CPBelt}$ represents the average annual greenhouse gas (GHG) sequestration for the carbon plantings (Belt) (Figure 524)

16.7.2. Final GHG Emissions Calculation for the carbon plantings (Belt) per Cell

Combining the above equations, the total GHG emissions for the carbon plantings (Belt) ($\mathbf{GHGE}_r^{Base,CPBelt}$) can be expressed as:

$\mathbf{GHGE}_r^{Base,CPBelt} = -(\mathbf{AGHG}_r^{CPBelt} \times \mathbf{RA}_r)$	Equation 325

where,

- $\mathbf{AGHG}_r^{CPBelt}$ represents the average annual greenhouse gas (GHG) sequestration for the carbon plantings (Belt) (Equation 324,Figure 524)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{GHGE}_r^{Base,CPBelt}$ represents the total GHG emissions for the carbon plantings (Belt)(Figure 525)

This equation calculates the net greenhouse gas emissions, considering both aboveground and belowground carbon sequestration, adjusted for fire risk and the potential reversal of carbon sequestration. The flowchart of computing $\mathbf{GHGE}_r^{Base,CPBelt}$ is illustrated in Figure 521.

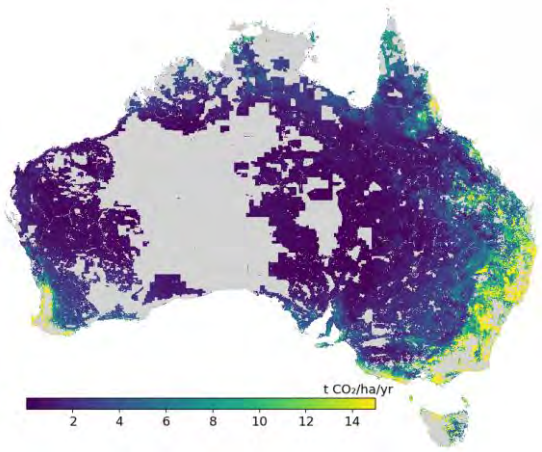

Figure 522 The average annual above-ground CO2 sequestration per hectare for carbon plantings (Belt)

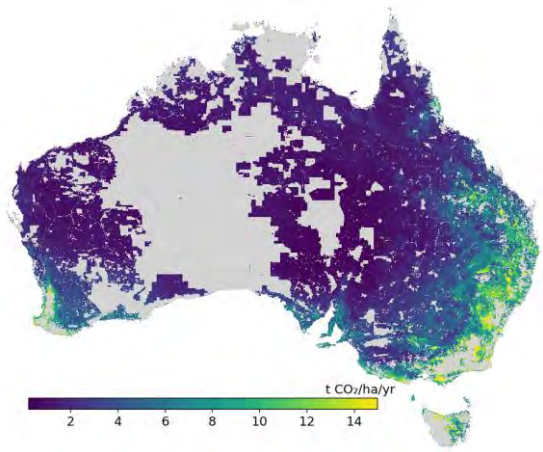

Figure 523 The average annual below-ground CO2 sequestration per hectare for carbon plantings (Belt)

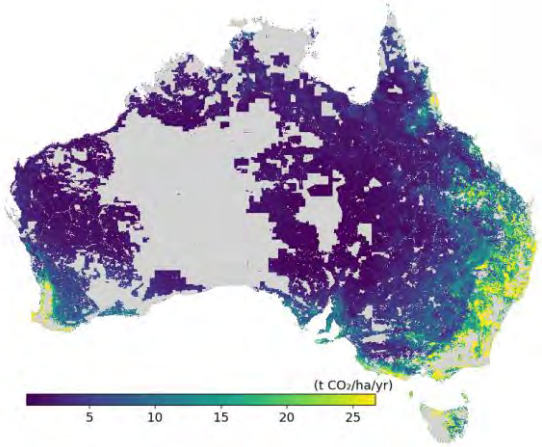

Figure 524 Average Annual GHG Sequestration for Carbon Plantings (Belt) Adjusted for Fire and Reversal Risk for year 2050

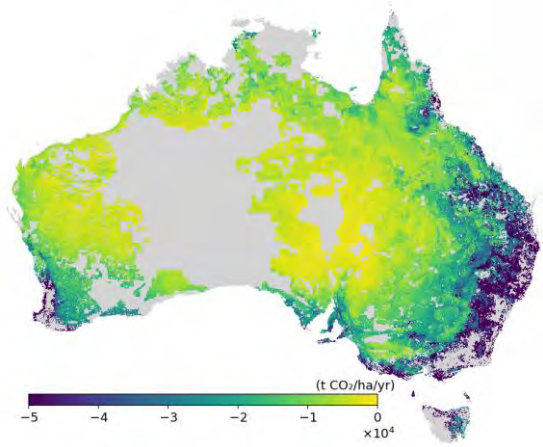

Figure 525 The total GHG emissions for carbon plantings (Belt) for year 2050

16.8. The Greenhouse Gas Emissions for Sheep-Carbon Plantings (Belt)

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This section computes the total GHG emissions for a combination of sheep farming and the base Carbon Planting (Belt) by adjusting the total GHG emissions for the for the base Carbon Planting (Belt) $\mathbf{GHGE}_r^{Base,CPBelt}$ (Equation 325) and the specific GHG emissions related to sheep farming. The equation is:

$$\mathbf{GHGE}_r^{Sheep,CPBelt} = \left(\mathbf{GHGE}_r^{Base,CPBelt} \times \mathbf{XCM}_r^{CPBelt}\right) + \left[\mathbf{GHGE}_r^{Sheep} \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$$	Equation 326

where,

- $\mathbf{GHGE}_r^{Sheep,CPBelt}$ is the total GHG emissions for sheep–carbon planting (Belt) for cell r
- $\mathbf{GHGE}_r^{Base,CPBelt}$ is the total GHG emissions for the base carbon planting (Belt) for cell r (Equation 325, Figure 525)
- $\mathbf{GHGE}_r^{Sheep}$ is the GHG emissions associated with sheep farming in modified land under dryland management system, calculated by Equation 319 (Figure 511).
- $\mathbf{XCM}_r^{CPBelt}$ is the exclusion matrix representing the proportion of land used for sheep-carbon plantings for the belt arrangement **(**Equation 304 and Figure 479)

The computed GHG emissions for sheep-carbon planting (Belt) $\mathbf{GHGE}_r^{Sheep,CPBelt}$ for year 2050 are illustrated in Figure 526.

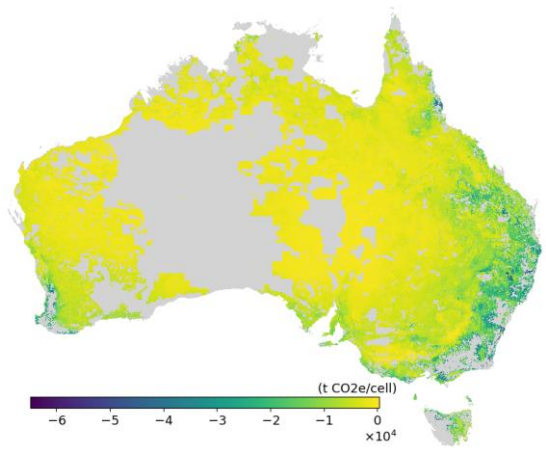	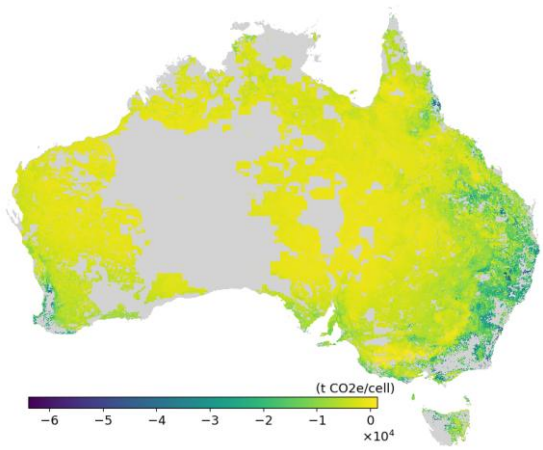
Figure 526 The total GHG emissions from sheep-Carbon Planting (Belt) under dryland management system	Figure 527 The total GHG emissions from beef-Carbon Planting (Belt) under dryland management system

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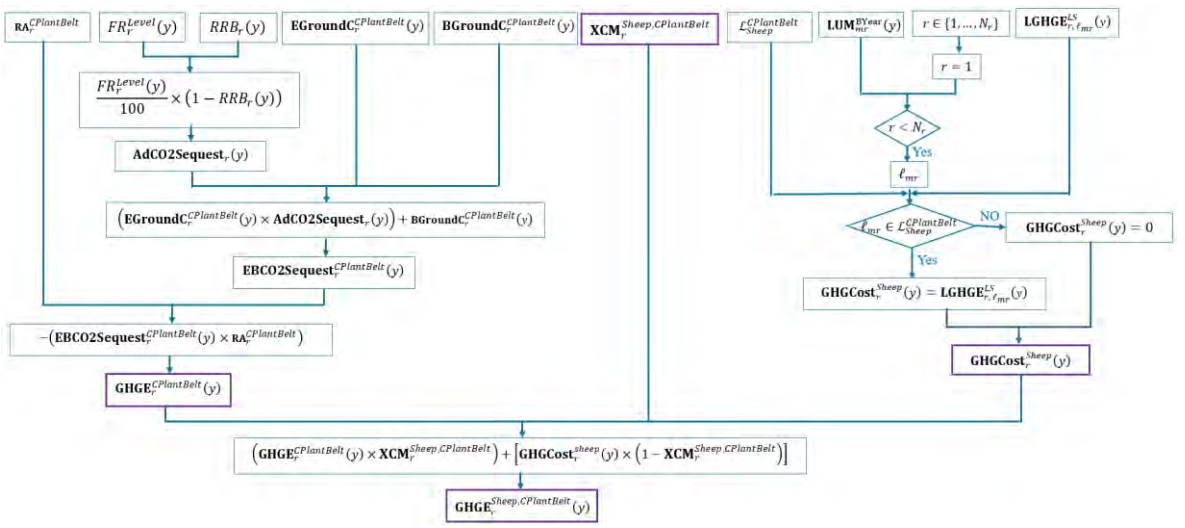


Figure 528 Greenhouse gas emissions for sheep farming and Carbon Plantings (Belt)

16.9. **The Greenhouse Gas Emissions for Beef-Carbon Plantings (Belt)**

This section computes the total GHG emissions for a combination of beef farming and the base carbon planting (Belt) by adjusting the total GHG emissions for the base Carbon Planting (Belt) $\mathbf{GHGE}_r^{CPBelt}$ (Equation 317) and the specific GHG emissions related to beef farming. The equation is:

$$\mathbf{GHGE}_r^{Beef,CPBelt} = \left(\mathbf{GHGE}_r^{Base,CPBelt} \times \mathbf{XCM}_r^{CPBelt}\right) + \left[\mathbf{GHGE}_r^{Beef} \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$$	Equation 327

where,

- $\mathbf{GHGE}_r^{Beef,CPBelt}$ is the total GHG emissions for beef–carbon planting (Belt) for cell r
- $\mathbf{GHGE}_r^{Base,CPBelt}$ is the total GHG emissions for the base Carbon Planting (Belt) for cell r (Equation 325, Figure 525)
- $\mathbf{GHGE}_r^{Beef}$ is the GHG emissions associated with beef farming in modified land under dryland management system, calculated by Equation 321 (Figure 514).
- $\mathbf{XCM}_r^{CPBelt}$ is the exclusion matrix representing the proportion of land used for sheep-carbon plantings for the belt arrangement (Equation 304 and Figure 479)

The computed GHG emissions for beef-carbon planting (Belt) $\mathbf{GHGE}_r^{Beef,CPBelt}$ for year 2050 are illustrated in Figure 529.

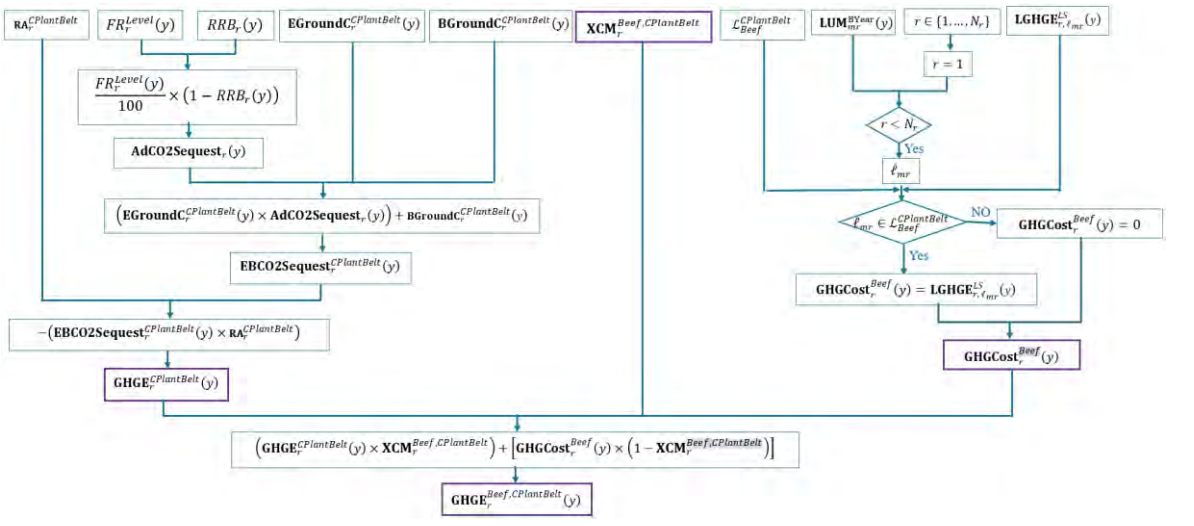


Figure 529 Greenhouse gas emissions for beef farming and Carbon Plantings (Belt)

16.10. Greenhouse Gas Emissions for Bioenergy with Carbon Capture and Storage (BECCS)

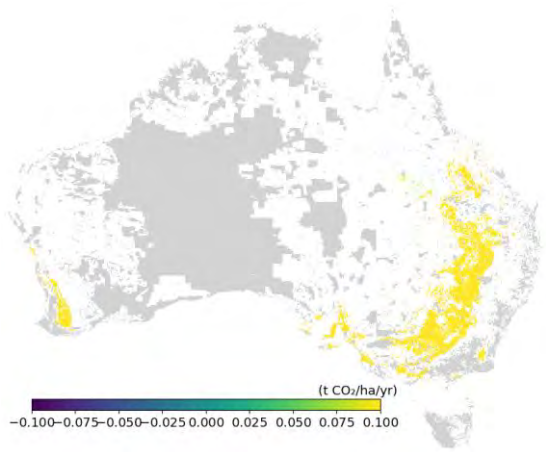
This section computes the greenhouse gas (GHG) emissions for bioenergy with carbon capture and storage (BECCS). The GHG emissions are based on carbon sequestration data, adjusted for factors such as fire risk and the risk of reversal. The flowchart of the method is presented in Figure 532.

Combining the relevant parameters, the total GHG emissions for BECCS ($\mathbf{GHGE}_r^{BECCS}$) can be expressed as:

$\mathbf{GHGE}_r^{BECCS} = -(\mathbf{AGHG}_r^{BECCS} \times \mathbf{RA}_r)$	Equation 328

where,

- $\mathbf{AGHG}_r^{BECCS}$ represents the average annual greenhouse gas (GHG) sequestration for BECCS (Figure 530)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $\mathbf{GHGE}_r^{BECCS}$ represents the total GHG emissions for BECCS (Figure 531)



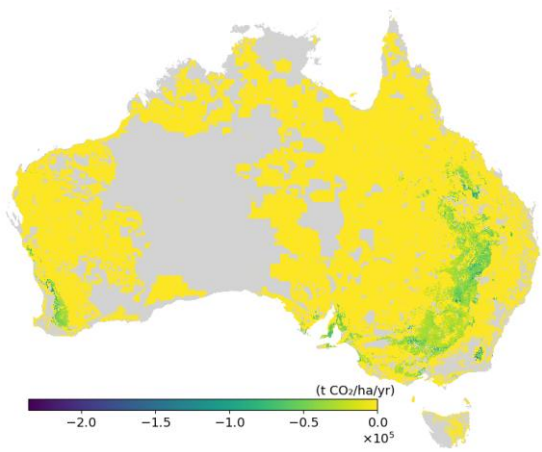


Figure 530 The average annual greenhouse gas (GHG) sequestration for BECCS under Dry land management system	Figure 531 The total GHG emissions for BECCS under Dry land management system

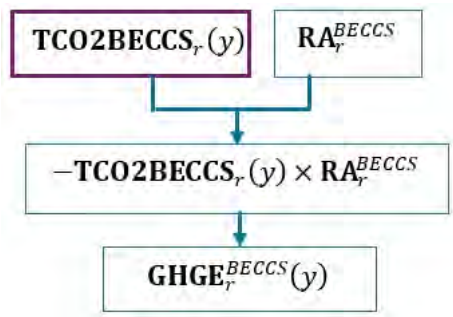


Figure 532 Greenhouse gas emissions for bioenergy with carbon capture and storage (BECCS)

16.11. Greenhouse Gas Emissions Matrix for all Non-Agricultural Land Uses

This section aggregates the greenhouse gas emissions of all non-agricultural land uses into a single matrix. The overall GHG matrix is constructed by concatenating the individual GHG vectors for each land use in the non-agricultural land-use set $\mathcal{L}_{\text{NonAgrLand}}$, as defined in Equation 13. The equation is:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 329
$\mathbf{GHGE}_{r\ell}^{NonAg}(y) = \text{concatenate}\begin{pmatrix} \mathbf{GHGE}_r^{EnvPlanting}, \mathbf{GHGE}_r^{RipPlant}, \mathbf{GHGE}_r^{Sheep,AgrFor}, \\ \mathbf{GHGE}_r^{Beef,AgrFor}, \mathbf{GHGE}_r^{CPBlock}, \mathbf{GHGE}_r^{Sheep,CPBelt}, \\ \mathbf{GHGE}_r^{Beef,CPBelt}, \mathbf{GHGE}_r^{BECCS} \end{pmatrix}$	

where,

- $\mathbf{GHGE}_{r\ell}^{NonAg}(y)$ is the aggregated greenhouse gas emissions matrix for all non-agricultural land uses in cell r for year y.
- $\mathcal{L}_{\text{NonAgrLand}}$ is a set the represents the classes of non-agricultural land uses (Equation 13)

The flowchart of computing $\mathbf{GHGE}_{r\ell}^{NonAg}$ is illustrated in Figure 533.

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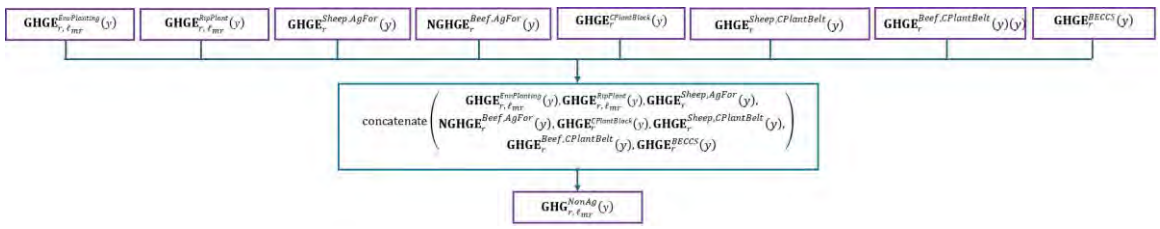

Figure 533 Greenhouse gas emissions matrix for non-Agricultural Land Uses

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Economics/Non Agricultural/ quantity.py

17. The Quantity of Non-Agricultural Land Use

17.1. Sheep Commodity Quantity Matrix Produced by Sheep Farming on Modified Land

This section computes the quantity of commodities produced by sheep across different cells. As mentioned in Equation 36, $\mathcal{L}_{\text{Commodities}}$ is a set that represents all the products considered in LUTO 2.0; where from this set, $\mathcal{L}^{Sheep}_{\text{Commodities}} \subset \mathcal{L}_{\text{Commodities}}$ represents the products associated with sheep farming (Equation 40). As Figure 534 illustrates, $\mathcal{L}^{Sheep}_{\text{Commodities}}$ corresponds to the same commodity set used in land-use classes $\text{Sheep} - \text{modified land}$ and $\text{Sheep} - \text{natural land}$.

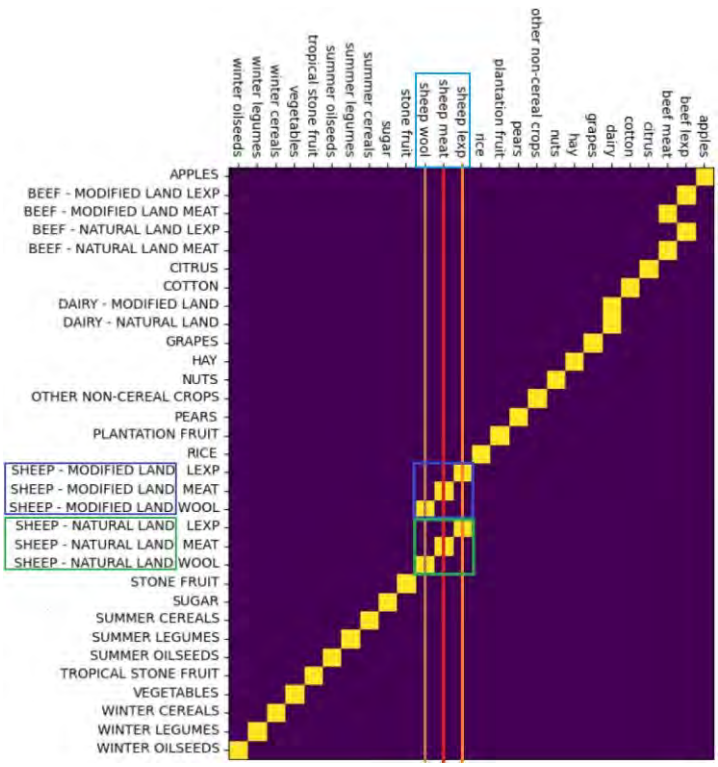


Figure 534 Land use to products matrix (**LU2ProdM**) for sheep farming under modified land

The commodity production matrix for the products associated with sheep farming $\mathbf{CPM}^{Sheep}_{\ell_{Com}}$ is initialized as a zero matrix of size $N_{Com} \times N_r$

$\forall r \in \{1, \dots, N_r\}\ \exists \ell_{mr}, \ell_{mr} \in \mathcal{L}_{\text{Commodities}}$	Equation 330
$\mathbf{CPM}^{Sheep}_{\ell_{Com}} = 0_{(N_{Com} \times N_r)}$	

where,

- N_{Com} is the number of commodities in $\mathcal{L}_{\text{Commodities}}$ (Equation 36), where in LUTO 2, $N_{Com} = 26$.
- N_r is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.

The values of $\mathbf{CPM}^{Sheep}_{\ell_{Com}}$ are updates as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\ \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	

$\mathbf{CPM}^{Sheep}_{r\ell_{Com}}(y) = \begin{cases} \mathbf{LQY}^{LS}_{r\ell_{Prod}}(y) & \text{If} \quad \ell_{Com} \in \mathcal{L}^{\text{Sheep}}_{\text{Commodities}} \\ 0 & \text{Otherwise} \end{cases}$	Equation 331

Here,

- $\mathcal{L}_{\text{Commodities}}$ is the set of all available commodities, which contains 26 members (Equation 36)
- $\mathcal{L}^{\text{Sheep}}_{\text{Commodities}}$ is the subset of commodities produced by sheep farming (Equation 40)
- $\mathbf{LQY}^{LS}_{\ell_{Prod}}$ is the computed livestock quantity (Equation 114)

By comparing the members of the sets $\mathcal{L}^{\text{Sheep}}_{\text{Commodities}}$ and $\mathcal{L}_{\text{Products}}$,, the values of $\mathbf{CPM}^{\text{Sheep}}_{r\ell_{Com}}$ remain zero for all commodities except those in $\mathcal{L}^{\text{Sheep}}_{\text{Commodities}}$ (Equation 40).

The assigned values to $\mathbf{CPM}^{\text{Sheep}}_{r\ell_{Com}}$ for the members of $\mathcal{L}^{\text{Sheep}}_{\text{Commodities}}$ are illustrated in Figure 535 - Figure 537.

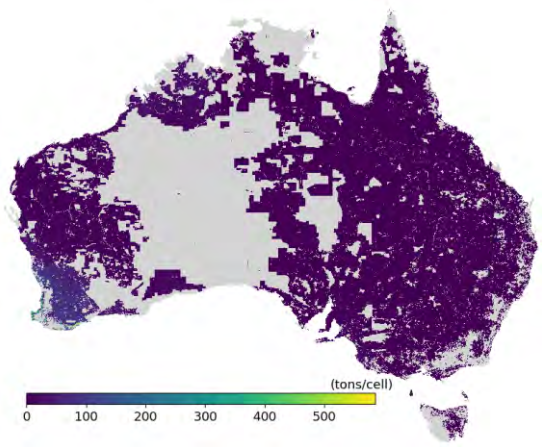
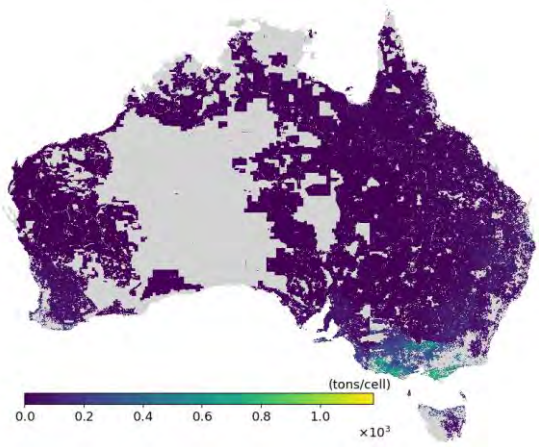
	

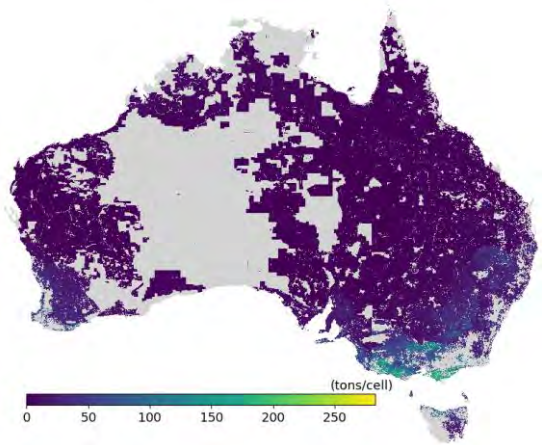
Figure 535 The quantity of commodity (ship live export) in each cell	Figure 536 The quantity of commodity (sheep meat) in each cell
	

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Figure 537 The quantity of commodity (sheep wool) in each cell	

17.2. Beef Commodity Quantity Matrix Produced by Beef Farming on Modified Land

This section computes the quantity of commodities produced by beef across different cells. As mentioned in Equation 36, $\mathcal{L}_{\text{Commodities}}$ is a set that represents all the products that considered in LUTO 2.0; from this set, $\mathcal{L}^{\text{Beef}}_{\text{Commodities}} \subset \mathcal{L}_{\text{Commodities}}$ represents the products associated with beef farming (Equation 41).

As Figure 534 illustrates, $\mathcal{L}^{\text{Beef}}_{\text{Commodities}}$ corresponds to the same commodity set used in land-use classes $\text{Beef} - \text{modified land}$ and $\text{Beef} - \text{natural land}$.

The commodity production matrix for the products associated with beef farming $\mathbf{CPM}^{Beef}_{\ell_{Com}}$ is initialized as a zero matrix of size $N_{Com} \times N_r$:

$\forall r \in \{1, \dots, N_r\}\ \exists \ell_{mr}, \ell_{mr} \in \mathcal{L}_{\text{Commodities}}$	Equation 332
$\mathbf{CPM}^{Beef}_{\ell_{Com}} = 0_{(N_{Com} \times N_r)}$	

where,

- N_{Com} is the number of commodities in $\mathcal{L}_{\text{Commodities}}$ (Equation 36), where in LUTO 2, $N_{Com} = 26$
- N_r is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$

The values of $\mathbf{CPM}^{Beef}_{\ell_{Com}}$ are updates as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\ \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 333
$\mathbf{CPM}^{Beef}_{r\ell_{Com}}(y) = \begin{cases} \mathbf{LQY}^{LS}_{r\ell_{Prod}}(y) & \text{If} \quad \ell_{Com} \in \mathcal{L}^{\text{Beef}}_{\text{Commodities}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathcal{L}_{\text{Commodities}}$ is the set of all available commodities, which contains 26 members (Equation 36)
- $\mathcal{L}^{\text{Beef}}_{\text{Commodities}}$ is the set of all available commodities produced by beef farming (Equation 41)
- $\mathbf{LQY}^{LS}_{\ell_{Prod}}$ is the computed livestock quantity (Equation 114)

By comparing the members of the sets $\mathcal{L}^{\text{Beef}}_{\text{Commodities}}$ and $\mathcal{L}_{\text{Products}}$, the values of $\mathbf{CPM}^{Beef}_{r\ell_{Com}}$ remain zero for all other commodities except those in $\mathcal{L}^{\text{Beef}}_{\text{Commodities}}$ (Equation 41). The assigned values to $\mathbf{CPM}^{Beef}_{r\ell_{Com}}$ for the members of $\mathcal{L}^{\text{Beef}}_{\text{Commodities}}$ are illustrated in Figure 538 and Figure 539.

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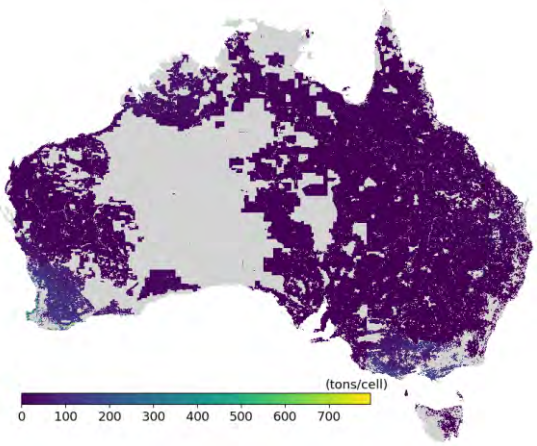	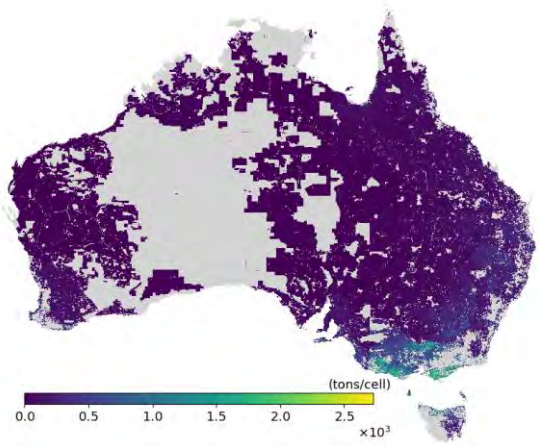
Figure 538 The quantity of commodity (beef live export) in each cell	Figure 539 The quantity of commodity (beef meat) in each cell

17.3. **Environmental Plantings Quantity**

This section defines the commodity production matrix for environmental plantings. Since environmental planting is not a member of $\mathcal{L}_{\text{Commodities}}$ and $\mathcal{L}_{\text{Products}}$, the values of $\mathbf{CPM}_{\ell_{Com}}^{EnvPlanting}$ are zero:

$\mathbf{CPM}_{\ell_{Com}}^{EnvPlanting}(y) = 0_{(N_{Com} \times N_r)}$	Equation 334

where,

- N_{Com} is the number of commodities in $\mathcal{L}_{\text{Commodities}}$ (Equation 36), where in LUTO 2, $N_{Com} = 26$
- N_r is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$

17.4. **Riparian Plantings Quantity**

This section defines the commodity production matrix for riparian plantings. Since riparian planting is not a member of $\mathcal{L}_{\text{Commodities}}$ and $\mathcal{L}_{\text{Products}}$, the values of $\mathbf{CPM}_{\ell_{Com}}^{RipPlant}$ are zero:

$\mathbf{CPM}_{\ell_{Com}}^{RipPlant}(y) = 0_{(N_{Com} \times N_r)}$	Equation 335

where,

- N_{Com} is the number of commodities in $\mathcal{L}_{\text{Commodities}}$ (Equation 36), where in LUTO 2, $N_{Com} = 26$
- N_r is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$

17.5. **Agroforestry Base Quantity**

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This section defines the commodity production matrix for agroforestry base. Since agroforestry base is not a member of $\mathcal{L}_{\text{Commodities}}$ and $\mathcal{L}_{\text{Products}}$, the values of $\mathbf{CPM}_{\ell_{Com}}^{AgrFor}$ are zero:

$\mathbf{CPM}_{\ell_{Com}}^{AgrFor}(y) = 0_{(N_{Com} \times N_r)}$	Equation 336

where,

- N_{Com} is the number of commodities in $\mathcal{L}_{\text{Commodities}}$ (Equation 36), where in LUTO 2, $N_{Com} = 26$
- N_r is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$

17.6. Sheep Agroforestry Quantity

This section computes the quantity of commodities for sheep agroforestry, as

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 337
$\mathbf{CPM}_{\ell_{Com}}^{Sheep,AgFor}(y) = \left[\mathbf{CPM}_{\ell_{Com}}^{Sheep}(y) \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right] + \left(\mathbf{CPM}_{\ell_{Com}}^{AgrFor} \times \mathbf{XCM}_r^{AgFor}\right)$	

where,

- $\mathbf{CPM}_{\ell_{Com}}^{Sheep}$ is produced using Equation 331
- $\mathbf{CPM}_{\ell_{Com}}^{AgrFor}$ is produced using Equation 336
- $\mathbf{XCM}_r^{AgFor}$ is the exclusion matrix representing the proportion of land used for agroforestry (Equation 295 and Figure 479)

Since $\mathbf{CPM}_{\ell_{Com}}^{AgrFor}$ is a zeros matrix (Equation 336), Equation 337 simplifies to:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 338
$\mathbf{CPM}_{\ell_{Com}}^{Sheep,AgFor}(y) = \mathbf{CPM}_{\ell_{Com}}^{Sheep}(y) \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)$	

The assigned values to $\mathbf{CPM}_{r\ell_{Com}}^{Sheep,AgFor}$ for the members of $\mathcal{L}_{\text{Commodities}}^{\text{Sheep}}$ are illustrated in Figure 540 - Figure 542.

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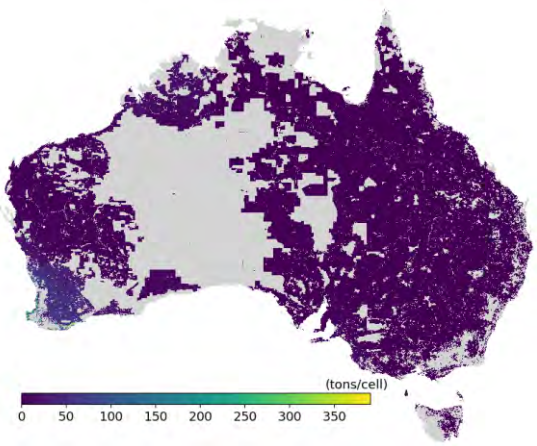	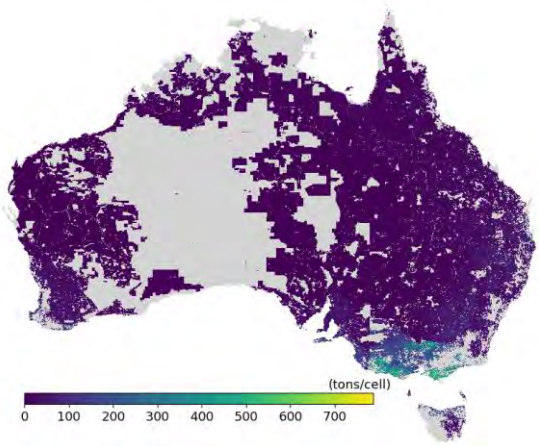
Figure 540 The quantity of the commodity (sheep live export) for Sheep-Agroforestry	Figure 541 The quantity of the commodity (sheep meat) for Sheep-Agroforestry
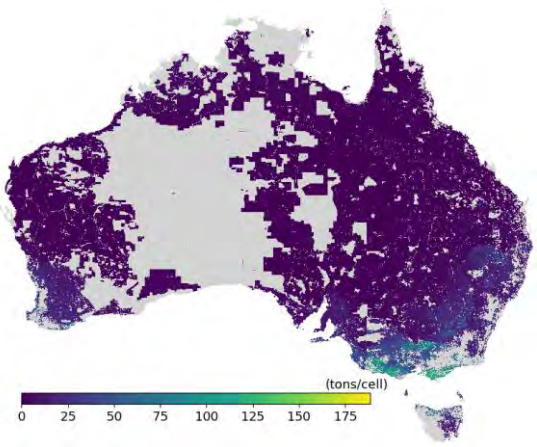	
Figure 542 The quantity of the commodity (sheep wool) for Sheep-Agroforestry	

17.7. **Beef Agroforestry Quantity**

This section computes the quantity of commodities for beef agroforestry, as

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 339
$\mathbf{CPM}_{\ell_{Com}}^{Beef,AgFor}(y) = \left[\mathbf{CPM}_{\ell_{Com}}^{Beef}(y) \times \left(1 - \mathbf{XCM}_{r}^{AgFor}\right)\right] + \left(\mathbf{CPM}_{\ell_{Com}}^{AgrFor}(y) \times \mathbf{XCM}_{r}^{AgFor}\right)$	

where,

- $\mathbf{CPM}_{\ell_{Com}}^{Beef}$ is produced using Equation 333
- $\mathbf{CPM}_{\ell_{Com}}^{AgrFor}$ is produced using Equation 336

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- $\mathbf{XCM}_r^{AgFor}$ is the exclusion matrix representing the proportion of land used for agroforestry (Equation 295 and Figure 479)

Since $\mathbf{CPM}_{\ell_{Com}}^{AgrFor}$ is a zeros matrix (Equation 336), Equation 339 simplifies to:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 340
$\mathbf{CPM}_{\ell_{Com}}^{Beef,AgFor}(y) = \mathbf{CPM}_{\ell_{Com}}^{Beef}(y) \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)$	

The assigned values to $\mathbf{CPM}_{r\ell_{Com}}^{Beef,AgFor}$ for the members of $\mathcal{L}_{\text{Commodities}}^{\text{Sheep}}$ are illustrated in Figure 543 - Figure 544.

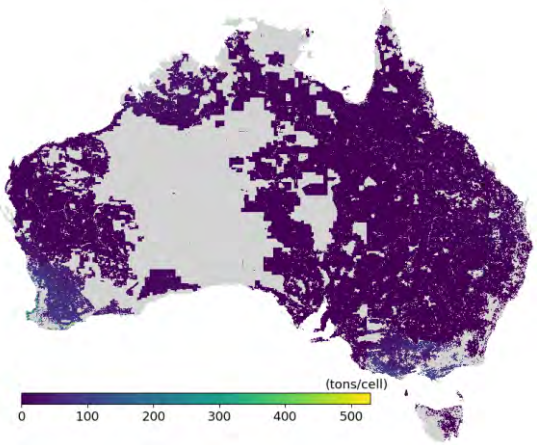	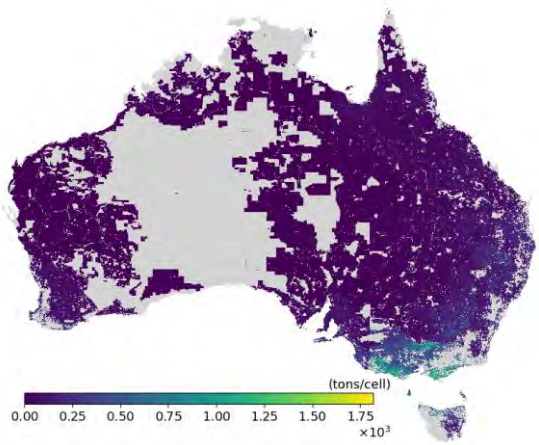
Figure 543 The quantity of the commodity (Beef live export) in each cell for beef-agroforestry	Figure 544 The quantity of the commodity (Beef meat) in each cell for beef-agroforestry

17.8. Carbon Plantings Block Quantity

This section defines the commodity production matrix for carbon plantings (Block). Since carbon planting (Block) is not a member of $\mathcal{L}_{\text{Commodities}}$ and $\mathcal{L}_{\text{Products}}$; the values of $\mathbf{CPM}_{\ell_{Com}}^{CPlantBlock}$ are zero:

$\mathbf{CPM}_{\ell_{Com}}^{CPBlock}(y) = 0_{(N_{Com} \times N_r)}$	Equation 341

where,

- N_{Com} is the number of commodities in $\mathcal{L}_{\text{Commodities}}$ (Equation 36), where in LUTO 2, $N_{Com} = 26$
- N_r is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$

17.9. Carbon Plantings Belt Base Quantity

This section defines the commodity production matrix for carbon plantings (Belt). Since carbon planting (Belt) base is not a member of $\mathcal{L}_{\text{Commodities}}$ and $\mathcal{L}_{\text{Products}}$, the values of $\mathbf{CPM}_{\ell_{Com}}^{CPlantBelt}$ are zero:

$\mathbf{CPM}_{\ell_{Com}}^{CPBelt}(y) = 0_{(N_{Com} \times N_r)}$	Equation 342

where,

- N_{Com} is the number of commodities in $\mathcal{L}_{\text{Commodities}}$ (Equation 36), where in LUTO 2, $N_{Com} = 26$
- N_r is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$

17.10. Sheep Carbon Plantings Belt Quantity

This section computes the quantity of commodities for sheep carbon plantings (Belt), as

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 343
$\mathbf{CPM}_{\ell_{Com}}^{Sheep,CPBelt}(y) = \left[\mathbf{CPM}_{\ell_{Com}}^{Sheep}(y) \times (1 - \mathbf{XCM}_r^{CPBelt})\right] + \left(\mathbf{CPM}_{\ell_{Com}}^{CPBelt} \times \mathbf{XCM}_r^{CPBelt}\right)$	

where,

- $\mathbf{CPM}_{\ell_{Com}}^{Sheep}$ is produced using Equation 331
- $\mathbf{CPM}_{\ell_{Com}}^{CPBelt}$ is produced using Equation 341
- $\mathbf{XCM}_r^{CPBelt}$ is the exclusion matrix representing the proportion of land used for sheep-carbon plantings for the belt arrangement (Equation 304 and Figure 479)

Since $\mathbf{CPM}_{\ell_{Com}}^{CPBelt}$ is a zeros matrix (Equation 341), Equation 343 simplifies to:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 344
$\mathbf{CPM}_{\ell_{Com}}^{Sheep,CPBelt}(y) = \mathbf{CPM}_{\ell_{Com}}^{Sheep}(y) \times (1 - \mathbf{XCM}_r^{CPBelt})$	

The assigned values to $\mathbf{CPM}_{r\ell_{Com}}^{Sheep,CPBelt}$ for the members of $\mathcal{L}_{\text{Commodities}}^{\text{Sheep}}$ are illustrated in Figure 545 - Figure 547.

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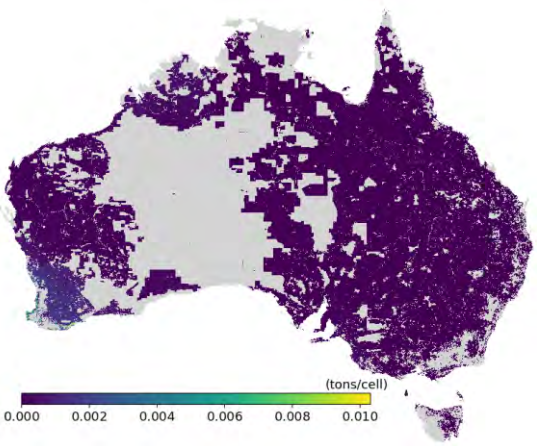	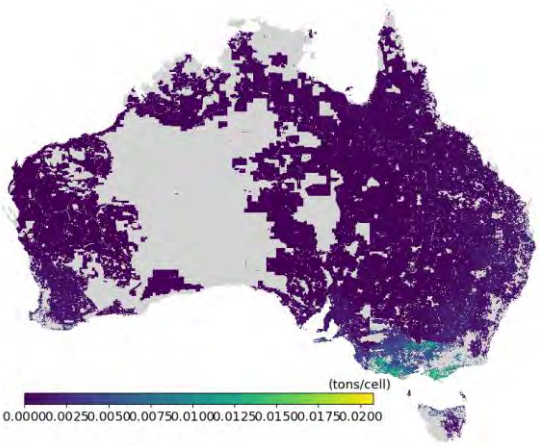
Figure 545 The quantity of the commodity (sheep live export) in each cell for Sheep- Carbon Plantings Belt	Figure 546 The quantity of the commodity (sheep meat) in each cell for Sheep- Carbon Plantings Belt
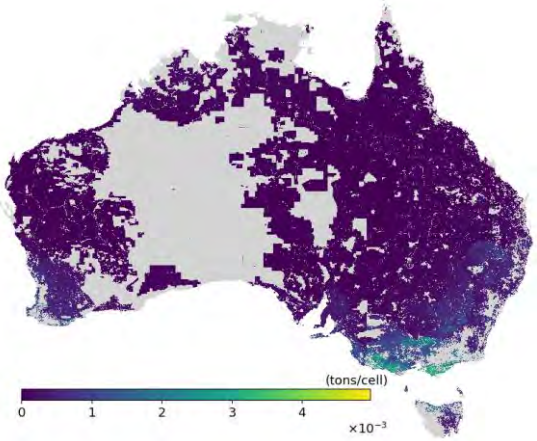	
Figure 547 The quantity of the commodity (sheep wool) in each cell for Sheep- Carbon Plantings Belt	

17.11. Beef Carbon Plantings Belt Quantity

This section computes the quantity of commodities for beef carbon plantings (Belt), as

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 345
$\mathbf{CPM}_{\ell_{Com}}^{Beef,CPBelt}(y) = \left[\mathbf{CPM}_{\ell_{Com}}^{Beef}(y) \times (1 - \mathbf{XCM}_{r}^{CPBelt})\right] + \left(\mathbf{CPM}_{\ell_{Com}}^{CPBelt}(y) \times \mathbf{XCM}_{r}^{CPBelt}\right)$	

where,

- $\mathbf{CPM}_{\ell_{Com}}^{Beef}$ is produced using Equation 333

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- $\mathbf{CPM}_{\ell_{Com}}^{CPBelt}$ is produced using Equation 341
- $\mathbf{XCM}_{r}^{CPBelt}$ is the exclusion matrix representing the proportion of land used for sheep-carbon plantings for the belt arrangement (Equation 304 and Figure 479)

Since $\mathbf{CPM}_{\ell_{Com}}^{CPBelt}$ is a zeros matrix (Equation 341), Equation 346 simplifies to:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell_{Com}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 346
$\mathbf{CPM}_{\ell_{Com}}^{Beef,CPBelt}(y) = \mathbf{CPM}_{\ell_{Com}}^{Beef}(y) \times (1 - \mathbf{XCM}_{r}^{CPBelt})$	

The assigned values to $\mathbf{CPM}_{r\ell_{Com}}^{Beef,CPBelt}$ for the members of $\mathcal{L}_{\text{Commodities}}^{\text{Beef}}$ are illustrated in Figure 548 - Figure 549.

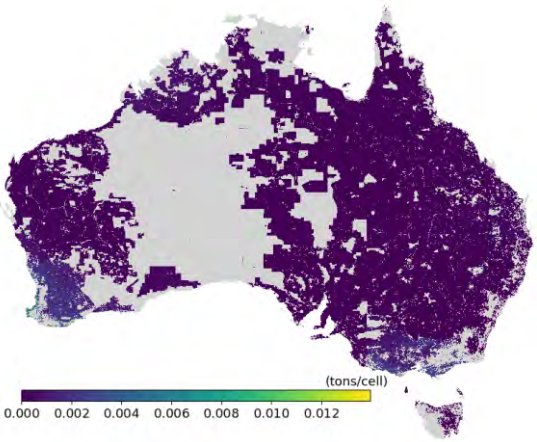	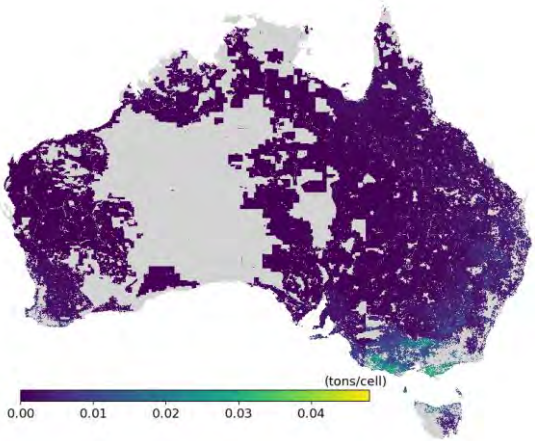
Figure 548 The quantity of the commodity (Beef live export) in each cell for Beef- Carbon Plantings Belt	Figure 549 The quantity of the commodity (Beef meat) in each cell for Beef- Carbon Plantings Belt

17.12. BECCS Quantity

This section defines the commodity production matrix for bioenergy with carbon capture and storage (BECCS). Since BECCS is not a member of $\mathcal{L}_{\text{Commodities}}$ and $\mathcal{L}_{\text{Products}}$, the values of $\mathbf{CPM}_{\ell_{Com}}^{BECCS}$ are zero:

$\mathbf{CPM}_{\ell_{Com}}^{BECCS}(y) = 0_{(N_{Com} \times N_r)}$	Equation 347

where,

- N_{Com} is the number of commodities in $\mathcal{L}_{\text{Commodities}}$ (Equation 36), where in LUTO 2, $N_{Com} = 26$
- N_r is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$

17.13. Non-Agricultural Quantity Matrix Construction

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This section constructs the overall quantity matrix for non-agricultural land uses. Let the $\mathbf{CPM}_{r\ell}^{NonAg}$ matrix contain the non-agricultural quantity of commodities produced, where $\ell \in \mathcal{L}_{\text{NonAgrLand}}$, as defined in Equation 13. The overall quantity of produced commodities matrix for all non-agricultural land uses is constructed by concatenating the individual quantity of produced commodities vectors for each land uses in $\mathcal{L}_{\text{NonAgrLand}}$:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 348
$\mathbf{CPM}_{r\ell}^{NonAg}(y) = \text{concatenate}\begin{pmatrix} \mathbf{CPM}_r^{EnvPlanting}, \mathbf{CPM}_r^{RipPlant}, \mathbf{CPM}_r^{Sheep,AgrFor}, \\ \mathbf{CPM}_r^{Beef,AgrFor}, \mathbf{CPM}_r^{CPBlock}, \mathbf{CPM}_r^{Sheep,CPBelt}, \\ \mathbf{CPM}_r^{Beef,CPBelt}, \mathbf{CPM}_r^{BECCS} \end{pmatrix}$	

The flowchart of computing $\mathbf{CPM}_{r\ell}^{NonAg}$ is illustrated in Figure 550.

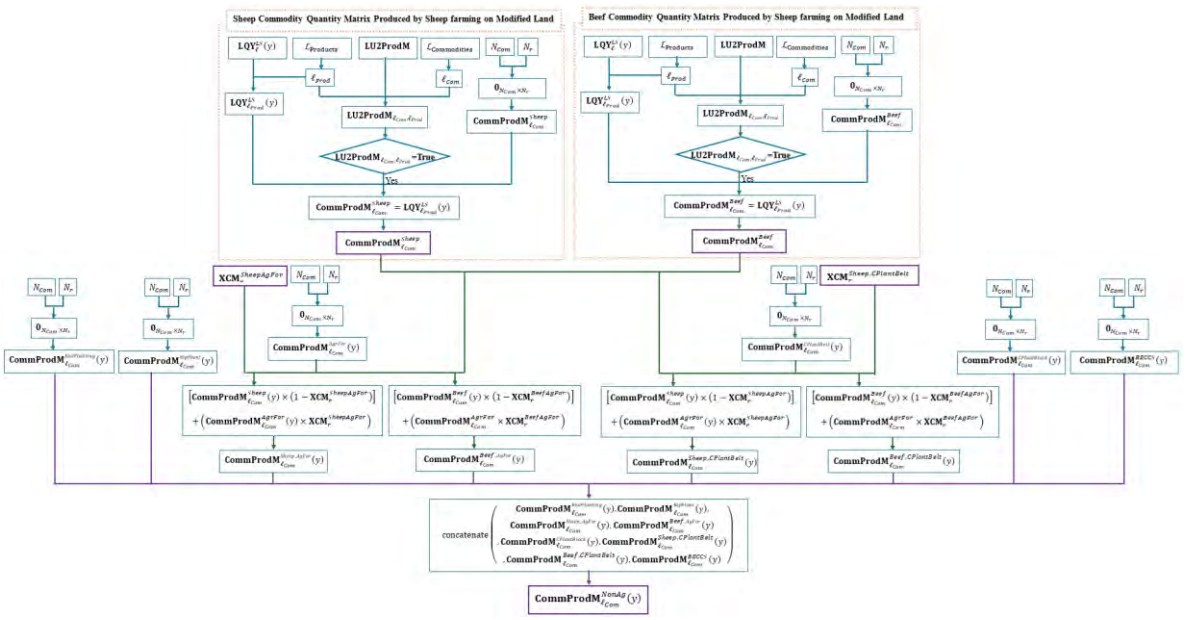

Figure 550 Non-Agricultural Quantity Matrix Construction

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Economics/Non Agricultural/ water.py

18. The Water Requirements

18.1. Environmental Plantings Water Requirements

The Water Yield Matrix for cell r in year y is determined by the type of vegetation present:

$\mathbf{WYield}_r(y) = \begin{cases} \mathbf{WYield}_r^{SR}(y) \times \mathbf{RA}_r & \text{if } \boldsymbol{G}_{(i)} \in \text{Short} - \text{rooted plants} \\ \mathbf{WYield}_r^{DR}(y) \times \mathbf{RA}_r & \text{if } \boldsymbol{G}_{(i)} \in \text{Deep} - \text{rooted plants} \\ \mathbf{WYield}_r^{NL}(y) \times \mathbf{RA}_r & \text{if } \boldsymbol{G}_{(i)} \in \text{Natural Area} \end{cases}$	Equation 349

where,

- $\mathbf{WYield}_r(y)$ is the Water Yield Matrix (Figure 558)
- $\mathbf{WYield}_r^{SR}(y)$ is the Water Yield value for Cells covered by Short-rooted plants (Figure 555)
- $\mathbf{WYield}_r^{DR}$ is the Water Yield value for Cells covered by Deep-rooted plants (Figure 556)
- $\mathbf{WYield}_r^{NL}(y)$ is the Water Yield value for Cells in the Natural Area Class (Figure 557)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

In LUTO 2.0, the Water Yield for Natural Areas $\mathbf{WYield}_r^{NL}(y)$ is calculated using the following equation.

$\mathbf{WYield}_r^{NL}(y) = \left(\mathbf{DRProp}_r(y) \times \mathbf{WYield}_r^{DR}(y)\right) + \left[\left(1 - \mathbf{DRProp}_r(y)\right) \times \mathbf{WYield}_r^{SR}(y)\right]$	Equation 350

Where:

- $\mathbf{DRProp}_r(y)$ represents the proportion of deep-rooted plants available in each cell (Figure 554)

The net water yield for environmental plantings is then:

$\mathbf{NetWYield}_r^{EnvPlanting}(y) = \mathbf{WYield}_r^{NL}(y)$	Equation 351

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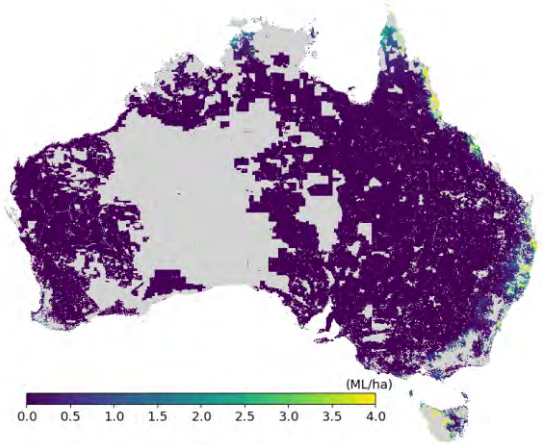


Figure 551 Water yields (runoff) from a cell into catchment by deep-rooted plants

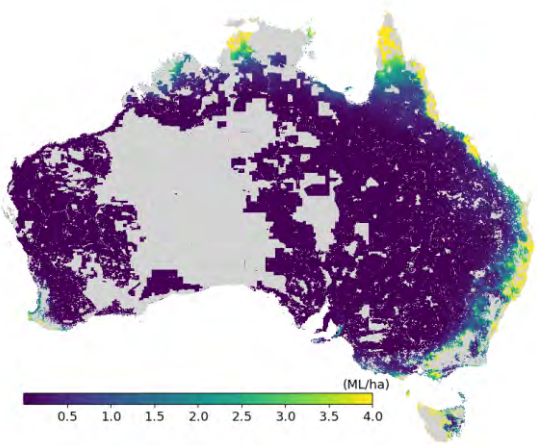


Figure 552 Water yields (runoff) from a cell into catchment by shallow-rooted plants

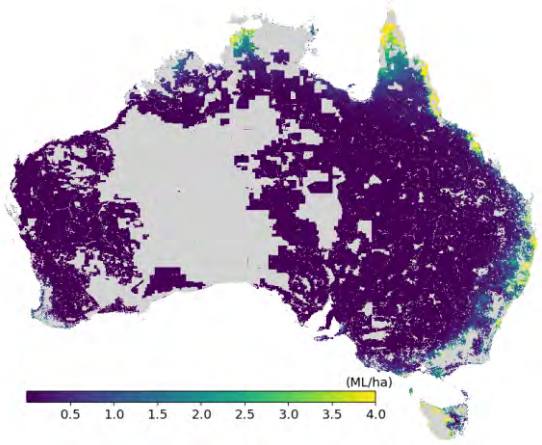


Figure 553 Water yields (runoff) from a cell into catchment by natural lands

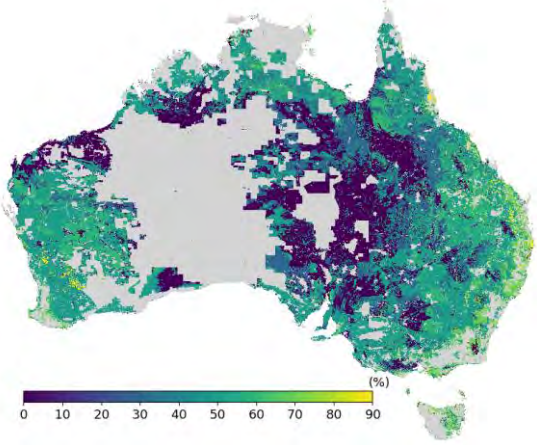
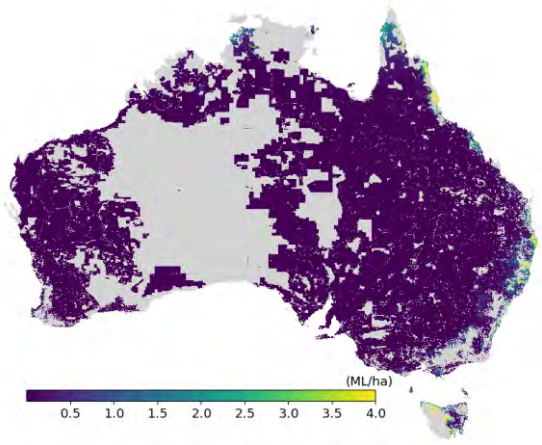


Figure 554 Proportion of deep-rooted plants available in each Cell



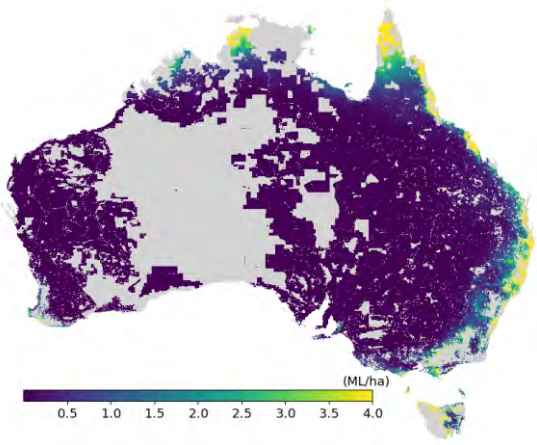


Figure 555 Water Yield value for cells covered by deep-rooted plants	Figure 556 Water Yield value for cells covered by shallow-rooted plants

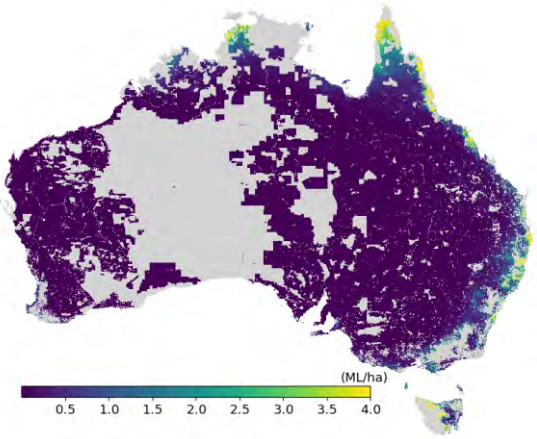
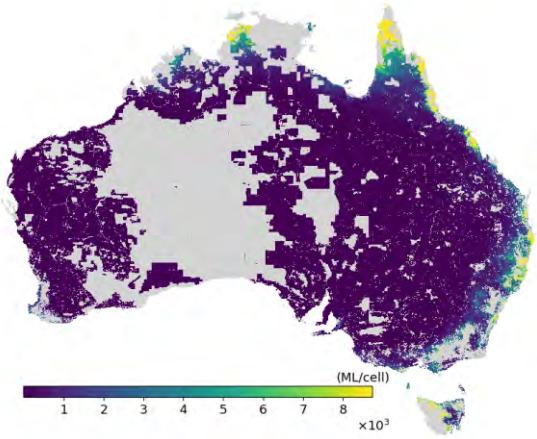

	

Figure 557 Water Yield value for cells covered by natural vegetation	Figure 558 Water requirements of environmental plantings

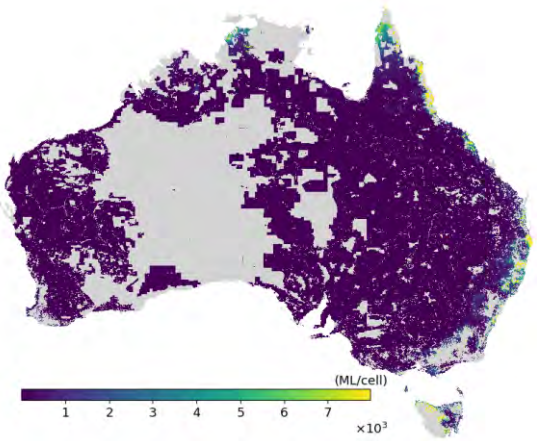
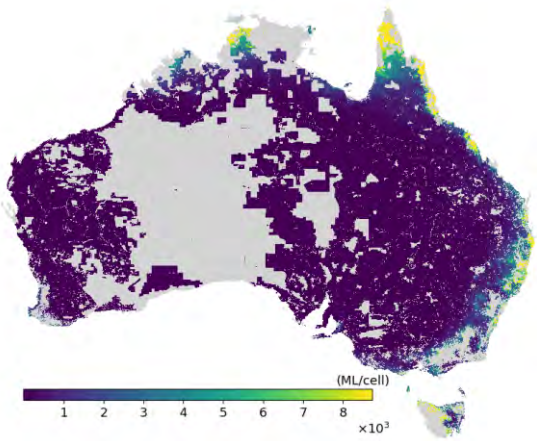

	

Figure 559 Water requirements of carbon plantings (Block)	Figure 560 Water requirements of riparian plantings

18.2. Carbon Plantings (Block) Water Requirements

This section computes the water requirements for carbon plantings in a block arrangement $\mathbf{NetWYield}_r^{CPBlock}$, representing the water usage if modified (i.e., cleared) land area was reforested with deep-rooted tree species. The assumption here is that plantations are all deep-rooted and thus use more water.

$\mathbf{NetWYield}_r^{CPBlock}(y) = \mathbf{WYield}_r^{DR}(y) \times \mathbf{RA}_r$	Equation 352

where,

- $\mathbf{WYield}_r^{DR}$ is the Water Yield value for Cells covered by deep-rooted plants (Figure 556)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{NetWYield}_r^{CPBlock}(y)$ is illustrated in Figure 559.

18.3. Riparian Plantings Water Requirements

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The calculation for riparian plantings water requirements is identical to that of environmental plantings.

$\mathbf{NetWYield}_r^{RipPlant}(y) = \mathbf{WYield}_r(y)$	Equation 353

where,

- $\mathbf{WYield}_r(y)$ represents the Water Yield Matrix determined by the type of vegetation present (Equation 349)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{NetWYield}_r^{RipPlant}(y)$ is illustrated in Figure 560.

18.4. Agroforestry Water Requirements (Base)

The base water requirements for agroforestry are identical to that of environmental plantings.

$\mathbf{NetWYield}_r^{Base,AgrFor}(y) = \mathbf{WYield}_r(y)$	Equation 354

where,

- $\mathbf{WYield}_r(y)$ represents the Water Yield Matrix which determined by the type of vegetation present (Equation 349)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{NetWYield}_r^{Base,AgrFor}(y)$ is illustrated in Figure 562.

18.5. Sheep Agroforestry Water Requirements

The water requirements for Sheep Agroforestry is computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}_{\text{Sheep, modified}}$	Equation 355
$\mathbf{NetWYield}_r^{Sheep,AgrFor}(y) = \left(\mathbf{NetWYield}_r^{Base,AgrFor}(y) \times \mathbf{XCM}_r^{AgFor}\right) + \left[\left(1 - \mathbf{XCM}_r^{AgFor}\right) \times \mathbf{NetWYield}_r^{Sheep}(y)\right]$	

where,

- $\mathbf{NetWYield}_r^{Base,AgrFor}$ is the base water requirements for agroforestry (Equation 354)
- $\mathbf{NetWYield}_r^{Sheep}$ is the sheep drinking water under dryland management systems (Equation 356 and Figure 563)
- $\mathbf{XCM}_r^{AgFor}$ is the updated exclusion matrix by considering Agroforestry Proportion (Equation 298)

The water requirements for sheep drinking water in lands under dryland management systems ($m = 0$) are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\text{BYear}}$	Equation 356

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$$\mathbf{NetWYield}_r^{Sheep}(y) = \begin{cases} \mathbf{WYield}_{mr\ell}^{Net}(y) & \text{If} \quad m = 0 \ \wedge \ \ell \in \mathcal{L}_{\text{Sheep, modified}} \\ 0 & \text{Otherwise} \end{cases}$$

where,

- $\mathbf{WYield}_{mr\ell}^{Net}(y)$ is the water net yield matrix (Equation 145).
- $\mathcal{L}_{\text{Sheep, modified}}$ is introduced in Equation 6

The computed $\mathbf{NetWYield}_r^{Base,AgrFor}$, $\mathbf{NetWYield}_r^{Sheep}(y)$, and $\mathbf{NetWYield}_r^{Sheep,AgFor}(y)$ are illustrated in Figure 562, Figure 563, and Figure 564, respectively. Moreover, the flowchart of $\mathbf{NetWYield}_r^{Sheep,AgFor}$ is illustrated in Figure 561.

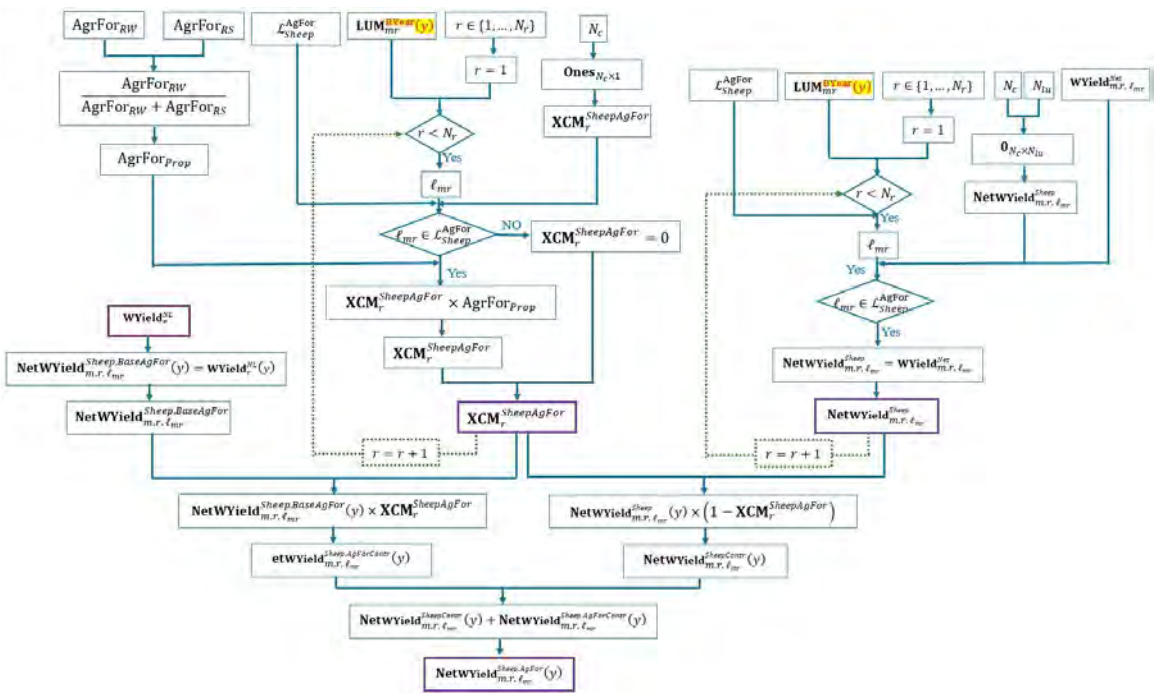

Figure 561 Sheep Agroforestry Water Requirements

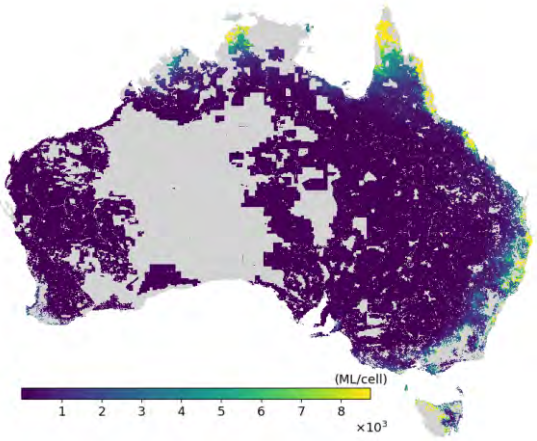	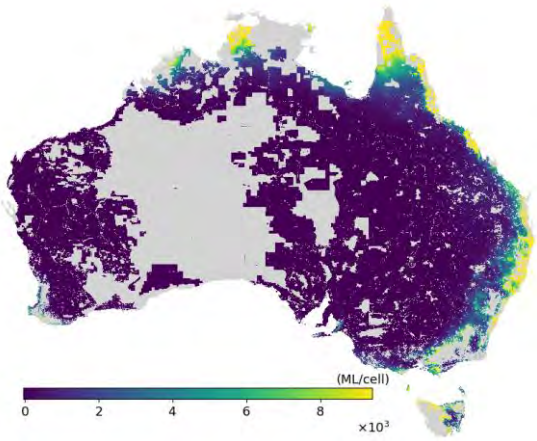
Figure 562 The water requirements of Agroforestry (Base)	Figure 563 Sheep Drinking Water Requirements under dry land management systems
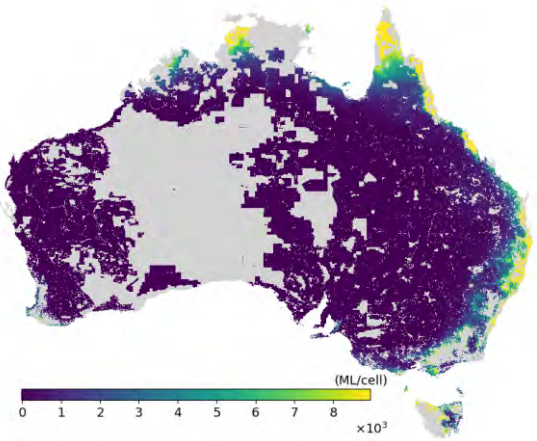	
Figure 564 The water requirements of Sheep-Agroforestry	

18.6. Beef Agroforestry Water Requirements

The water requirements for Beef Agroforestry are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}_{\text{Beef, modified}}$	Equation 357
$\mathbf{NetWYield}_r^{Beef,AgFor}(y) = \left(\mathbf{NetWYield}_r^{Base,AgrFor}(y) \times \mathbf{XCM}_r^{AgFor}\right) + \left[\left(1 - \mathbf{XCM}_r^{AgFor}\right) \times \mathbf{NetWYield}_r^{Beef}(y)\right]$	

where,

- $\mathbf{NetWYield}_r^{Base,AgrFor}$ is the base water requirements for agroforestry (Equation 354 and Figure 562)

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- $\mathbf{NetWYield}_r^{Beef}$ is the beef drinking water in lands under dry land management systems (Equation 358, and Figure 565)
- $\mathbf{XCM}_r^{AgFor}$ is the updated exclusion matrix by considering Agroforestry Proportion (Equation 298)

The water requirements for beef drinking water in lands under dry land management systems ($m = 0$) are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\mathrm{BYear}}$	Equation 358
$\mathbf{NetWYield}_r^{Beef}(y) = \begin{cases} \mathbf{WYield}_{mr\ell}^{Net}(y) & \text{If} \quad \mathrm{m} = 0 \wedge \ell \in \mathcal{L}_{\text{Beef, modified}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{WYield}_{mr\ell}^{Net}(y)$ is the water net yield matrix (Equation 145).
- $\mathcal{L}_{\text{Beef, modified}}$ is introduced in Equation 5

The computed $\mathbf{NetWYield}_r^{Beef}(y)$, and $\mathbf{NetWYield}_r^{Beef,AgFor}(y)$ are illustrated in Figure 565 and Figure 566, respectively. Moreover, the flowchart of $\mathbf{NetWYield}_r^{Beef,AgFor}$ is illustrated in Figure 567.

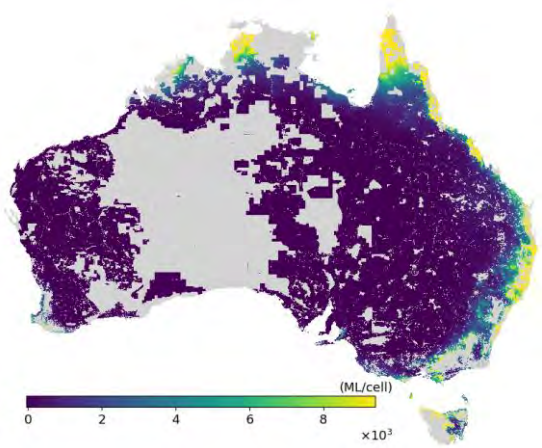	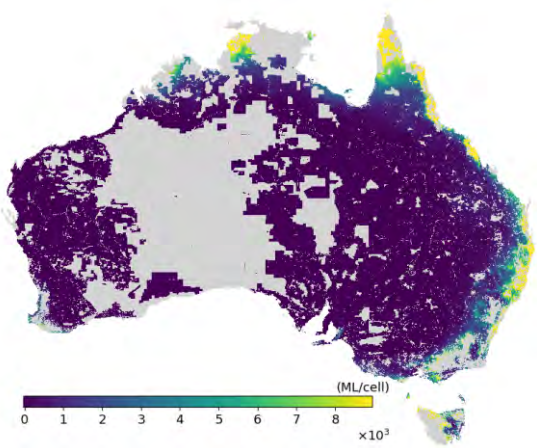
Figure 565 Beef Drinking Water Requirements under dry land management systems	Figure 566 The water requirements of Beef-Agroforestry

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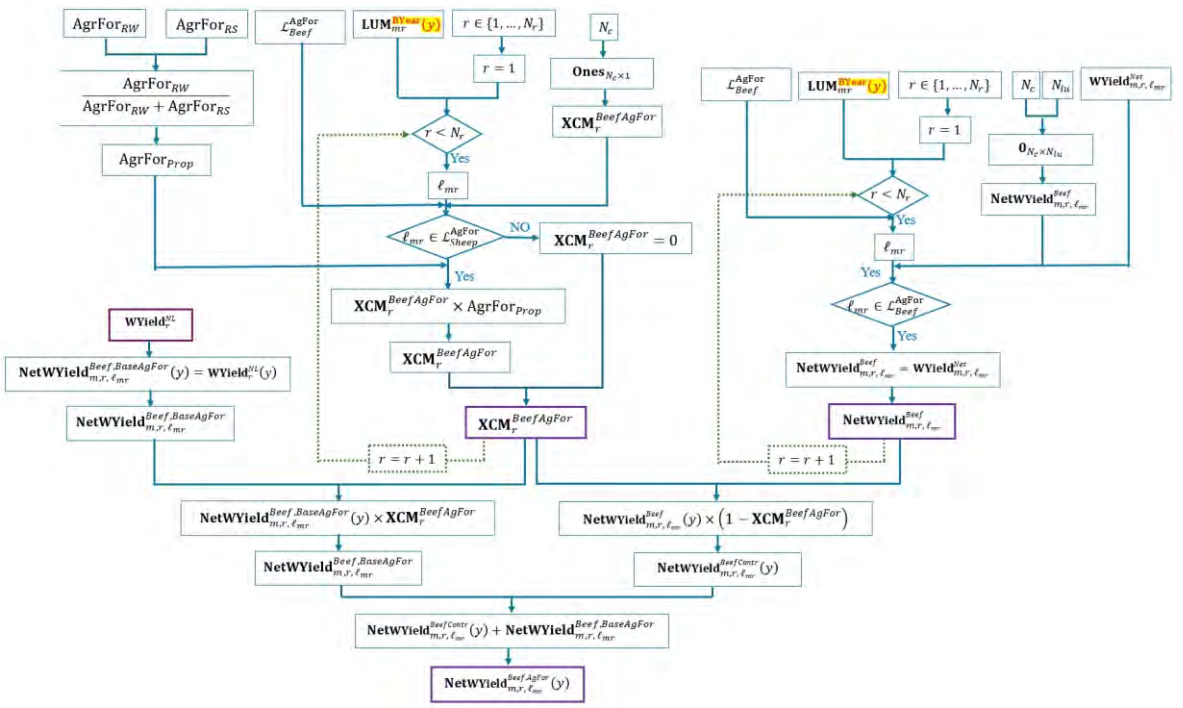

Figure 567 Beef Agroforestry Water Requirements

18.7. Carbon Plantings (Belt) Water Requirements

This section computes the water requirements for carbon plantings in a Belt arrangement $\mathbf{NetWYield}_r^{CPBelt}$, representing the water usage if modified (i.e., cleared) land area was reforested with deep-rooted tree species. The assumption here is that plantations are all deep-rooted and thus use more water.

$\mathbf{NetWYield}_r^{Base,CPBelt}(y) = \mathbf{WYield}_r^{DR}(y) \times \mathbf{RA}_r$	Equation 359

where,

- $\mathbf{WYield}_r^{DR}$ is the Water Yield value for Cells covered by deep-rooted plants (Figure 556)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

As can be seen, the computed $\mathbf{NetWYield}_r^{CPBelt}$ is the same as $\mathbf{NetWYield}_r^{CPBlock}$, introduced in Equation 352. Therefore, it can alternatively be represented as:

$\mathbf{NetWYield}_r^{Base,CPBelt} = \mathbf{NetWYield}_r^{Base,CPBlock}$	Equation 360

The computed $\mathbf{NetWYield}_r^{CPBelt}(y)$ is illustrated in Figure 559.

18.8. Sheep Carbon Plantings (Belt) Water Requirements

The water requirements for Sheep Carbon Planting (Belt) are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}_{\text{Sheep, modified}}$	Equation 361
$\mathbf{NetWYield}_r^{Sheep,CPBelt}(y) = \left(\mathbf{NetWYield}_r^{Base,CPBelt}(y) \times \mathbf{XCM}_r^{CPBelt}\right) + \left[(1 - \mathbf{XCM}_r^{CPBelt}) \times \mathbf{NetWYield}_r^{Sheep}(y)\right]$	

where,

- $\mathbf{NetWYield}_r^{Base,CPBelt}$ is the base water requirements for Carbon Planting (Belt) (Equation 359, and Figure 569)

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- $\mathbf{NetWYield}_r^{Sheep}$ is the sheep drinking water under dryland management systems (Equation 356 and Figure 563)
- $\mathbf{XCM}_r^{CPBelt}$ is the updated exclusion matrix by considering Carbon Planting (Belt) Proportion (Equation 307)

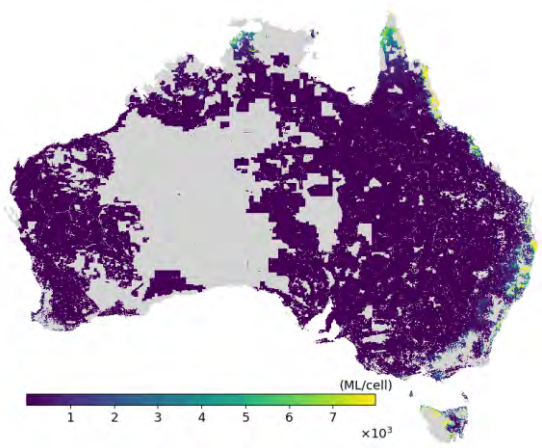

Figure 569 The water requirements of Carbon Planting (Belt)

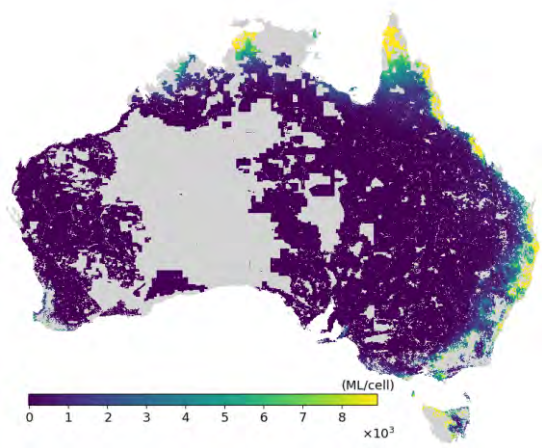

Figure 570 The water requirements of Sheep-Carbon Planting (Belt)

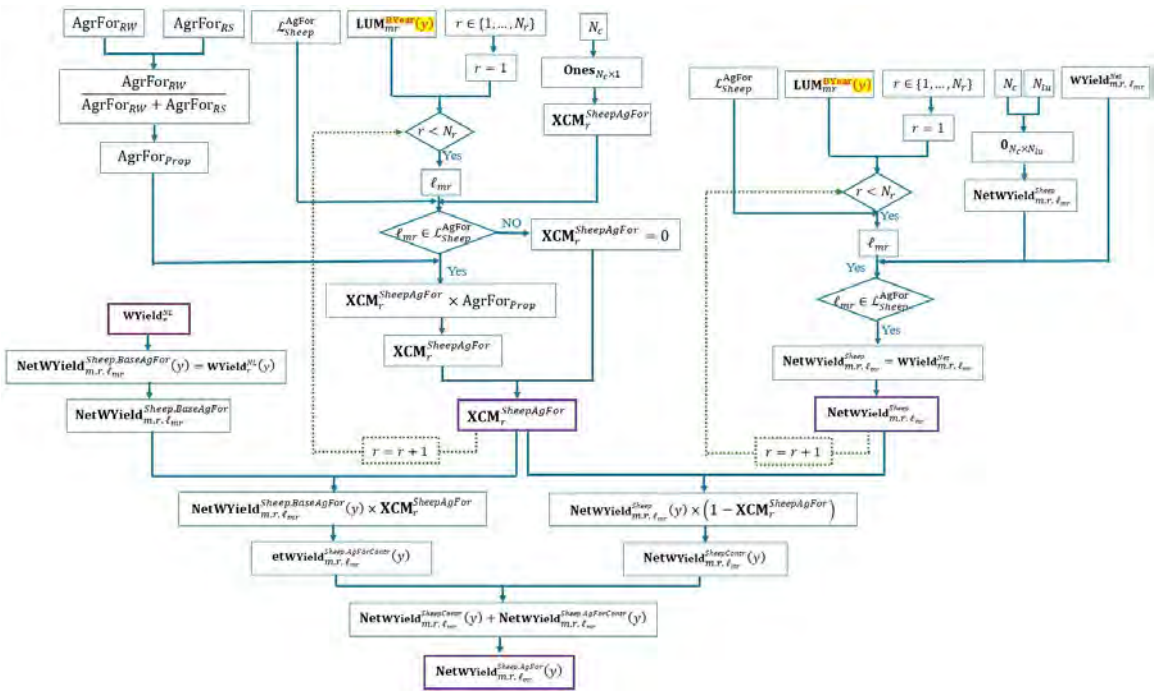

Figure 568 Sheep Agroforestry Water Requirements

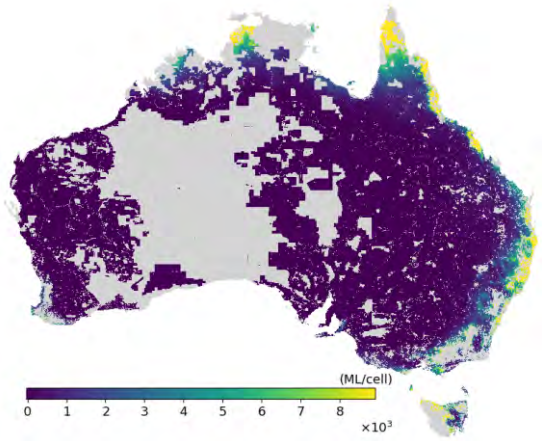	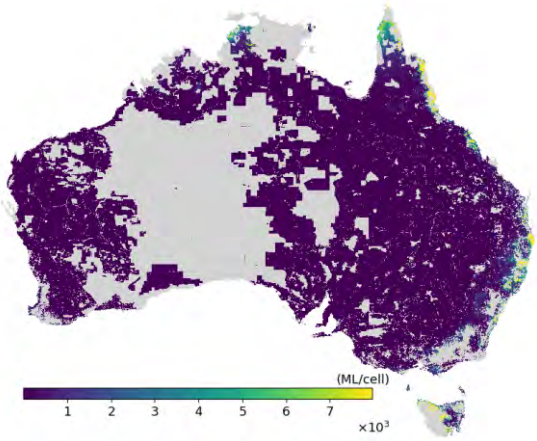
Figure 571 The water requirements of Beef-Agroforestry	Figure 572 The water requirements of BECCS

18.9. **Beef Carbon Plantings (Belt) Water Requirements**

The water requirements for Beef Carbon Planting (Belt) are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\ \ell_{mr}, \ell_{mr} \in \mathcal{L}_{\text{Beef, modified}}$	Equation 362
$\mathbf{NetWYield}_r^{Beef,CPBelt}(y) = \left(\mathbf{NetWYield}_r^{Base,CPBelt}(y) \times \mathbf{XCM}_r^{CPBelt}\right) + \left[(1 - \mathbf{XCM}_r^{CPBelt}) \times \mathbf{NetWYield}_r^{Beef}(y)\right]$	

where,

- $\mathbf{NetWYield}_r^{Base,CPBelt}$ is the base water requirements for Carbon Planting (Belt) (Equation 359, and Figure 569)
- $\mathbf{NetWYield}_r^{Beef}$ is the beef drinking water in lands under dryland management systems (Equation 358, and Figure 565)
- $\mathbf{XCM}_r^{CPBelt}$ is the updated exclusion matrix by considering Agroforestry Proportion (Equation 298)

The computed $\mathbf{NetWYield}_r^{Beef,CPBelt}(y)$ is illustrated in Figure 571. Moreover, the flowchart of $\mathbf{NetWYield}_r^{Beef,CPBelt}$ is illustrated in Figure 573.

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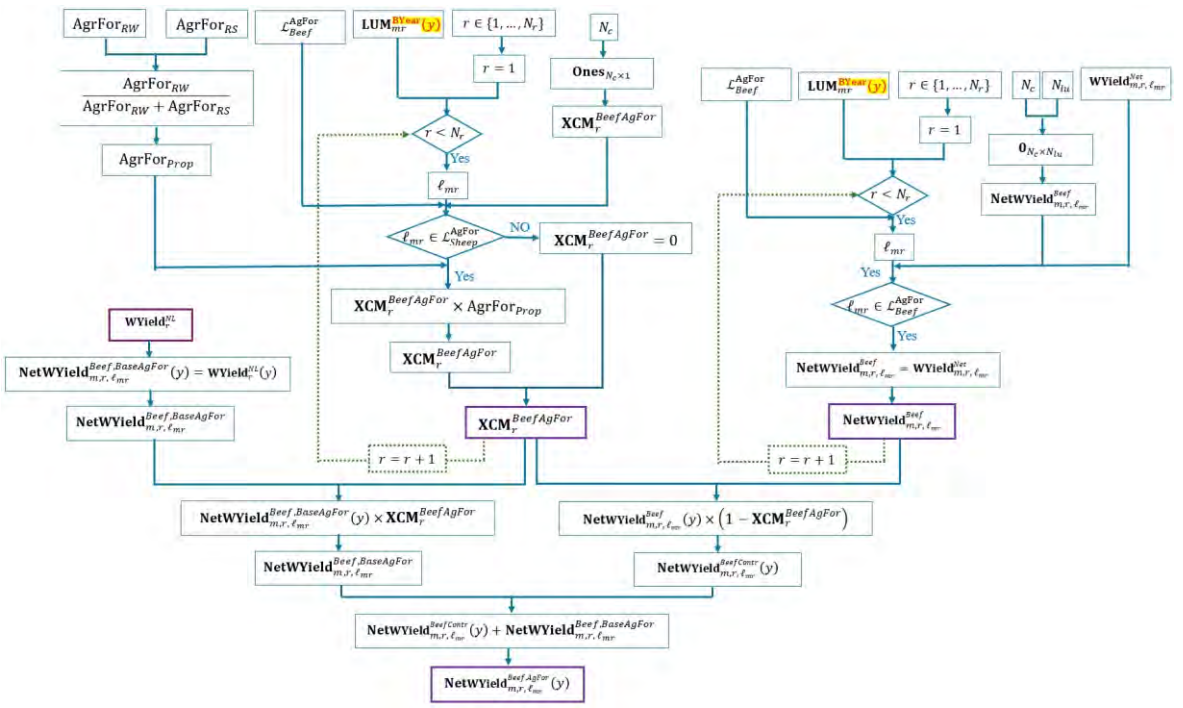

Figure 573 Beef Agroforestry Water Requirements

18.10. BECCS Water Requirements

This section computes the water requirements for Bioenergy with Carbon Capture and Storage (BECCS) arrangement $\mathbf{NetWYield}_r^{BECCS}$, representing the water usage if modified (i.e., cleared) land area was reforested with deep-rooted tree species. The assumption here is that plantations are all deep-rooted and thus use more water.

$\mathbf{NetWYield}_r^{BECCS}(y) = \mathbf{WYield}_r^{DR}(y) \times \mathbf{RA}_r$	Equation 363

where,

- $\mathbf{WYield}_r^{DR}$ is the Water Yield value for cells covered by deep-rooted plants (Figure 556)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

As can be seen, the computed $\mathbf{NetWYield}_r^{BECCS}$ is the same as $\mathbf{NetWYield}_r^{Base,CPBelt}$ and $\mathbf{NetWYield}_r^{CPBlock}$, which are introduced in Figure 341. The results of $\mathbf{NetWYield}_r^{BECCS}$ are illustrated in Figure 572.

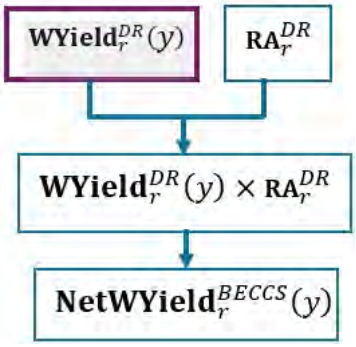

Figure 574 Bioenergy with carbon capture and storage (BECCS) water requirements

18.11. Non-Agricultural Land Uses Water Requirements Matrix

The general form of the matrix $\mathbf{WRM}_{r\ell}^{NonAg}$, where $\ell \in \mathcal{L}_{\text{NonAgrLand}}$, $\mathcal{L}_{\text{NonAgrLand}}$ is defined in Equation 13. The overall water requirements matrix for all non-agricultural land uses is constructed by concatenating the individual water requirements vectors for each land uses in $\mathcal{L}_{\text{NonAgrLand}}$:

$\mathbf{WRM}_{r\ell}^{NonAg}(y) = \text{concatenate}\left(\begin{matrix}\mathbf{NetWYield}_r^{EnvPlanting}(y), \mathbf{NetWYield}_r^{RipPlant}(y), \mathbf{NetWYield}_r^{Sheep,AgFor}(\\ \mathbf{NetWYield}_r^{Beef,AgFor}(y), \mathbf{NetWYield}_r^{CPBlock}(y), \mathbf{NetWYield}_r^{Sheep,\text{CPBelt}}(y \\ \mathbf{NetWYield}_r^{Beef,\text{CPBelt}}(y), \mathbf{NetWYield}_r^{BECCS}(y)\end{matrix}\right)$	Equation 364

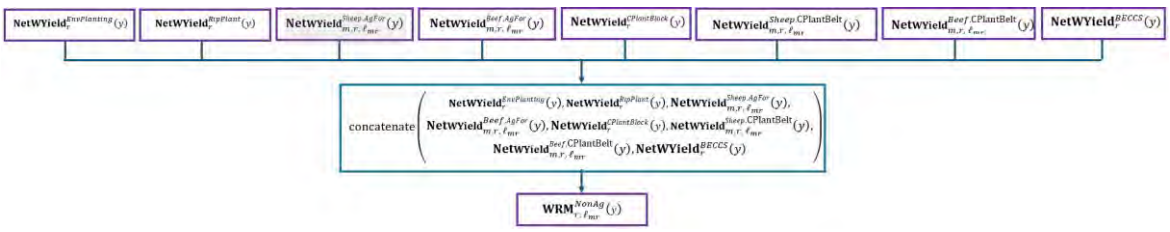

Figure 575 Non-Agricultural Land Uses Water Requirements Matrix

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Economics/Non Agricultural/ biodiversity.py

19. The biodiversity

19.1. The Biodiversity Impact Assessment of Environmental Planting

This section computes the biodiversity score for environmental plantings, as:

$\mathbf{BSM}_r^{EnvPlanting} = \mathbf{WBS}_r \times \mathbf{RA}_r \times BBC^{EnvPlanting}$	Equation 365

Where,

- $\mathbf{WBS}_r$ is the weighted biodiversity score (Figure 582)
- $BBC^{EnvPlanting}$ is the biodiversity benefit coefficient for environmental planting; LUTO 2.0 assumes $BBC^{EnvPlanting} = 0.8$
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The weighted biodiversity score ($\mathbf{WBS}_r$) is computed as:

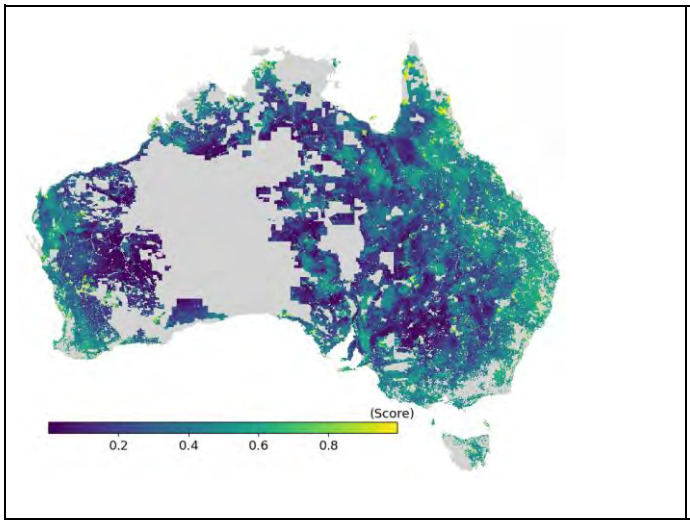
$\mathbf{WBS}_r = \mathbf{RBS}_r \times \mathrm{CAS}_r$	Equation 366

where,

- $\mathbf{RBS}_r$ is the raw biodiversity priority score
- CAS_r is the Connectivity Adjustment Score for cell r

The raw biodiversity priority score under different SSP climate scenarios, including SSP 126, SSP 245, SSP 370, and the SSP 585, are presented in Figure 576-Figure 579, where SSP 245 is selected as default scenario in LUTO 2.0.

The Connectivity Scores across Landscapes according to the DCCEEW National Connectivity Index (NCI) and distance to the nearest natural land area (based on the National Land Use Map of Australia) are shown in Figure 580 and Figure 581. The computed $\mathbf{WBS}_r$ using climate scenario of SSP 245 (Figure 577) and the Connectivity Scores across Landscapes according to the DCCEEW NCI (Figure 580) is shown in Figure 582, and this was used to compute $\mathbf{BSM}_r^{EnvPlanting}$, illustrated in Figure 583. The proposed unit for Biodiversity is Area Weighted Hectare (AwH).



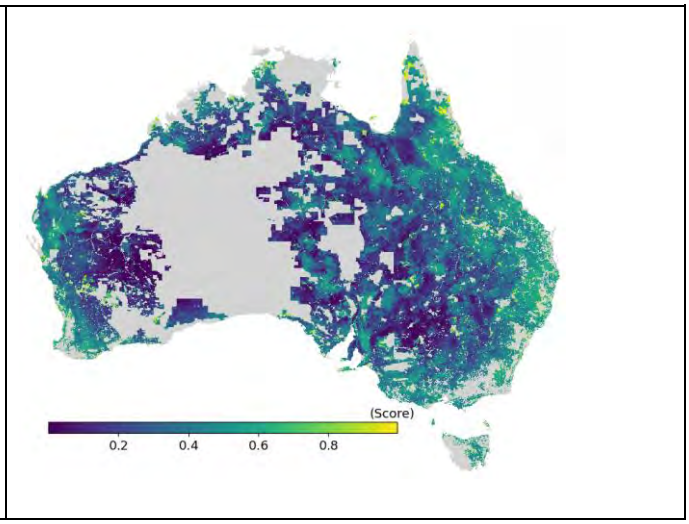


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Figure 576 The raw biodiversity priority score under the SSP 126 climate scenario

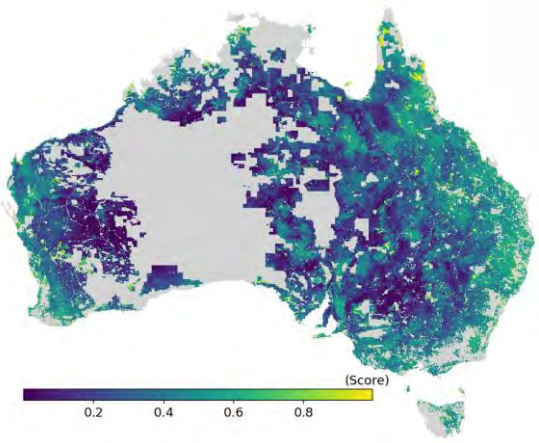

Figure 577 The raw biodiversity priority score under the SSP 245 climate scenario

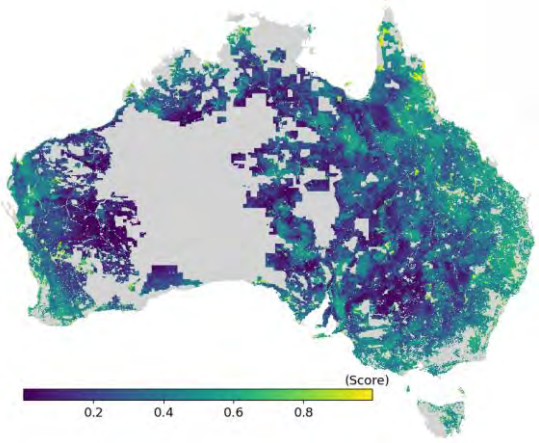

Figure 578 The raw biodiversity priority score under the SSP 370 climate scenario

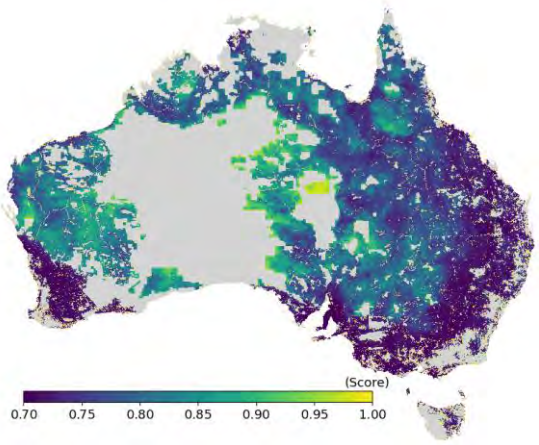

Figure 579 The raw biodiversity priority score under the SSP 585 climate scenario

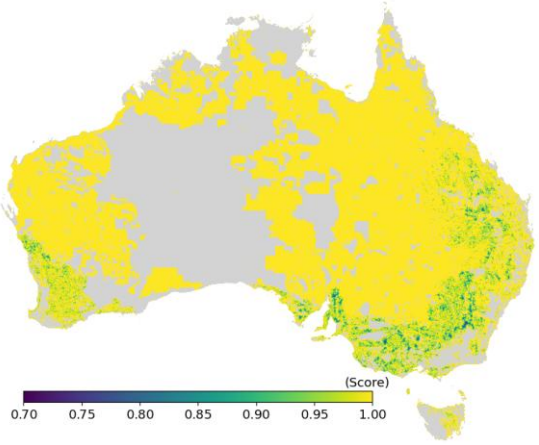

Figure 580 Connectivity Scores across Landscapes according to the DCCEEW National Connectivity Index (NCI)

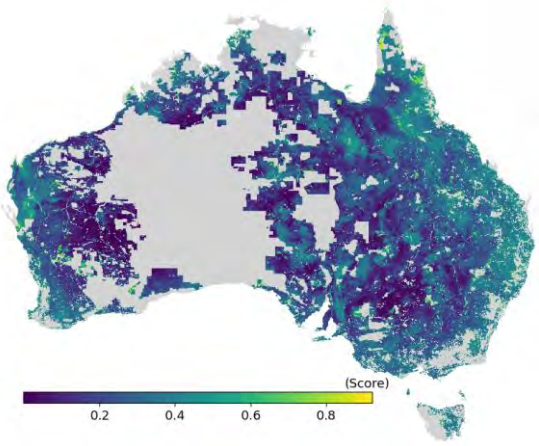

Figure 581 Connectivity Score Calculated as Distance to Nearest Natural Land Area Based on the National Land Use Map of Australia

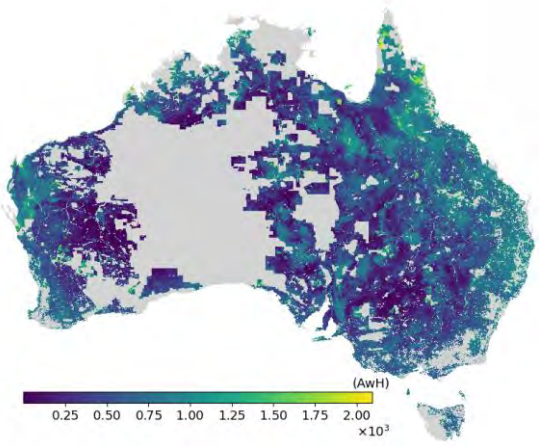

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Figure 582 Weighted Biodiversity Score Combining DCCEEW National Connectivity Index (NCI) and Raw Biodiversity Priority under the SSP 245 Climate Scenario	Figure 583 The biodiversity of Environmental Plantings

19.2. **Biodiversity Impact Assessment of Riparian Planting**

This section calculates the biodiversity score for riparian plantings, as:

$\mathbf{BSM}_r^{RipPlant} = \mathbf{WBS}_r \times \mathbf{RA}_r \times BBC^{RipPlant}$	Equation 367

where,

- $\mathbf{WBS}_r$ is the weighted biodiversity score (Equation 366 and Figure 582)
- $BBC^{RipPlant}$ is the biodiversity benefit coefficient for riparian planting; LUTO 2.0 assumes $BBC^{RipPlant} = 1$
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{BSM}_r^{RipPlant}$ is based on $\mathbf{WBS}_r$ from Figure 582, which was calculated using the SSP 245 climate scenario (Figure 577) and the Connectivity Scores across Landscapes according to the DCCEEW NCI (Figure 580). The result is illustrated in Figure 584.

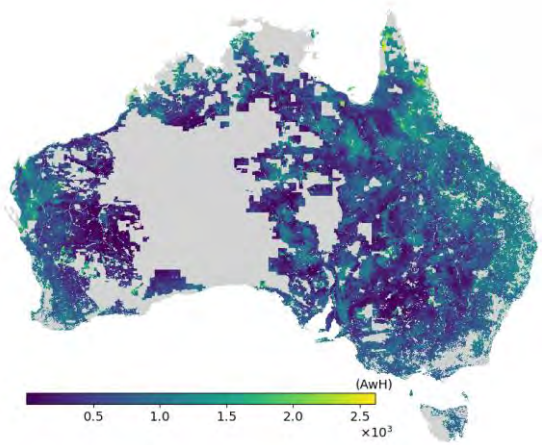	
Figure 584 The biodiversity of Riparian Plantings	

19.3. **Biodiversity Impact Assessment of Agroforestry (Base)**

This section calculates the biodiversity score for Agroforestry (base), as:

$\mathbf{BSM}_r^{Base,AgFor} = \mathbf{WBS}_r \times \mathbf{RA}_r \times BBC^{AgFor}$	Equation 368

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where,

- $\mathbf{WBS}_r$ is the weighted biodiversity score (Equation 366 and Figure 582)
- BBC^{AgFor} is the biodiversity benefit coefficient for Agroforestry; LUTO 2.0 assumes $BBC^{AgFor} = 0.75$
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{BSM}_r^{Base,AgFor}$ is presented in Figure 585.

19.4. Biodiversity Impact Assessment of Sheep Agroforestry

Since the contribution of cell r that belongs to the class 'Sheep-modified land' (where $\ell \in \mathcal{L}_{\text{Sheep, modified}}$) consists of the contribution from both agroforestry and sheep to the biodiversity score matrix. The Sheep Agroforestry contribution to the biodiversity score matrix can be computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}_{\text{Sheep, modified}}$	Equation 369
$\mathbf{BSM}_r^{Sheep,AgFor} = \left(\mathbf{BSM}_r^{Base,AgFor} \times \mathbf{XCM}_r^{AgFor}\right) + \left[\left(1 - \mathbf{XCM}_r^{AgFor}\right) \times \mathbf{BSM}_r^{Sheep}\right]$	

where,

- $\mathbf{BSM}_r^{Base,AgFor}$ is the base biodiversity score for agroforestry (Equation 368, and Figure 585)
- $\mathbf{BSM}_r^{Sheep}$ is the sheep impacts on biodiversity in dryland systems (Equation 370 and Figure 586)
- $\mathbf{XCM}_r^{AgFor}$ is the updated exclusion matrix considering Agroforestry Proportion (Equation 298)

The first term $\left(\mathbf{BSM}_r^{Base,AgFor} \times \mathbf{XCM}_r^{AgFor}\right)$ represents the agroforestry contribution (Figure 587), while the second term $\left[\left(1 - \mathbf{XCM}_r^{AgFor}\right) \times \mathbf{BSM}_r^{Sheep}\right]$ captures the sheep contribution (Figure 588). Here, $\mathbf{BSM}_r^{Sheep}$ is the baseline biodiversity impact of sheep grazing in cell r, and $\left(1 - \mathbf{XCM}_r^{AgFor}\right)$ reflects the remaining area not used for agroforestry.

The computed $\mathbf{BSM}_r^{Sheep,AgFor}$ is presented in Figure 589.

The biodiversity score matrix for the class "Sheep-modified land" in dryland systems ($m = 0$) is extracted from of the biodiversity score matrix of agriculture ($\mathbf{BSM}_{mr\ell}$), as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\text{BYear}}$	Equation 370
$\mathbf{BSM}_r^{Sheep} = \begin{cases} \mathbf{BSM}_{mr\ell} & \text{if} \quad m = 0 \ \wedge \ell \in \mathcal{L}_{\text{Sheep, modified}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{BSM}_{mr\ell}$ is the biodiversity score matrix from Equation 179
- $\mathcal{L}_{\text{Sheep, modified}}$ is defined in Equation 6

19.5. Biodiversity Impact Assessment of Beef Agroforestry

Since the contribution of cell r that belongs to the class 'Beef-modified land' (where $\ell \in \mathcal{L}_{\text{Beef, modified}}$) consists of the contribution from both agroforestry and beef to the biodiversity score matrix, the beef agroforestry contribution can be computed as:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}_{\text{Beef, modified}}$	Equation 371
$\mathbf{BSM}_r^{Beef,AgFor} = \left(\mathbf{BSM}_r^{Base,AgFor} \times \mathbf{XCM}_r^{AgFor}\right) + \left[\left(1 - \mathbf{XCM}_r^{AgFor}\right) \times \mathbf{BSM}_r^{Beef}\right]$	

where,

- $\mathbf{BSM}_r^{Base,AgFor}$ is the base biodiversity score for agroforestry (Equation 368, and Figure 585)
- $\mathbf{BSM}_r^{Beef}$ is the beef impacts score in dryland systems (Equation 372 and Figure 590)
- $\mathbf{XCM}_r^{AgFor}$ is the exclusion matrix based on agroforestry proportion (Equation 298)

The first term $\left(\mathbf{BSM}_r^{Base,AgFor} \times \mathbf{XCM}_r^{AgFor}\right)$ represents the agroforestry contribution (Figure 587), while the second term $\left[\left(1 - \mathbf{XCM}_r^{AgFor}\right) \times \mathbf{BSM}_r^{Beef}\right]$ represents the beef contribution (Figure 591). Here, $\mathbf{BSM}_r^{Beef}$ is the baseline biodiversity impact of beef grazing in the cell r, and $\left(1 - \mathbf{XCM}_r^{AgFor}\right)$ reflects the remaining proportion of a given cell r not covered by agroforestry. The computed $\mathbf{BSM}_r^{Beef,AgFor}$ is presented in Figure 592.

The biodiversity score matrix for the class "Beef-modified land" is extracted from of the biodiversity score matrix of agriculture ($\mathbf{BSM}_{mr\ell}$), as:

$\forall r \in \{1, \dots, N_r\}, m = 0\ \exists\, \ell, \ell \in \mathcal{L}_{\text{Beef, modified}}$	Equation 372
$\mathbf{BSM}_r^{Beef} = \begin{cases} 1 & \text{if} \quad \mathbf{BSM}_{mr\ell} = \text{True} \\ 0 & \text{if} \quad \mathbf{BSM}_{mr\ell} = \text{False} \end{cases}$	

where,

- $\mathbf{BSM}_{mr\ell}$ is the biodiversity score matrix from Equation 179
- $\mathcal{L}_{\text{Beef, modified}}$ is defined in Equation 5

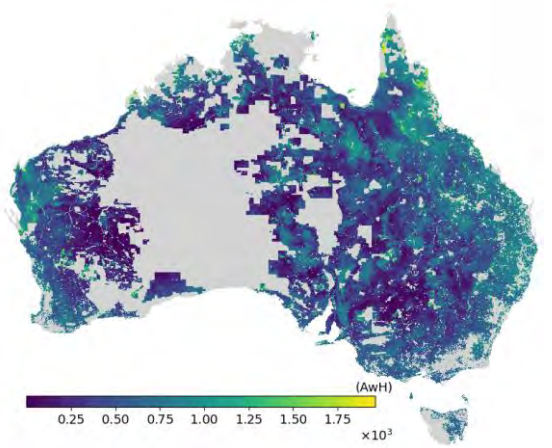	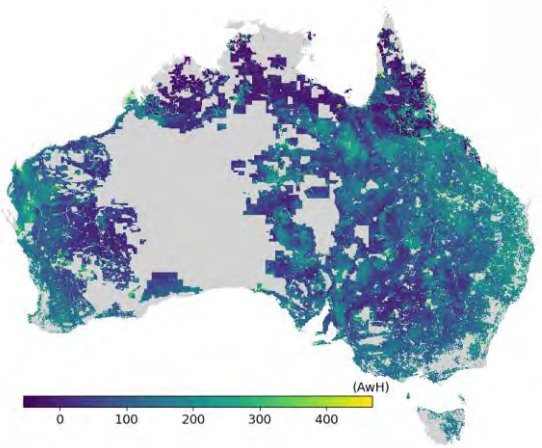
Figure 585 The biodiversity score for Agroforestry (base)	Figure 586 Sheep impacts on the biodiversity in lands under dryland management systems

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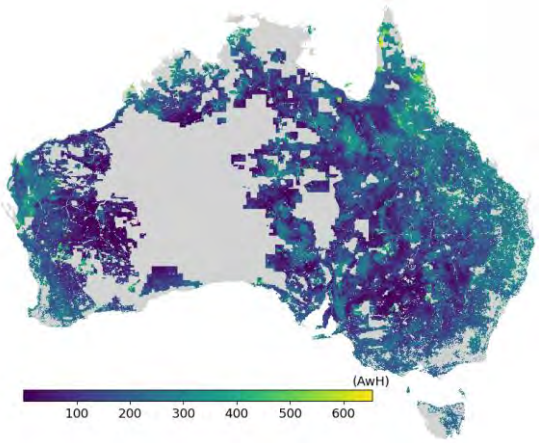

Figure 587 The agroforestry contributions in the Sheep Agroforestry impacts on the biodiversity

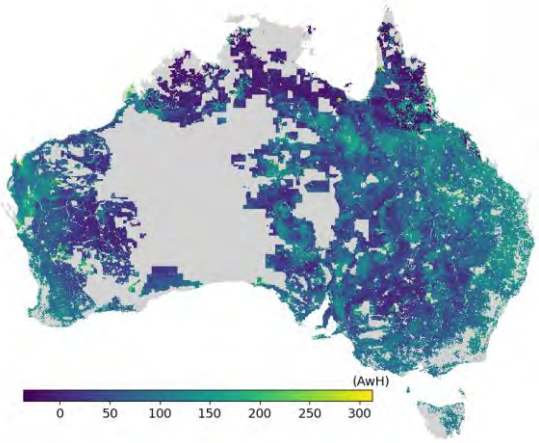

Figure 588 Sheep contributions in the Sheep Agroforestry impacts on the biodiversity

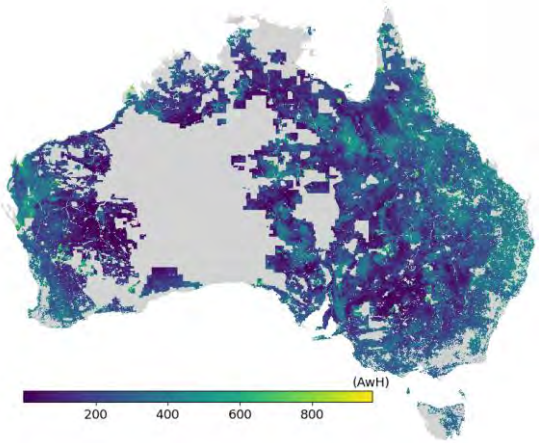

Figure 589 The biodiversity of Sheep-Agroforestry

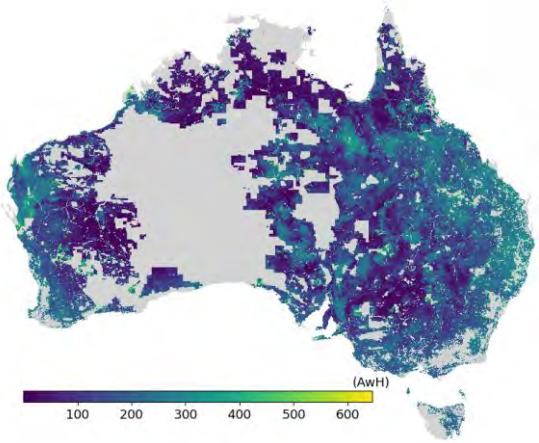

Figure 590 Beef impacts on the biodiversity in lands under dryland management systems

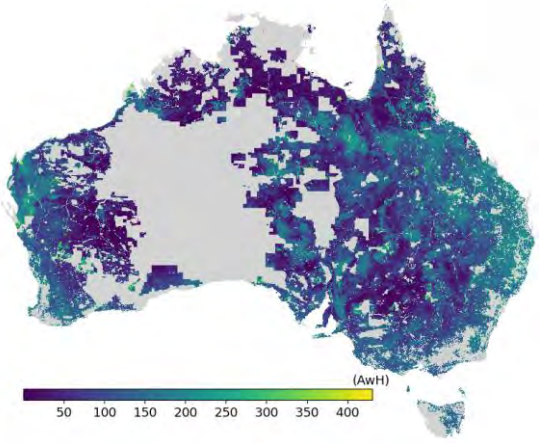

Figure 591 Beef contributions in the Beef Agroforestry impacts on the biodiversity

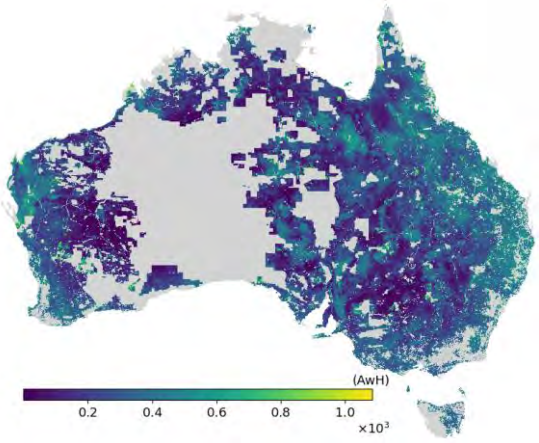

Figure 592 The biodiversity of Beef-Agroforestry

19.6. **Biodiversity Impact Assessment of Carbon Planting (Block)**

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This section calculates the biodiversity score for Carbon Planting (Block), as:

$\mathbf{BSM}_r^{CPBlock} = \mathbf{WBS}_r \times \mathbf{RA}_r \times BBC^{CPBlock}$	Equation 373

where,

- $\mathbf{WBS}_r$ is the weighted biodiversity score (Equation 366 and Figure 582)
- $BBC^{CPBlock}$is the biodiversity benefit coefficient for Carbon Planting (Block); LUTO 2.0 assumes $BBC^{CPBlock} = 0.1$
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{BSM}_r^{CPBlock}$, based on $\mathbf{WBS}_r$ from Figure 582 (computed using climate scenario of SSP 245 - Figure 577) and DCCEEW NCI Connectivity Scores (Figure 580) is illustrated in Figure 593.

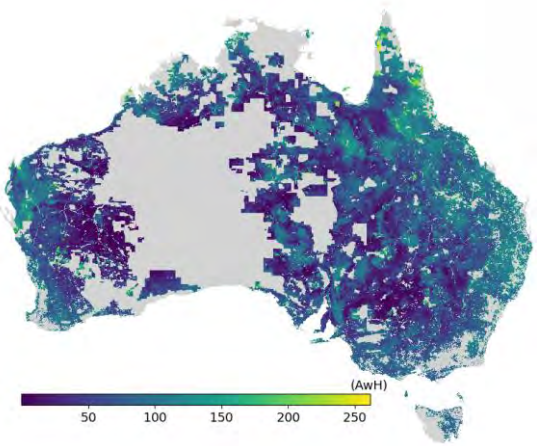	
Figure 593 The biodiversity of Carbon Planting (Block)	

19.7. Biodiversity Impact Assessment of Carbon Plantings (Belt)

This section calculates the base biodiversity score for Carbon Plantings (Belt), as:

$\mathbf{BSM}_r^{Base,CPBelt} = \mathbf{WBS}_r \times \mathbf{RA}_r \times BBC^{CPBelt}$	Equation 374

Where,

- $\mathbf{WBS}_r$ is the weighted biodiversity score (Equation 366 and Figure 582)
- BBC^{CPBelt} is the biodiversity benefit coefficient for Carbon Plantings (Belt); LUTO 2.0 assumes $BBC^{CPBelt} = 0.1$
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{BSM}_r^{Base,AgFor}$ is presented in Figure 594.

19.8. Biodiversity Impact Assessment of Sheep Carbon Plantings (Belt)

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Since the contribution of cell r that belongs to the class 'Sheep-modified land' (where $\ell \in \mathcal{L}_{\text{Sheep, modified}}$) consists of the contribution from both Carbon Plantings (Belt) and sheep to the biodiversity score matrix, the Sheep Carbon Plantings (Belt) contribution can be computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}_{\text{Sheep, modified}}$	Equation 375
$\mathbf{BSM}_r^{Sheep,CPBelt} = \left(\mathbf{BSM}_r^{Base,CPBelt} \times \mathbf{XCM}_r^{CPBelt}\right) + \left[(1 - \mathbf{XCM}_r^{CPBelt}) \times \mathbf{BSM}_r^{Sheep}\right]$	

where,

- $\mathbf{BSM}_r^{Base,CPBelt}$ is the base biodiversity score for Carbon Plantings (Belt) (Equation 374, and Figure 594)
- $\mathbf{BSM}_r^{Sheep}$ is the sheep impact score on the biodiversity in dryland systems (Equation 370 and Figure 586)
- $\mathbf{XCM}_r^{CPBelt}$ is the updated exclusion matrix based on Carbon Planting (Belt) proportion (Equation 307)

The first term $\left(\mathbf{BSM}_r^{Base,CPBelt} \times \mathbf{XCM}_r^{CPBelt}\right)$ represents the Carbon Planting (Belt) contribution (Figure 595), and the second term $\left[(1 - \mathbf{XCM}_r^{CPBelt}) \times \mathbf{BSM}_r^{Sheep}\right]$ represents the sheep contribution (Figure 596). Here, $\mathbf{BSM}_r^{Sheep}$ is the baseline measure or impact of sheep grazing in the cell r; and $(1 - \mathbf{XCM}_r^{CPBelt})$ indicates the remaining proportion of a given cell r not covered by Carbon Plantings (Belt), effectively representing the area or resource availability for sheep. The second term, therefore, shows the contribution of sheep to the total outcome, accounting for the reduced area due to Carbon Plantings (Belt).

The computed $\mathbf{BSM}_r^{Sheep,CPBelt}$ is illustrated in Figure 597.

19.9. Biodiversity Impact Assessment of Beef Carbon Plantings (Belt)

Since the contribution of cell r that belongs to the class 'Beef-modified land' (where $\ell \in \mathcal{L}_{\text{Beef, modified}}$) consists of the contribution from both Carbon Planting (Belt) and beef to the biodiversity score matrix, the Beef Carbon Planting (Belt) contribution can be computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell \in \mathcal{L}_{\text{Beef, modified}}$	Equation 376
$\mathbf{BSM}_r^{Beef,CPBelt} = \left(\mathbf{BSM}_r^{Base,CPBelt} \times \mathbf{XCM}_r^{CPBelt}\right) + \left[(1 - \mathbf{XCM}_r^{CPBelt}) \times \mathbf{BSM}_r^{Beef}\right]$	

where,

- $\mathbf{BSM}_r^{Base,CPBelt}$ is the base biodiversity score for Carbon Planting (Belt) (Equation 368, and Figure 594)
- $\mathbf{BSM}_r^{Beef}$ is the beef impacts on the biodiversity in lands under dry land management systems (Equation 372 and Figure 590)
- $\mathbf{XCM}_r^{CPBelt}$ is the updated exclusion matrix by considering Carbon Planting (Belt) Proportion (Equation 307)

In this equation, as mentioned before, the first term, $\left(\mathbf{BSM}_r^{Base,CPBelt} \times \mathbf{XCM}_r^{CPBelt}\right)$, represents the Carbon Planting (Belt) contribution (Figure 595). The second term $\left[(1 - \mathbf{XCM}_r^{CPBelt}) \times \mathbf{BSM}_r^{Beef}\right]$, represents the beef contribution (Figure 598). Here, $\mathbf{BSM}_r^{Beef}$ is the baseline measure or impact of beef grazing in the cell r; and $(1 - \mathbf{XCM}_r^{CPBelt})$ indicates the remaining proportion of a given cell r not covered by Carbon Planting

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(Belt), effectively representing the area or resource availability for beef. The second term, therefore, shows the contribution of beef to the total outcome, accounting for the reduced area due to Carbon Planting (Belt).

The computed $\mathbf{BSM}_r^{Beef,CPBelt}$ is presented in Figure 599.

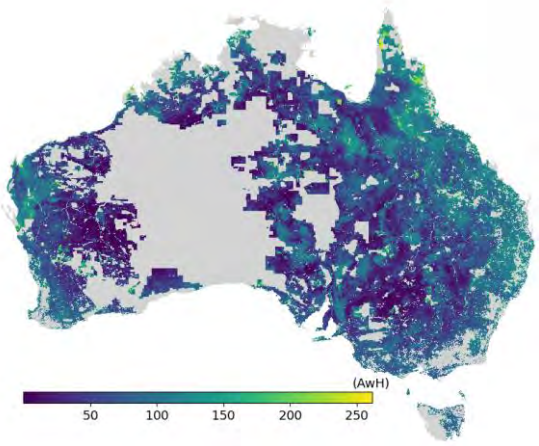

Figure 594 The biodiversity score for Carbon Planting (Belt)

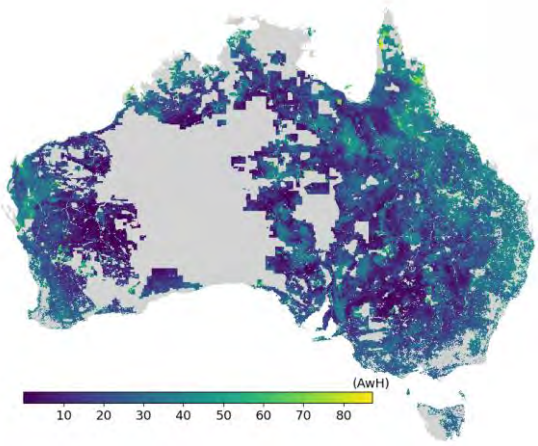

Figure 595 The Carbon Planting (Belt) contributions in the Sheep Carbon Planting (Belt) impacts on the biodiversity

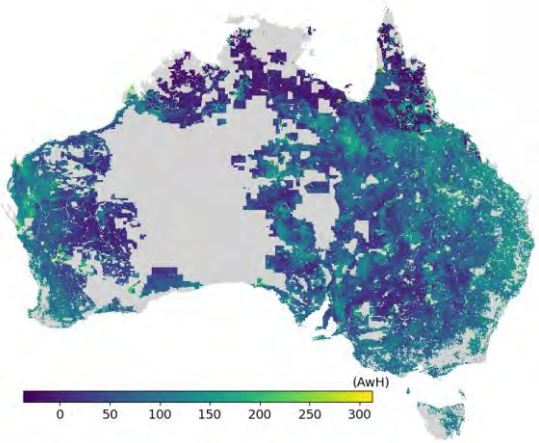

Figure 596 Sheep contributions in the Sheep Carbon Planting (Belt) impacts on the biodiversity

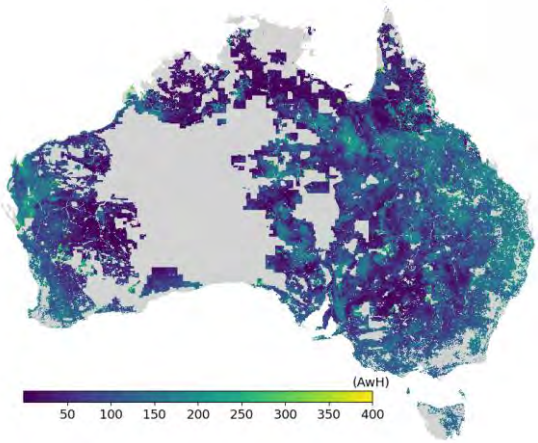

Figure 597 The biodiversity of Sheep-Carbon Planting (Belt)

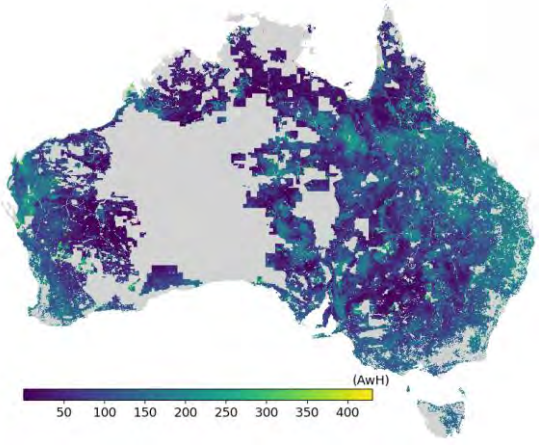

Figure 598 Beef contributions in the Beef Carbon Planting (Belt) impacts on the biodiversity

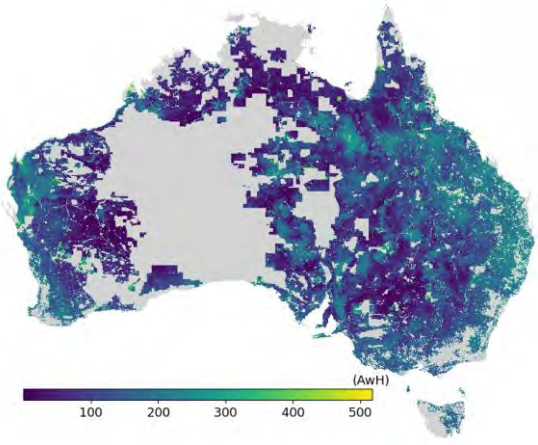

Figure 599 The biodiversity of Beef- Carbon Planting (Belt)

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19.10. Biodiversity Impact Assessment of BECCS

This section calculates the biodiversity score for BECCS, as:

$\mathbf{BSM}_r^{BECCS} = \mathbf{WBS}_r \times \mathbf{RA}_r \times BBC^{BECCS}$	Equation 377

where,

- $\mathbf{WBS}_r$ is the weighted biodiversity score (Equation 366 and Figure 582)
- BBC^{BECCS} is the biodiversity benefit coefficient for BECCS; LUTO 2.0 assumes $BBC^{BECCS} = 0$
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{BSM}_r^{BECCS}$ is based on $\mathbf{WBS}_r$ (Figure 582) which is computed using the climate scenario SSP 245 (Figure 577) and the Connectivity Scores across Landscapes from the DCCEEW NCI (Figure 580). As $BBC^{BECCS} = 0$, $\mathbf{BSM}_r^{BECCS}$ results in a zero matrix.

19.11. Biodiversity Impact Assessment of Non-Agricultural Land Uses

The general form of the matrix $\mathbf{BSM}_{r\ell}^{NonAg}$, where $\ell \in \mathcal{L}_{\text{NonAgrLand}}$ (defined in Equation 13), is used to aggregate biodiversity impacts across all non-agricultural land uses. The overall biodiversity impact matrix is constructed by concatenating the individual biodiversity impact vectors for each land use in $\mathcal{L}_{\text{NonAgrLand}}$:

$\mathbf{BSM}_{r\ell}^{NonAg}(y) = \text{concatenate}\begin{pmatrix} \mathbf{BSM}_r^{EnvPlanting}(y), \mathbf{BSM}_r^{RipPlant}(y), \mathbf{BSM}_r^{Sheep,AgFor}(y), \\ \mathbf{BSM}_r^{Beef,AgFor}(y), \mathbf{BSM}_r^{CPBlock}(y), \mathbf{BSM}_r^{Sheep,\text{CPBelt}}(y), \\ \mathbf{BSM}_r^{Beef,\text{CPBelt}}(y), \mathbf{BSM}_r^{BECCS}(y) \end{pmatrix}$	Equation 378

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Economics/ Non Agricultural / revenue.py

20. The Revenue

This section outlines the calculations for revenue based on carbon sequestration and agricultural outputs for various non-agricultural land uses.

20.1. The revenue produced by environmental plantings

The revenue generated by environmental plantings is calculated as:

$\mathbf{Rev}_{EnvPlanting}^{NonAg}(y) = \mathbf{AGHG}_r^{EnvPlanting} \times \mathbf{RA}_r \times CO2Price(y)$	Equation 379

where,

- $\mathbf{Rev}_{EnvPlanting}^{NonAg}$ is the revenue produced by environmental plantings
- $\mathbf{AGHG}_r^{EnvPlanting}$ represents the average annual greenhouse gas (GHG) sequestration for environmental plantings (block) (Equation 312 and Figure 498)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $CO2Price(y)$ is the market CO_2 price in AUD per Tonne of CO_2 (Figure 349)

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The computed $\mathbf{Rev}_{EnvPlanting}^{NonAg}$ is presented in Figure 602.

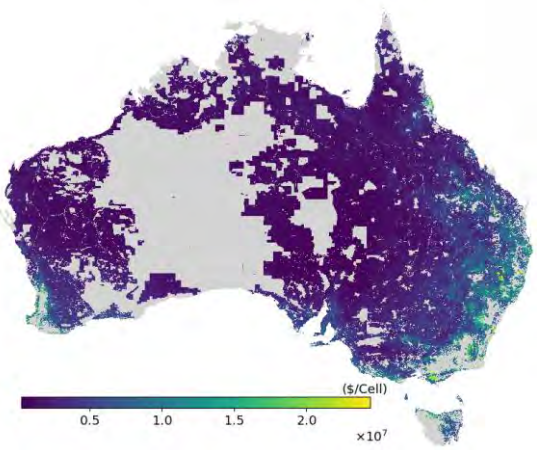

Figure 600 The revenue produced by environmental plantings

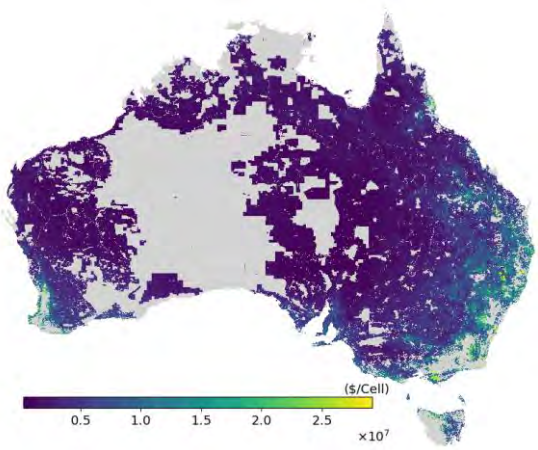

Figure 601 The revenue produced by riparian plantings

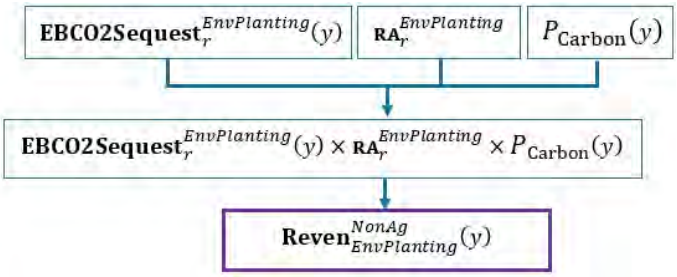

Figure 602 The revenue produced from environmental plantings flowchart

20.2. The revenue produced by riparian plantings

The revenue generated by riparian plantings is calculated as:

$\mathbf{Rev}_{RipPlant}^{NonAg}(y) = \mathbf{AGHG}_r^{RipPlant} \times \mathbf{RA}_r \times CO2Price(y)$	Equation 380

where,

- $\mathbf{Rev}_{RipPlant}^{NonAg}$ is the revenue produced by riparian plantings
- $\mathbf{AGHG}_r^{RipPlant}$ represents the average annual greenhouse gas (GHG) sequestration for riparian plantings (block) (Equation 314 and Figure 501)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $CO2Price(y)$ is the market CO_2 price in AUD per Tonne of CO_2 (Figure 349)

The computed $\mathbf{Rev}_{RipPlant}^{NonAg}$ is presented in Figure 602.

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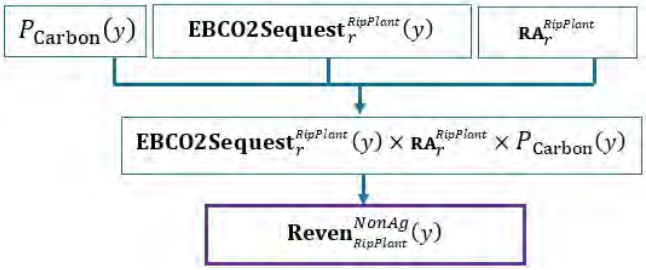

Figure 603 The revenue produced from riparian flowchart

20.3. The revenue produced by Agroforestry (Base)

The revenue generated by Agroforestry plantings (Base) is calculated as:

$\mathbf{Rev}_{AgrFor}^{NonAg}(y) = \mathbf{AGHG}_r^{AgrFor} \times \mathbf{RA}_r \times CO2Price(y)$	Equation 381

where,

- $\mathbf{Rev}_{AgrFor}^{NonAg}$ is the revenue produced by Agroforestry plantings (Base)
- $\mathbf{AGC}_r^{AgrFor}$ represents the average annual aboveground CO2 sequestration per hectare for the base agroforestry (Equation 316 and Figure 506)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $CO2Price(y)$ is the market CO_2 Price in AUD per Tonne of CO_2 (Figure 349)

The computed $\mathbf{Rev}_{AgrFor}^{NonAg}$ is presented in Figure 604.

20.4. Revenue produced by Sheep-Agroforestry

The revenue generated by sheep-agroforestry plantings is calculated as:

$\mathbf{Rev}_r^{Sheep,AgFor}(y) = \left(\mathbf{Rev}_{AgrFor}^{NonAg} \times \mathbf{XCM}_r^{AgFor}\right) + \left[\mathbf{Rev}_r^{Sheep} \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right]$	Equation 382

where,

- $\mathbf{Rev}_{AgrFor}^{NonAg}$ is the revenue generated by Agroforestry plantings (Base) (Equation 381, and Figure 604)
- $\mathbf{Rev}_r^{Sheep}$ is the revenue generated by sheep in lands under dryland management systems (Equation 383 and Figure 605)
- $\mathbf{XCM}_r^{AgFor}$ is the updated exclusion matrix by considering Agroforestry Proportion (Equation 298)

In this equation, the first term, $\left(\mathbf{Rev}_{AgrFor}^{NonAg} \times \mathbf{XCM}_r^{AgFor}\right)$, represents the Agroforestry plantings contribution (Figure 606). The second term $\left[\mathbf{Rev}_r^{Sheep} \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right]$ represents the sheep contribution (Figure 607). Here, $\mathbf{Rev}_r^{Sheep}$ is the revenue generated by sheep grazing in the cell r; and

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$\left(1 - \mathbf{XCM}_r^{AgFor}\right)$ indicates the remaining proportion of a given cell r not covered by Agroforestry plantings, effectively representing the area or resource availability for sheep. The second term, therefore, shows the contribution of sheep to the total revenue, accounting for the reduced area due to Agroforestry plantings.

The revenue generated by sheep $\mathbf{Rev}_r^{Sheep}$ is computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\mathrm{BYear}}$	Equation 383
$\mathbf{Rev}_r^{Sheep} = \begin{cases} \mathbf{Revenue}_{mr\ell} & \text{if} \quad \mathrm{m} = 0 \ \wedge \ell \in \mathcal{L}_{\text{Sheep, modified}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{Revenue}_{mr\ell}$ is the computed revenue matrix that contains both crop revenue and livestock revenue (Equation 216)
- $\mathcal{L}_{\text{Sheep, modified}}$ is introduced in Equation 6

The computed $\mathbf{Rev}_r^{Sheep,AgFor}$ is presented in Figure 608.

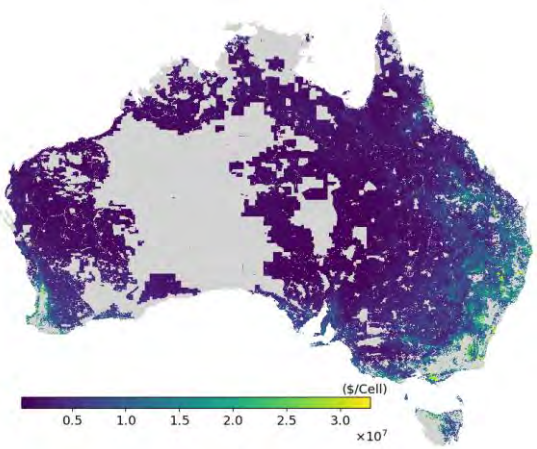	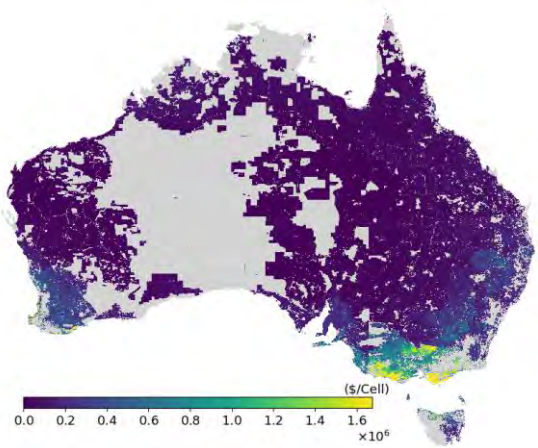
Figure 604 The revenue produced by Agroforestry plantings (Base)	Figure 605 The revenue produced by sheep under dryland management systems

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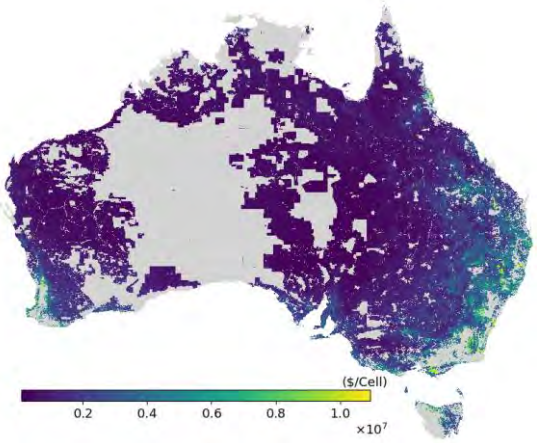	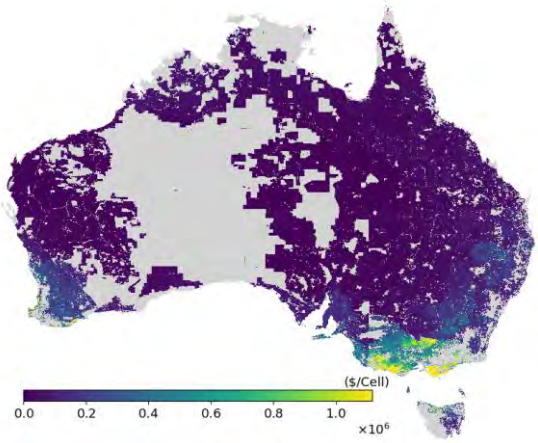
Figure 606 The Agroforestry plantings contributions to sheep-agroforestry plantings revenue	Figure 607 The sheep contributions to sheep-agroforestry revenue
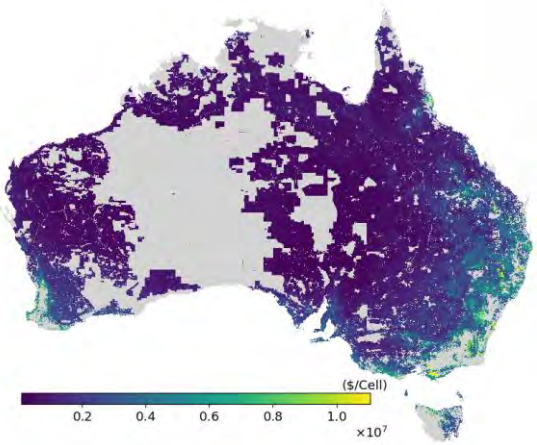	
Figure 608 The total revenue produced by sheep-agroforestry plantings	

20.5. **Revenue produced by Beef-Agroforestry**

The revenue generated by beef-agroforestry plantings is calculated as:

$$\mathbf{Rev}_r^{Beef,AgFor}(y) = \left(\mathbf{Rev}_{AgrFor}^{NonAg} \times \mathbf{XCM}_r^{AgFor}\right) + \left[\mathbf{Rev}_r^{Beef} \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right]$$	Equation 384

where,

- $\mathbf{Rev}_{AgrFor}^{NonAg}$ is the revenue generated by Agroforestry plantings (Base) (Equation 381, and Figure 604)
- $\mathbf{Rev}_r^{Beef}$ is the revenue generated by beef in lands under dry land management systems (Equation 385 and Figure 609)
- $\mathbf{XCM}_r^{AgFor}$ is the updated exclusion matrix by considering Agroforestry Proportion (Equation 298)

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In this equation, the first term, $\left(\mathbf{Rev}_{AgrFor}^{NonAg} \times \mathbf{XCM}_{r}^{AgFor}\right)$ represents the *Agroforestry plantings contribution* (Figure 606). The second term $\left[\mathbf{Rev}_{r}^{Beef} \times \left(1 - \mathbf{XCM}_{r}^{AgFor}\right)\right]$ represents the *Beef contribution* (Figure 610). Here, $\mathbf{Rev}_{r}^{Beef}$ is the revenue generated by beef grazing in the cell r; and $\left(1 - \mathbf{XCM}_{r}^{AgFor}\right)$ indicates the remaining proportion of a given cell r not covered by Agroforestry plantings, effectively representing the area or resource availability for beef. The second term, therefore, shows the contribution of beef to the total revenue, accounting for the reduced area due to Agroforestry plantings.

The revenue generated by sheep $\mathbf{Rev}_{r}^{Beef}$ is computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\mathrm{BYear}}$	Equation 385
$\mathbf{Rev}_{r}^{Beef} = \begin{cases} \mathbf{Revenue}_{mr\ell} & \text{if} \quad \mathrm{m} = 0 \ \wedge \ell \in \mathcal{L}_{\text{Beef, modified}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{Revenue}_{mr\ell}$ is the computed revenue matrix that contains both crop revenue and livestock revenue (Equation 216)
- $\mathcal{L}_{\text{Beef, modified}}$ is introduced in Equation 6

The computed $\mathbf{Rev}_{r}^{Beef,AgFor}$ is presented in Figure 611.

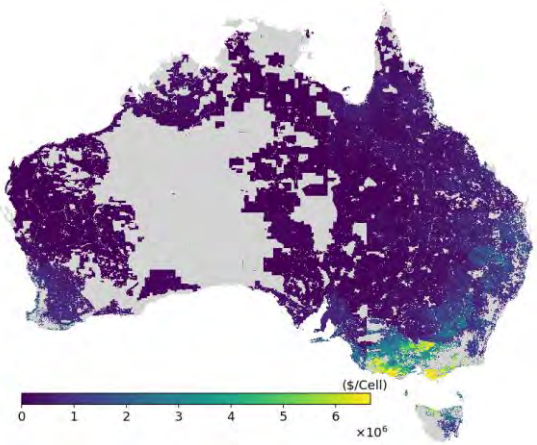

Figure 609 The revenue produced by beef under dryland systems

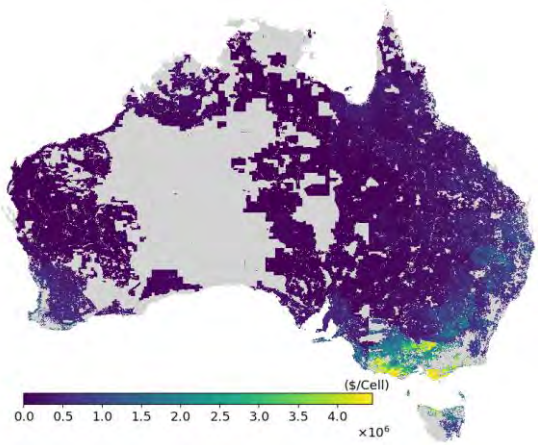

Figure 610 The beef contributions to beef - agroforestry revenue

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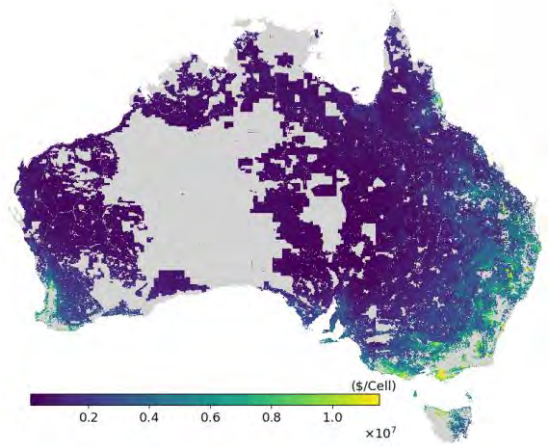

Figure 611 The total revenue from beef - agroforestry

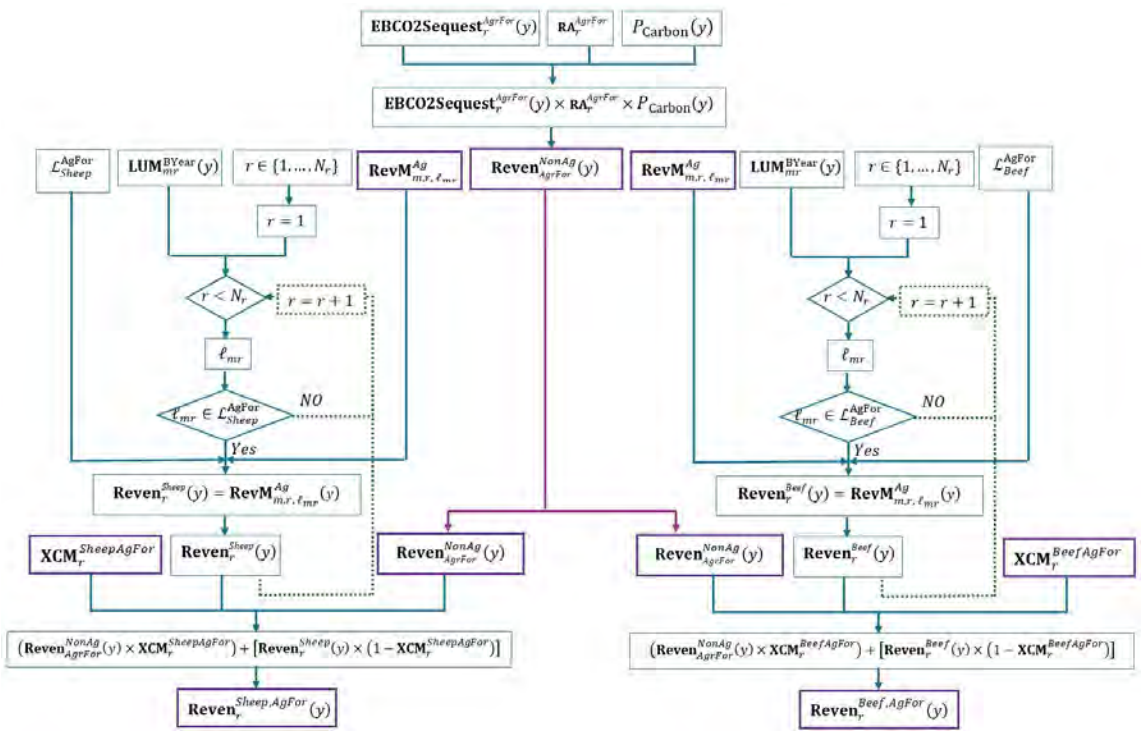

Figure 612: The revenue produced by Sheep and Beef from agroforestry plantings flowchart

20.6. **The revenue produced by carbon plantings (block) plantings**

The revenue generated by carbon plantings (Block) is calculated as:

$\mathbf{Rev}_{CPBlock}^{NonAg}(y) = \mathbf{AGHG}_{r}^{CPBlock} \times \mathbf{RA}_{r} \times CO2Price(y)$	Equation 386

where,

- $\mathbf{Rev}_{CPBlock}^{NonAg}$ is the revenue produced by carbon plantings (Block)

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- $\mathbf{AGHG}_r^{CPBlock}$ represents the average annual greenhouse gas (GHG) sequestration for carbon plantings (Block) (Equation 322,Figure 524)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $CO2Price(y)$ is the market CO_2 Price (AUD per Tonne of CO_2) (Figure 349)

The computed $\mathbf{Rev}_{CPBlock}^{NonAg}$ is presented in Figure 613.

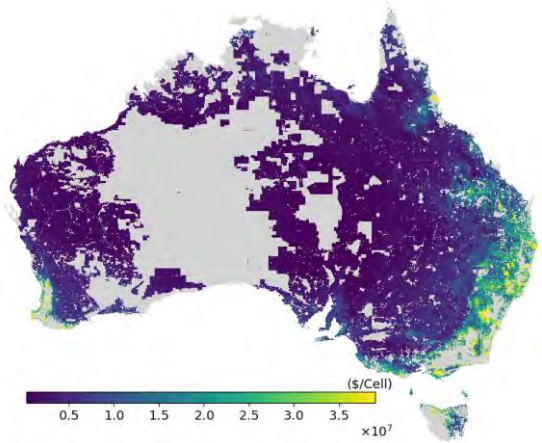

Figure 613 The revenue produced from carbon plantings (Block) flowchart

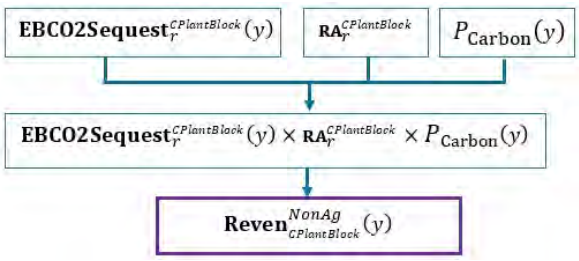

Figure 614 The revenue produced from carbon plantings (block) flowchart

20.7. The revenue produced by Carbon Plantings (Belt)-base

The revenue generated by carbon planting in a belt arrangement is calculated as:

$\mathbf{Rev}_{CPBelt}^{NonAg}(y) = \mathbf{AGHG}_r^{CPBelt} \times \mathbf{RA}_r \times CO2Price(y)$	Equation 387

where,

- $\mathbf{Rev}_{CPBelt}^{NonAg}$ is the revenue produced by Carbon Planting (Belt)
- $\mathbf{AGHG}_r^{CPBelt}$ represents the average annual greenhouse gas (GHG) sequestration for the carbon plantings (Belt) (Equation 324, and Figure 524)
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $CO2Price(y)$ is the market CO_2 Price in AUD per Tonne of CO_2 (Figure 349)

The computed $\mathbf{Rev}_{CPBelt}^{NonAg}$ is presented in Figure 615.

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20.8. Revenue produced by Sheep-Carbon Plantings (Belt)

The revenue generated by sheep-carbon planting (belt arrangement) is calculated as:

$$\mathbf{Rev}_r^{Sheep,CPBelt}(y) = \left(\mathbf{Rev}_{CPBelt}^{NonAg} \times \mathbf{XCM}_r^{CPBelt}\right) + \left[\mathbf{Rev}_r^{Sheep} \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$$	Equation 388

where,

- $\mathbf{Rev}_{CPBelt}^{NonAg}$ is the revenue generated by carbon plantings (Belt) (Equation 387, and Figure 615)
- $\mathbf{Rev}_r^{Sheep}$ is the revenue generated by sheep in lands under dryland management systems (Equation 383 and Figure 605)
- $\mathbf{XCM}_r^{CPBelt}$ is the exclusion matrix representing the proportion of land used for carbon plantings (Belt arrangement) (Equation 304 and Figure 487)

In this equation,

- The first term, $\left(\mathbf{Rev}_{CPBelt}^{NonAg} \times \mathbf{XCM}_r^{CPBelt}\right)$ represents the *Carbon Planting (Belt) contribution* (Figure 606).
- The second term $\left[\mathbf{Rev}_r^{Sheep} \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$ represents the *sheep contribution* (Figure 607).

Here, $\mathbf{Rev}_r^{Sheep}$ is the revenue from sheep grazing in cell r; and $(1 - \mathbf{XCM}_r^{CPBelt})$ indicates the remaining proportion of that cell r not covered by Carbon Planting (Belt), effectively representing the area or resource availability for sheep grazing. The second term, therefore, captures the sheep's contribution to total revenue, accounting for the reduced area resulting from the carbon planting.

The computed $\mathbf{Rev}_r^{Sheep,CPBelt}$ is presented in Figure 608.

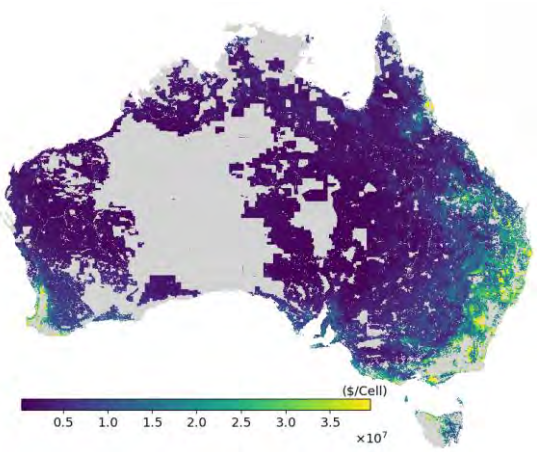	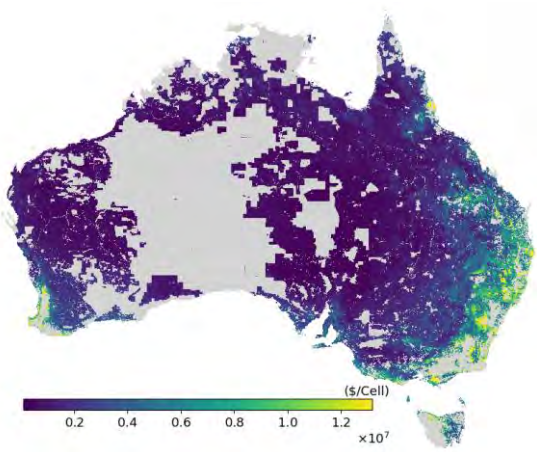
Figure 615 The revenue produced by base Carbon Planting (Belt)	Figure 616 The Carbon Planting (Belt) contribution to the revenue of Sheep–Carbon Planting (Belt)

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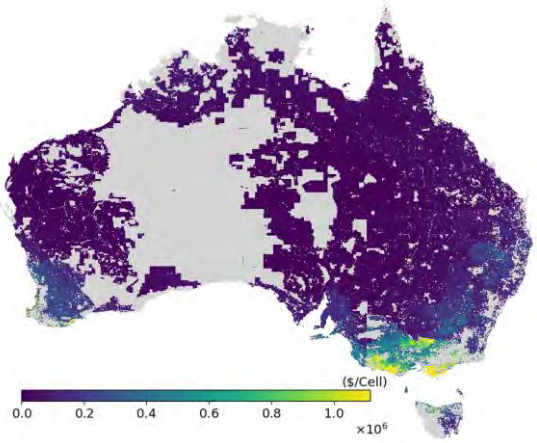	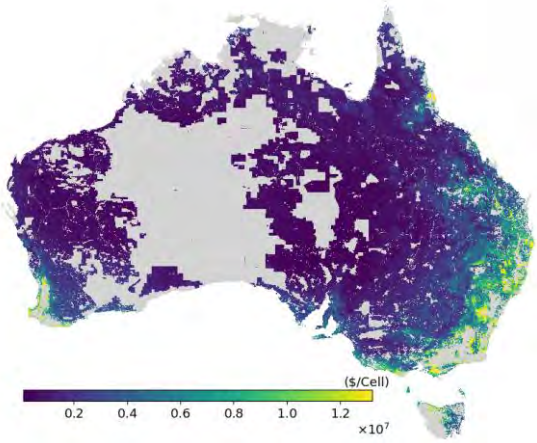
Figure 617 The sheep contribution to the revenue of Sheep–Carbon Planting (Belt)	Figure 618 The total revenue produced by Sheep–Carbon Planting (Belt)

20.9. **Revenue produced by Beef- Carbon Plantings (Belt)**

The revenue generated by beef-Carbon Planting (Belt) is calculated as:

$$\mathbf{Rev}_r^{Beef,CPBelt}(y) = \left(\mathbf{Rev}_{CPBelt}^{NonAg} \times \mathbf{XCM}_r^{CPBelt}\right) + \left[\mathbf{Rev}_r^{Beef} \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$$	Equation 389

where,

- $\mathbf{Rev}_{CPBelt}^{NonAg}$ is the revenue generated by Carbon Planting (Belt) (Equation 387, and Figure 615)
- $\mathbf{Rev}_r^{Beef}$ is the revenue generated by beef in lands under dryland management systems (Equation 385 and Figure 609)
- $\mathbf{XCM}_r^{CPBelt}$ is the exclusion matrix representing the proportion of land used for carbon plantings in the belt arrangement (Equation 304 and Figure 487)

In this equation,

- The first term, $\left(\mathbf{Rev}_{CPBelt}^{NonAg} \times \mathbf{XCM}_r^{CPBelt}\right)$, represents the *Carbon Planting (Belt) contribution* (Figure 616).
- The second term $\left[\mathbf{Rev}_r^{Beef} \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$, represents the *Beef contribution* (Figure 619).

Here, $\mathbf{Rev}_r^{Beef}$ represents the revenue generated by beef grazing in cell r; and $(1 - \mathbf{XCM}_r^{CPBelt})$ reflects the remaining proportion of the cell not covered by Carbon Planting (Belt), effectively representing the area available for beef production. This second term thus captures the contribution of beef to the total revenue, accounting for the reduced land area due to Carbon Planting (Belt).

The computed $\mathbf{Rev}_r^{Beef,CPBelt}$ is presented in Figure 620.

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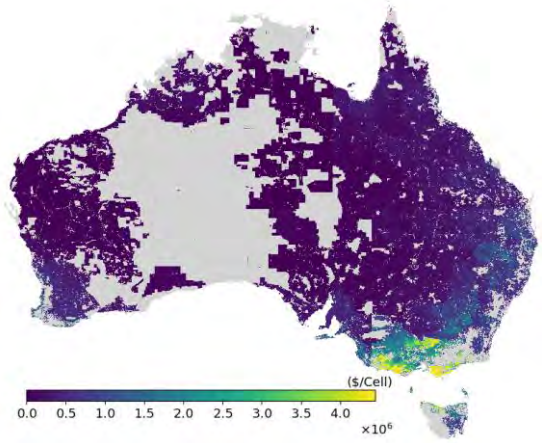	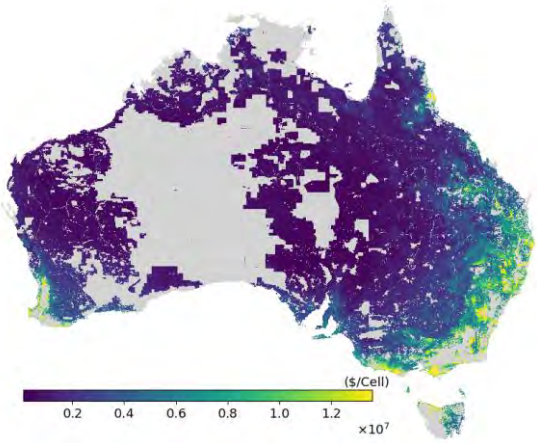
Figure 619 The beef contribution to the revenue of Beef–Carbon Planting (Belt)	Figure 620 The total revenue from Beef–Carbon Planting (Belt)

20.10. Revenue Produced by Bioenergy with Carbon Capture and Storage (BECCS)

The revenue generated by BECCS is calculated as:

$$\mathbf{Rev}_r^{BECCS}(y) = \left(\mathbf{Rev}_{BECCS}^{NonAg} \times RM_\ell^{BECCS}(y) \times \mathbf{RA}_r\right) + \left(\mathbf{AGHG}_r^{BECCS} \times \mathbf{RA}_r \times CO2Price(y)\right)$$	Equation 390

where,

- $\mathbf{Rev}_{BECCS}^{NonAg}$ is the base revenue generated by BECCS (Figure 621)
- $\mathbf{AGHG}_r^{BECCS}$ represents the average annual greenhouse gas (GHG) sequestration for BECCS (Figure 530)
- $RM_\ell^{BECCS}(y)$ is the revenue multiplier
- $\mathbf{RA}_r$ represents the real area (Figure 5)
- $CO2Price(y)$ is the market CO_2 Price in AUD per Tonne of CO_2 (Figure 349)

In this equation, the first term, $\left(\mathbf{Rev}_{BECCS}^{NonAg} \times RM_\ell^{BECCS}(y) \times \mathbf{RA}_r\right)$ represents the base contribution of *BECCS* (Figure 622).

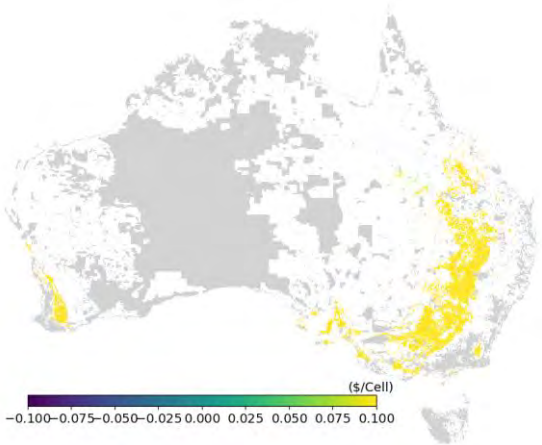	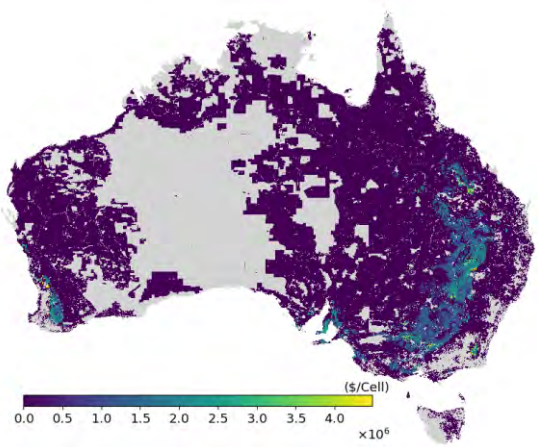

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Figure 621 The average annual revenue for BECCS under dryland management system	Figure 622 The base revenue from BECCS under dryland management system
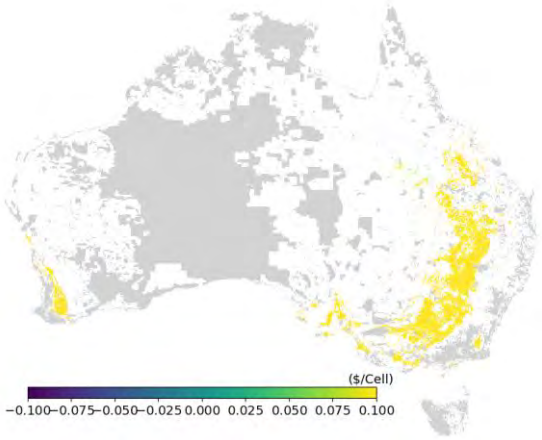	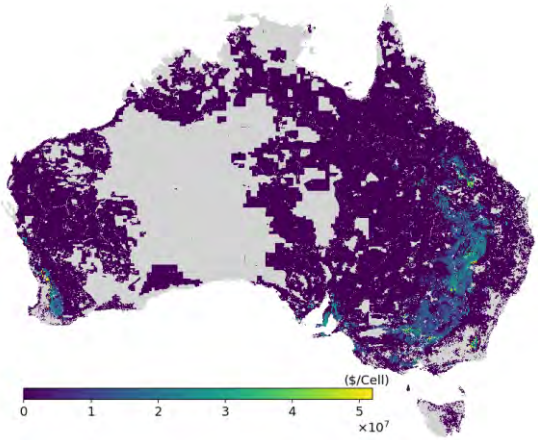
Figure 623 Annual CO_2 sequestration per hectare by BECCS	Figure 624 Total revenue produced by BECCS

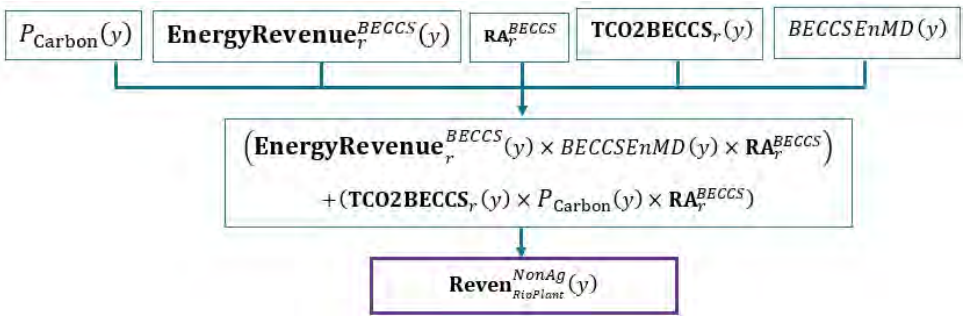

Figure 625 Revenue computation flowchart for BECC

20.11. Revenue Produced from Non-Agricultural Land Uses

The general form of the revenue matrix $\mathbf{Rev}_{r\ell}^{NonAg}$, where $\ell \in \mathcal{L}_{\text{NonAgrLand}}$ and $\mathcal{L}_{\text{NonAgrLand}}$ is defined in Equation 13 , is constructed by concatenating the individual revenue vectors for each land use class in the non-agricultural land use set $\mathcal{L}_{\text{NonAgrLand}}$:

$$\mathbf{Rev}_{r\ell}^{NonAg}(y) = \text{concatenate}\begin{pmatrix} \mathbf{Rev}_r^{EnvPlanting}(y), \mathbf{Rev}_r^{RipPlant}(y), \mathbf{Rev}_r^{Sheep,AgFor}(y), \\ \mathbf{Rev}_r^{Beef,AgFor}(y), \mathbf{Rev}_r^{CPBlock}(y), \mathbf{Rev}_r^{Sheep,\text{CPBelt}}(y), \\ \mathbf{Rev}_r^{Beef,\text{CPBelt}}(y), \mathbf{Rev}_r^{BECCS}(y) \end{pmatrix} \quad \text{Equation 391}$$

This equation integrates the revenue outcomes from all non-agricultural land use types into a single matrix for cell r in year y.

- Economics/non_Agricultural/ transition.py

21. The Transition Matrix from Agricultural Land Uses to Non-Agricultural Classes

21.1. Transition Cost from Agricultural Land to Environmental Plantings

21.1.1. Base Transition Cost from Agricultural Land to Environmental Plantings

Let $\mathbf{RTCM}^{\mathrm{AgToEP}}$ represent the raw transition cost matrix indicating the base cost of transition (in AUD per hectare) from agricultural land use to environmental plantings (EP). It is defined as a matrix of size 1×28, where each element $\mathbf{RTCM}^{\mathrm{AgToEP}}_{\ell_i,\ell_j}$ denotes the cost of converting from land use class ℓ_i to $\ell_j = \mathrm{EP}$, and $\ell_i \in \mathcal{L}$ with $\mathcal{L}$ being the set of all land uses defined in Equation 1.

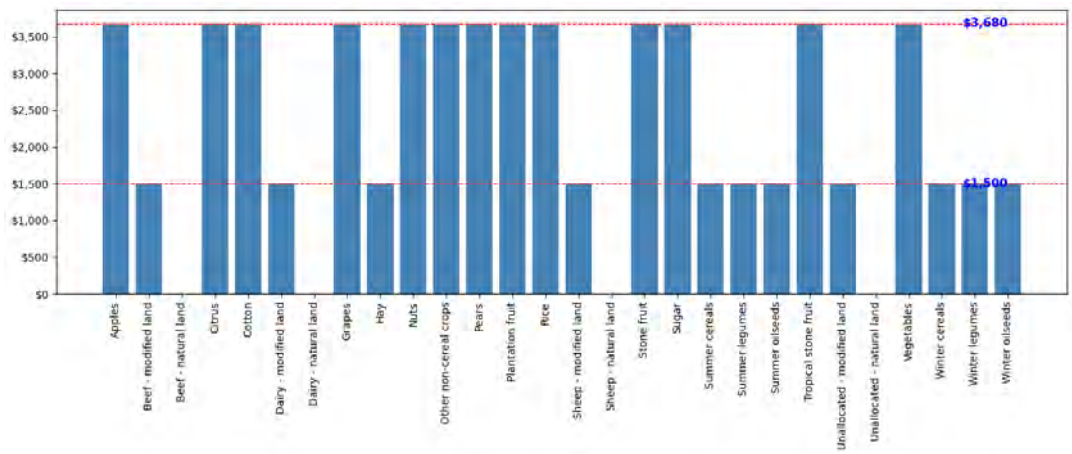

Figure 626 Land Use Categories and Associated Transition Costs

Let $\mathbf{BTCM}^{\mathrm{AgToEP}}_{mr\ell}$ be the base transition cost matrix representing the cost of transition (AUD/ha) from agricultural land to environmental planting for each cell r under land management $m \in \{0,1\}$. Initially, $\mathbf{BTCM}^{\mathrm{AgToEP}}_{mr\ell}$ is initialized as a zero matrix:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 392
$\mathbf{BTCM}^{\mathrm{AgToEP}}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c: number of spatial cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_k = 2$: number of agricultural management types $m \in \mathcal{M}$ (Equation 21)
- $N_{lu} = 28$: number of agricultural land-use classes.

The matrix is updated using the values from $\mathbf{RTCM}^{\mathrm{AgToEP}}$ as follows:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 393
$\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}} = \begin{cases} \mathbf{RTCM}_{\ell}^{\text{AgToEP}} & \text{if} \quad \ell \in \mathcal{L} \\ \mathbf{0} & \text{otherwise} \end{cases}$	

21.1.2. Amortized Base Cost of Transition from Agriculture to Environmental Planting

The computed base transition cost $\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}}$ (Equation 393) must be amortized using the amortization formula (Equation 249). The amortized base transition cost is calculated as:

$\mathbf{ABTCM}_{mr\ell}^{\text{AgToEP}} = \dfrac{\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}} \times \text{DR} \times (1 + \text{DR})^{\text{NP}}}{(1 + \text{DR})^{\text{NP}} - 1}$	Equation 394

Where:

- $\mathbf{ABTCM}_{mr\ell}^{\text{AgToEP}}$ is the amortized base transition cost of $\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}}$
- $\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}}$ is the base transition cost from agriculture to environmental plantings (Equation 393)
- DR is the discount rate per period (LUTO 2.0 uses 7% or 0.07)
- NP is the number of periods (LUTO 2.0 uses 30 years)

The amortized transition cost $\mathbf{ABTCM}_{mr\ell}^{\text{AgToEP}}$ for selected land use classes is shown in Figure 629 and Figure 630.

21.1.3. Adjusted Amortized Cost for Beginning-of-Period Payments

As defined in Equation 251-Equation 255, LUTO 2.0 assumes payments are made at the beginning of each period. The payment calculation is adjusted accordingly:

$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToEP}} = \mathbf{ABTCM}_{mr\ell}^{\text{AgToEP}} \times \dfrac{1}{1 + DR}$	Equation 395

Substituting Equation 394) into this expression:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 396
$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToEP}} = \dfrac{\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}} \times DR \times (1 + DR)^{NP}}{(1 + DR)^{NP} - 1} \times \dfrac{1}{1 + DR}$	

For a given year y, this simplifies to:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 397
$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToEP}} = \dfrac{\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}} \times DR \times (1 + DR)^{NP-1}}{(1 + DR)^{NP} - 1}$	

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For example, using LUTO 2.0 parameters $DR = 0.07$ and $NP = 30$:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 398
$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToEP}} = \dfrac{\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}} \times 0.07 \times (1+0.07)^{30-1}}{(1+0.07)^{30}-1}$	

Thus:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 399
$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToEP}} = \dfrac{\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}} \times 0.07 \times (1+0.07)^{29}}{(1+0.07)^{30}-1}$	

This equation represents a tensor of the equivalent annual payment (i.e. amortized value) of the computed $\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}}$, calculated over a 30-year period at a 7% discount rate, assuming payments are made at the beginning of each period.

21.1.4. Total Transition Cost

The total transition cost incorporates both the amortised base cost of transitioning from agricultural land to environmental planting and, where applicable, the pre-amortised cost of water licensing and irrigation installation/removal (as defined in Equation 272). The equation is:

$\mathbf{TCM}_{mr\ell}^{\text{AgToEP}}(y) = \mathbf{ABTCM}_{mr\ell}^{\text{AgToEP}} + \mathbf{WLC}_{mr\ell}(y)$	Equation 400

where,

- $\mathbf{TCM}_{mr\ell}^{\text{AgToEP}}$ represent that total transition cost matrix ($/ha) to convert land from Agriculture to Environmental Planting
- $\mathbf{ABTCM}_{mr\ell}^{\text{AgToEP}}$ is the amortized base transition cost (Equation 395)
- $\mathbf{WLC}_{mr\ell}(y)$ is the amortized cost of water licensing and irrigation system changes, where applicable (Equation 274)

21.1.5. Total transition cost for each cell

In the next step, the total transition cost matrix $\mathbf{TCM}_{mr\ell}^{\text{AgToEP}}$ (Equation 405) must be adjusted to apply only to agricultural cells. This is achieved by multiplying it element-wise with the Boolean tensor $\mathbf{BLuLmM}_{mr\ell}$ (Equation 234), which has a value of 1 for agricultural land uses and 0 for non-agricultural ones. Thus, $\mathbf{BLuLmM}_{mr\ell}$ ensures that transition costs are only applied to valid agricultural cells within the $m-$th management states, $r-$th cell and $\ell-$th land use category.

The total transition cost for each cell r is calculated as:

$\mathbf{TCM}_{r}^{\text{AgToEP}}(y) = \sum_{m,\ell} \left(\mathbf{TCM}_{mr\ell}^{\text{AgToEP}}(y) \times \mathbf{BLuLmM}_{mr\ell}\right)$	Equation 401

where,

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- $\mathbf{BLuLmM}_{mr\ell}$ is the Boolean land-use and management matrix (Equation 234)
- $\mathbf{TCM}_{mr\ell}^{\mathrm{AgToEP}}$ is the total transition cost matrix per hectare ($/ha) from agriculture to environmental plantings (Equation 405, and Figure 633)

21.1.6. Establishment Cost

Let $\mathbf{AEstCost}_r^{\mathrm{EP}}(y)$ be the amortized establishment cost per hectare ($/ha) for environmental planting. This cost accounts for the initial outlay spread over a specified time horizon using a fixed discount rate, and is computed as:

$$\mathbf{AEstCost}_r^{\mathrm{EP}}(y) = \frac{\mathbf{IEstCost}_r^{\mathrm{EP}}(y) \times \mathrm{DR} \times (1+\mathrm{DR})^{\mathrm{NP}}}{(1+\mathrm{DR})^{\mathrm{NP}} - 1}$$	Equation 402

Where:

- $\mathbf{AEstCost}_r^{\mathrm{EP}}$: Amortized base establishment cost per hectare ($/ha) (Figure 635)
- $\mathbf{IEstCost}_r^{\mathrm{EP}}$: Initial establishment cost per hectare ($/ha) for transition from agricultural land to environmental plantings (Equation 403 and Figure 635)
- DR : Discount rate per period (set to 7% or 0.07 in LUTO 2.0)
- NP: Number of periods (set to 30 years in LUTO 2.0)

$$\mathbf{IEstCost}_r^{\mathrm{EP}}(y) = \mathbf{EstCostD}_r^{\mathrm{EP}} \times ECMD(y)$$	Equation 403

where,

- $\mathbf{EstCostD}_r^{\mathrm{EP}}$ is the Establishment Cost per hectare Data ($/ha) which is provided by LUTO 2 (Figure 634)
- $ECMD(y)$ represents the establishment cost multiplier data for each year y.

21.1.7. Final Total Cost including Establishment

$$\mathbf{TotTCM}_r^{\mathrm{AgToEP}}(y) = \left(\mathbf{TCM}_r^{\mathrm{AgToEP}}(y) + \mathbf{AEstCost}_r^{\mathrm{EP}}(y)\right) \times \mathbf{RA}_r$$	Equation 404

where,

- $\mathbf{TotTCM}_r^{\mathrm{AgToEP}}$ is the total cost transition cost from agricultural land to environmental plantings
- $\mathbf{TCM}_r^{\mathrm{AgToEP}}$ is the transition costs from agricultural land to environmental plantings (Equation 406)
- $\mathbf{AEstCost}_r^{\mathrm{EP}}$ is the amortized establishment cost per hectare ($/ha) for environmental planting (Equation 408, and Figure 635)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{TotTCM}_r^{\mathrm{AgToEP}}$ is illustrated in Figure 636.

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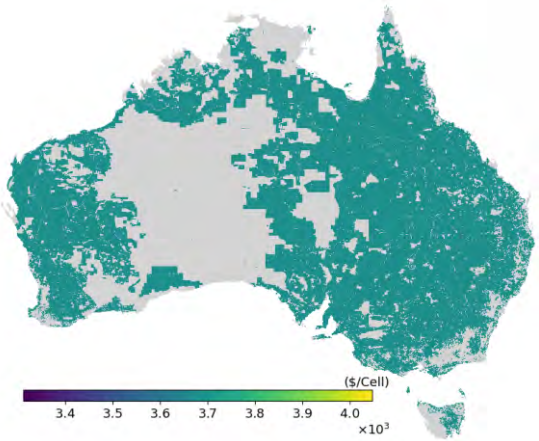

Figure 627 Transition cost from Apple to Environmental Plantings (sample with $3680 transition cost)

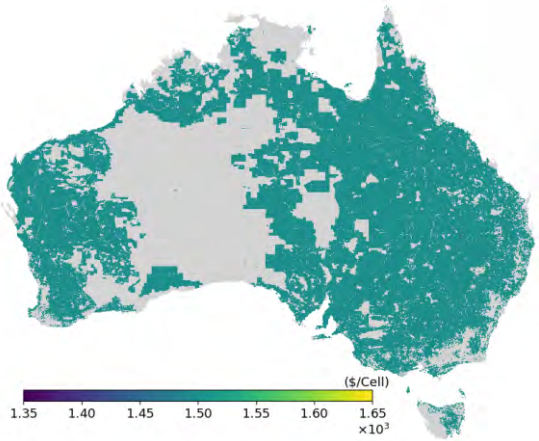

Figure 628 Transition cost from Apple to Environmental Plantings (sample with $1,500 transition cost)

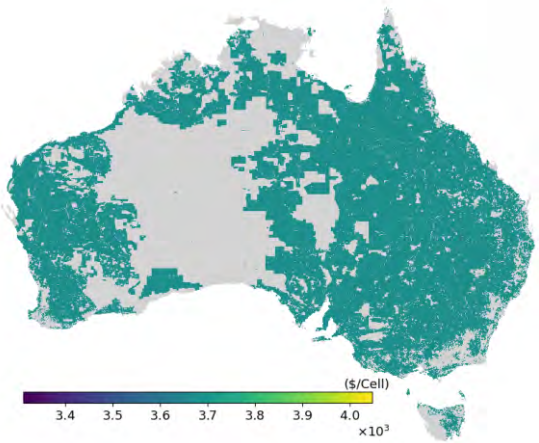

Figure 629 Amortized base transition cost from Apple to Environmental Plantings (sample with $3,680 transition cost)

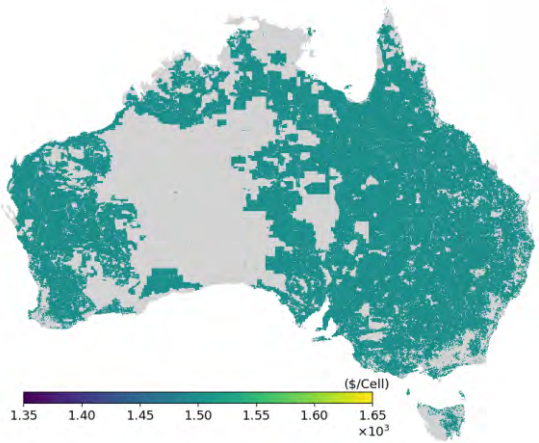

Figure 630 Amortized base transition cost from Beef-Modified Land to Environmental Plantings

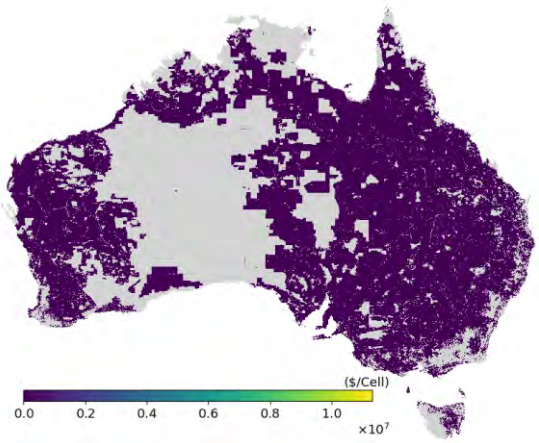

Figure 631 Water cost adjustment (installation/removal of irrigation) added to transition cost from Apple to Environmental Plantings

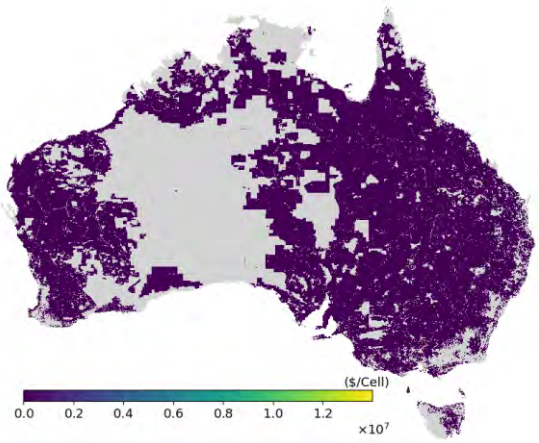

Figure 632 Water cost adjustment (installation/removal of irrigation) added to transition cost from Beef-Modified Land to Environmental Plantings

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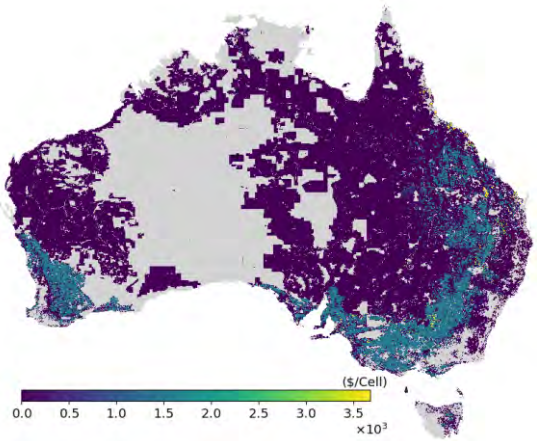	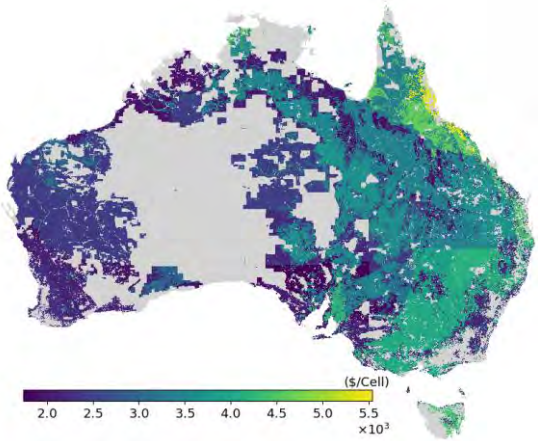
Figure 633 Total transition cost for each cell converting to Environmental Plantings	Figure 634 Initial Establishment Cost per hectare
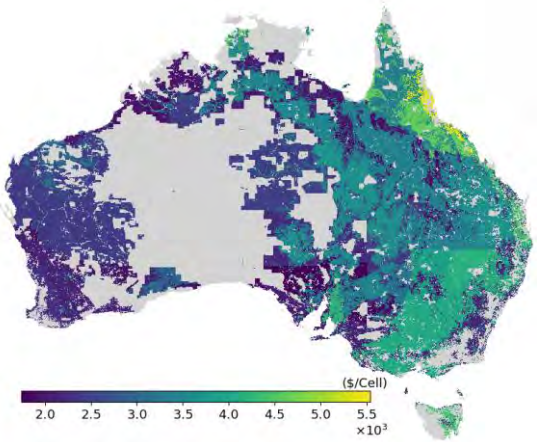	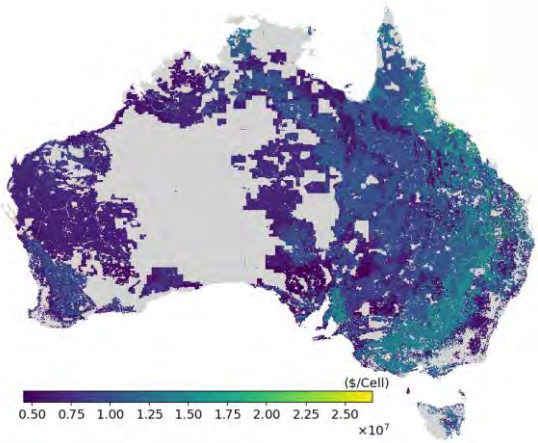
Figure 635 Amortized Establishment Cost per hectare	Figure 636 Total transition cost from Agricultural Land to Environmental Plantings

21.2. Transition costs from agricultural land to riparian plantings

Let $\mathbf{TotTCM}_{mr\ell}^{\mathrm{AgToRP}}(y)$ be the transition cost matrix for converting agricultural land into riparian planting. It is calculated as:

$\mathbf{TotTCM}_{r}^{\mathrm{AgToRP}}(y) = \mathbf{BTCM}_{r}^{\mathrm{AgToRP}} + \mathbf{FCM}_{r}^{\mathrm{RP}}$	Equation 405

where,

- $\mathbf{BTCM}_{r}^{\mathrm{AgToRP}}$ is the base transition cost from agricultural land to riparian plantings.
- $\mathbf{FCM}_{r}^{\mathrm{AgToRP}}$ is the fencing cost matrix for converting agricultural land to riparian plantings.

LUTO 2.0 assumes that $\mathbf{BTCM}_{r}^{\mathrm{AgToRP}}$ is equals to the total transition cost for environmental plantings $\mathbf{TotTCM}_{r}^{\mathrm{AgToEP}}$(Equation 404), thus:

$\mathbf{BTCM}_{r}^{\mathrm{AgToRP}} = \mathbf{TotTCM}_{r}^{\mathrm{AgToEP}}$	Equation 406

The fencing cost $\mathbf{FCM}_{r}^{\mathrm{RP}}$ is calculated as:

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$\mathbf{FCM}_r^{\mathrm{RP}} = \mathbf{FL}_r^{\mathrm{RP}} \times FCost \times FCMD(y) \times \mathbf{RA}_r$	Equation 407

where,

- $\mathbf{FL}_r^{\mathrm{RP}}$ is the fencing length (Equation 408, and Figure 637)
- $FCost$ is the cost per meter of fencing, assumed as $FCost = 5\ \$$
- $FCMD(y)$ is the fencing cost multiplier for year y.
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The fencing length $\mathbf{FL}_r^{\mathrm{RP}}$ is computed as:

$\mathbf{FL}_r^{\mathrm{RP}} = \dfrac{2 \times TF^{\mathrm{RP}} \times SL}{\mathbf{RA}_r}$	Equation 408

where,

- TF^{RP} is the tortuosity factor for riparian planting. LUTO 2.0 assumes $TF^{\mathrm{RP}} = 0.5$.
- SL is the stream length per cell.
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The fencing length $\mathbf{FL}_r^{\mathrm{RP}}$ is illustrated in Figure 637.

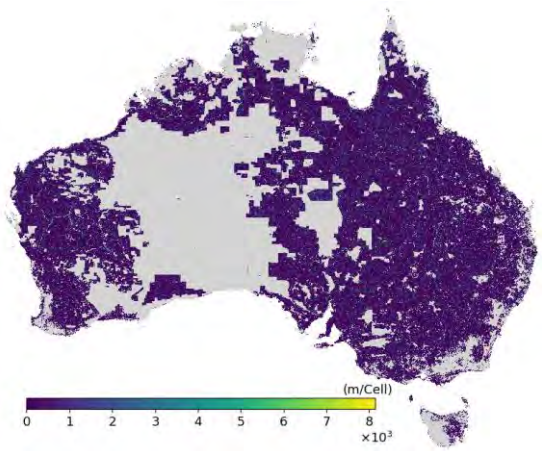	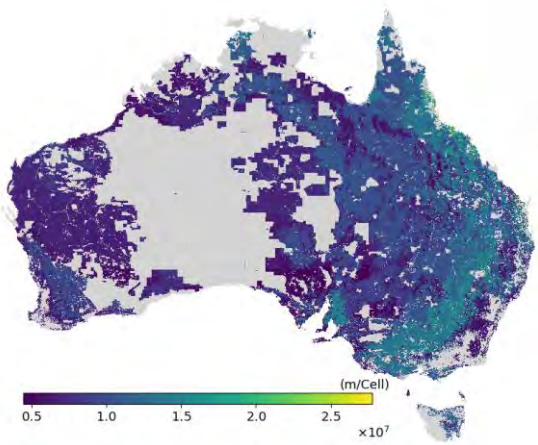
Figure 637 The stream length data in metres of stream per cell	Figure 638 The total transition costs from agricultural land to riparian plantings

21.3. Transition Costs from Agricultural Land to Agroforestry Plantings (Base)

Let $\mathbf{TotTCM}_{mr\ell}^{\mathrm{Base,AgToAF}}(y)$ be the total transition cost matrix for converting agricultural land into agroforestry planting. It is computed as:

$\mathbf{TotTCM}_r^{\mathrm{Base,AgToAF}}(y) = \mathbf{BTCM}_r^{\mathrm{AgToAF}} + \mathbf{FCM}_r^{\mathrm{AF}}$	Equation 409

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where,

- $\mathbf{BTCM}_r^{\mathrm{AgToAF}}$ is the base cost for converting agricultural land into agroforestry planting
- $\mathbf{FCM}_r^{\mathrm{AF}}$ is the fencing cost matrix for converting agricultural land to agroforestry plantings

LUTO 2.0 assumes that the base transition cost for converting agricultural land to agroforestry plantings, $\mathbf{BTCM}_r^{\mathrm{AgToAF}}$, is equal to the total transition cost for converting agricultural land to environmental plantings, $\mathbf{TotTCM}_r^{\mathrm{AgToEP}}$, as calculated in Equation 404; therefore, it can be expressed as

$\mathbf{BTCM}_r^{\mathrm{AgToAF}} = \mathbf{TotTCM}_r^{\mathrm{AgToEP}}$	Equation 410

The fencing cost $\mathbf{FCM}_r^{\mathrm{AF}}$ is computed as:

$\mathbf{FCM}_r^{\mathrm{AF}} = \mathbf{FL}_r^{\mathrm{AF}} \times FCost \times FCMD(y) \times \mathbf{RA}_r$	Equation 411

where,

- $\mathbf{FL}_r^{\mathrm{AF}}$ is the fencing length (Equation 412, and Figure 637)
- $FCost$ is the fencing cost per linear meter. Luto 2 assumes that $FCost = 5\ \$$
- $FCMD(y)$ is the fencing cost multiplier for year y.
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed fencing cost $\mathbf{FCM}_r^{\mathrm{AF}}$ is illustrated in Figure 641.

The fencing length $\mathbf{FL}_r^{\mathrm{AF}}$ is computed as:

$\mathbf{FL}_r^{\mathrm{AF}} = \dfrac{20000}{\mathrm{AgFor}_{RW} + \mathrm{AgFor}_{RS}}$	Equation 412
$\mathbf{FL}_r^{\mathrm{AF}} = \dfrac{20000}{20 + 40} = 333.33$	

where,

- AgFor_{RW} is the Agroforestry row width in metres, a constant parameter in LUTO 2.0, set as $\mathrm{AgFor}_{RW} = 20$
- AgFor_{RS} is the Agroforestry row spacing in metres, a constant parameter in LUTO 2.0, set as $\mathrm{AgFor}_{RS} = 40$

The belt width is then:

$\mathrm{AgFor}_{Belt} = \mathrm{AgFor}_{RS} + \mathrm{AgFor}_{RW}$	Equation 413
$\mathrm{AgFor}_{Belt} = 20 + 40 = 60\ m$	
$NBH = \dfrac{100}{\mathrm{AgFor}_{Belt}} = \dfrac{100}{60} = 1.666$	

where,

- NBH represents the number of belts per hectare

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Regarding NBH, we can also compute $\mathbf{FL}_r^{\mathrm{AF}}$, as:

$\mathbf{FL}_r^{\mathrm{AF}} = 100 \times NBH \times 2$	Equation 414

Figure 639 illustrates the concept and layout for calculating $\mathbf{FL}_r^{\mathrm{AF}}$.

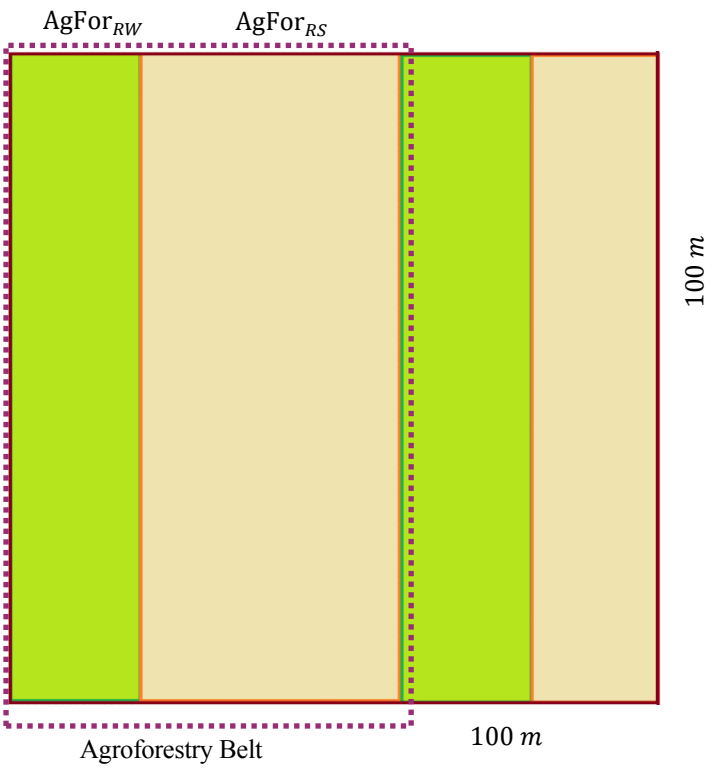

Figure 639 The length of fencimg required for agroforestry planting

21.4. Transition costs from agricultural land to sheep-agroforestry plantings

The transition cost matrix for converting agricultural land into sheep-agroforestry planting is calculated as:

$\mathbf{TotTCM}_r^{Sheep,AgFor}(y) = \left(\mathbf{TotTCM}_r^{\mathrm{Base,AgToAF}} \times \mathbf{XCM}_r^{AgFor}\right) + \left[\mathbf{Cost}_r^{Sheep} \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right]$	Equation 415

where,

- $\mathbf{TotTCM}_r^{\mathrm{Base,AgToAF}}$ is the base transition cost for converting agricultural land to agroforestry planting (Base) (Equation 381, and Figure 640)
- $\mathbf{Cost}_r^{Sheep}$ is the non-irrigation-related raw transition cost for cells transitioning to sheep-modified land under dryland management (Equation 385 and Figure 642)
- $\mathbf{XCM}_r^{AgFor}$ is the exclusion matrix indicating the proportion of land allocated to agroforestry (Equation 298)

In this equation,

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- The first term, $\left(\mathbf{TotTCM}_r^{\text{Base,AgToAF}} \times \mathbf{XCM}_r^{AgFor}\right)$, represents the *Agroforestry plantings contribution* (Figure 644).
- The second term $\mathbf{Cost}_r^{Sheep} \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)$, represents the *Sheep contribution* (Figure 643).

Here, $\mathbf{Cost}_r^{Sheep}$ captures the cost associated with land-use transition to sheep-modified land under dryland management. The expression $\left(1 - \mathbf{XCM}_r^{AgFor}\right)$ reflects the proportion of cell r not assigned to agroforestry and thus available for sheep. The combination of both components captures the total transition cost for sheep-agroforestry.

The non-irrigation-related raw transition cost $\mathbf{Cost}_r^{Sheep}$ is calculated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\text{BYear}}$	Equation 416
$\mathbf{Cost}_r^{Sheep} = \begin{cases} \mathbf{TotTranMatC}_{mr\ell}^{AG}(y) & \text{if} \quad \mathrm{m} = 0 \ \wedge \ell \in \mathcal{L}_{\text{Sheep, modified}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{TotTranMatC}_{mr\ell}^{AG}(y)$ is the total costs associated with land-use transitions (Equation 216, and Figure 461-Figure 469)
- $\mathcal{L}_{\text{Sheep, modified}}$ is defined in Equation 5

The final computed matrix $\mathbf{TotTCM}_r^{Sheep,AgFor}$ is illustrated in Figure 645.

21.5. Transition Costs from Agricultural Land to Beef-Agroforestry Plantings costs from agricultural land to beef-agroforestry plantings

The transition cost matrix for converting agricultural land into beef-agroforestry planting is calculated as:

$\mathbf{TotTCM}_r^{Beef,AgFor}(y) = \left(\mathbf{TotTCM}_r^{\text{Base,AgToAF}} \times \mathbf{XCM}_r^{AgFor}\right) + \left[\mathbf{Cost}_r^{\text{Beef}} \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)\right]$	Equation 417

where,

- $\mathbf{TotTCM}_r^{\text{Base,AgToAF}}$ is the base transition cost for converting agricultural land into agroforestry (Equation 381, and Figure 640)
- $\mathbf{Cost}_r^{\text{Beef}}$ is the non-irrigation-related raw transition costs for cells converted from 2050 land use (Equation 385, and Figure 646) to beef - modified land under dryland management (AUD per ha)
- $\mathbf{XCM}_r^{AgFor}$ is the updated exclusion matrix indicating the proportion of land used for agroforestry (Equation 298)

In this equation,

- The first term, $\left(\mathbf{TotTCM}_r^{\text{Base,AgToAF}} \times \mathbf{XCM}_r^{AgFor}\right)$ represents the agroforestry contribution to total transition cost (Figure 644).
- The second term $\mathbf{Cost}_r^{\text{Beef}} \times \left(1 - \mathbf{XCM}_r^{AgFor}\right)$ represents the Beef contribution (Figure 647).

Here, $\mathbf{Cost}_r^{\text{Beef}}$ represents the non-irrigation-related raw transition costs for cells converted from the 2050 baseline land use (Equation 385, and Figure 646) to beef-modified land under dryland management (AUD per hectare). The term $\left(1 - \mathbf{XCM}_r^{AgFor}\right)$ reflects the remaining proportion of each cell r not allocated to agroforestry, thereby indicating the area available for beef production. This second term captures the beef-related contribution to the total transition cost matrix resulting from Beef-Agroforestry conversion.

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The raw transition costs $\mathbf{Cost}_r^{\text{Beef}}$ for cells converted from the 2050 land use (Figure 393) to beef-modified land under dryland management are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\text{BYear}}$	Equation 418
$\mathbf{Cost}_r^{\text{Beef}} = \begin{cases} \mathbf{TotTranMatC}_{mr\ell}^{AG}(y) & \text{if} \quad \text{m} = 0 \ \wedge \ell \in \mathcal{L}_{\text{Beef, modified}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{TotTranMatC}_{mr\ell}^{AG}(y)$ is the total costs associated with land-use transitions from agricultural uses, as defined in Equation 216, and illustrated in Figure 461-Figure 469.
- $\mathcal{L}_{\text{Beef, modified}}$ is the set of land-use classes corresponding to beef-modified land under dryland management, as introduced in Figure 6
- The computed total transition cost matrix for conversion to Beef-Agroforestry, $\mathbf{TotTCM}_r^{Beef,AgFor}$ is shown in Figure 648.

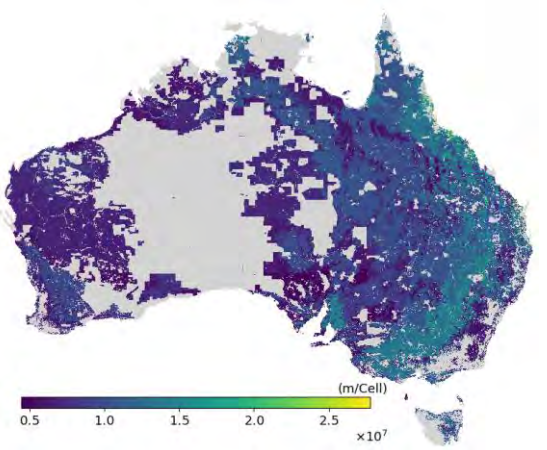


Figure 640 The total transition costs for transitioning from agricultural land to Agroforestry plantings (base)

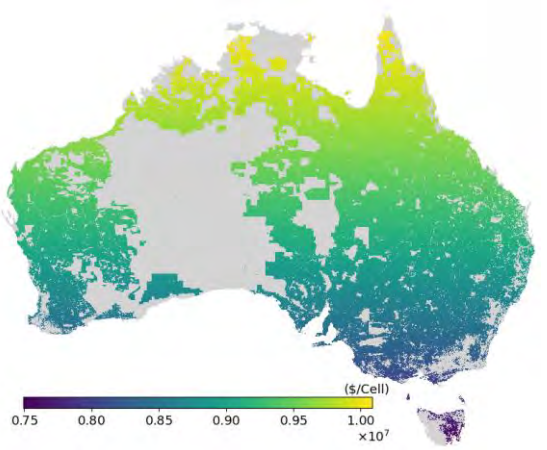
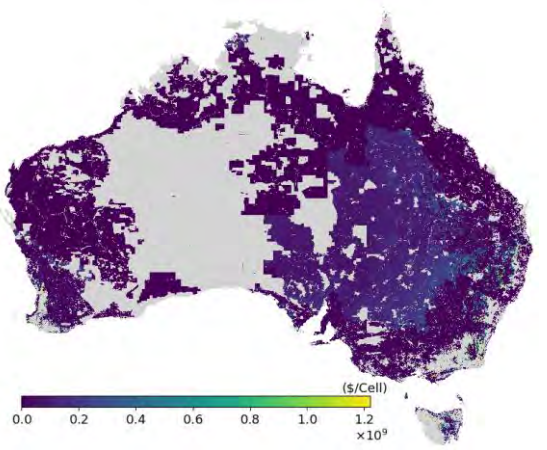


Figure 641 The fencing cost per cell from agricultural land uses to agroforestry for each cell



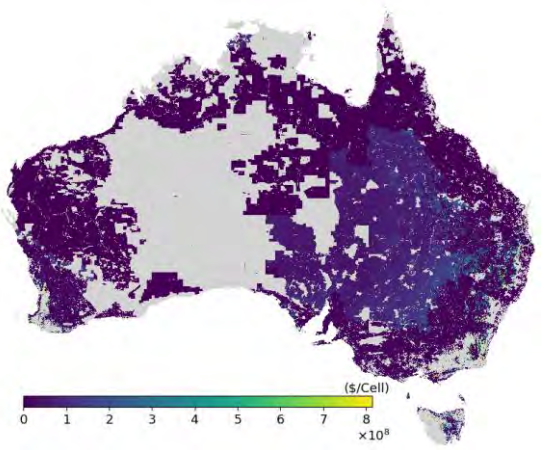


Figure 642 The non-irrigation-related raw transition costs for cells converted from land use in 2050 (Figure 393) to sheep - modified land under dryland management (AUD per ha)	Figure 643 The sheep contributions in the transition costs for cells converted from land use in 2050 (Figure 393) to Sheep-Agroforestry under dryland management (AUD per ha)

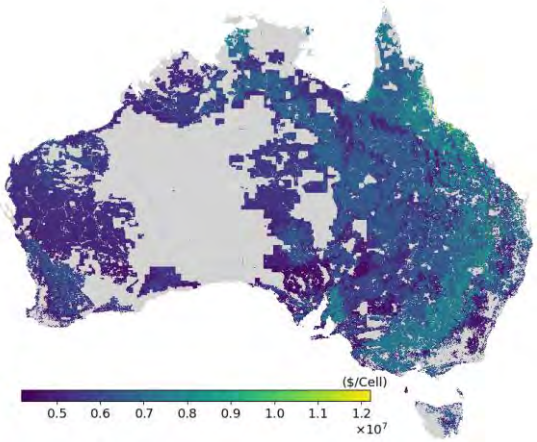
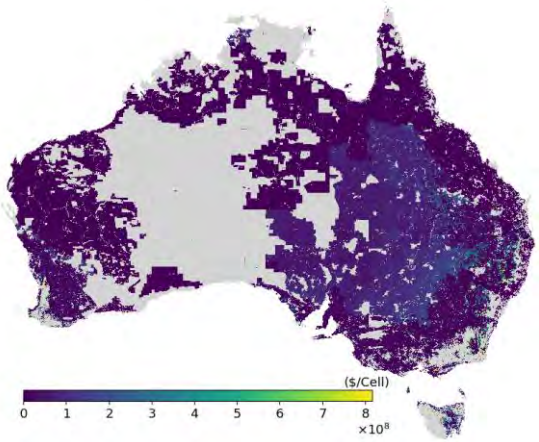

	

Figure 644 The Agroforestry plantings contribution in the transition costs for cells converted from land use in 2050 (Figure 393) to Sheep-Agroforestry under dryland management (AUD per ha)	Figure 645 The total transition costs for transitioning from agricultural land to Sheep-Agroforestry plantings (AUD per ha)

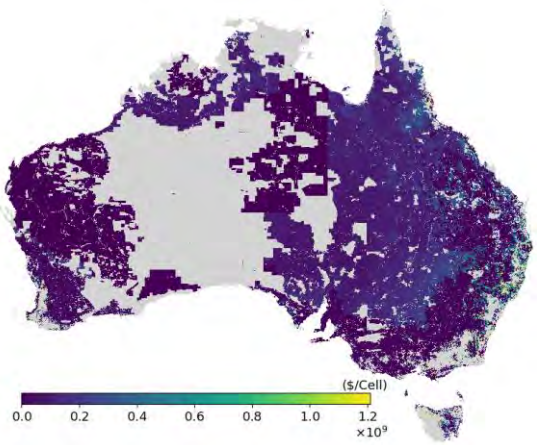
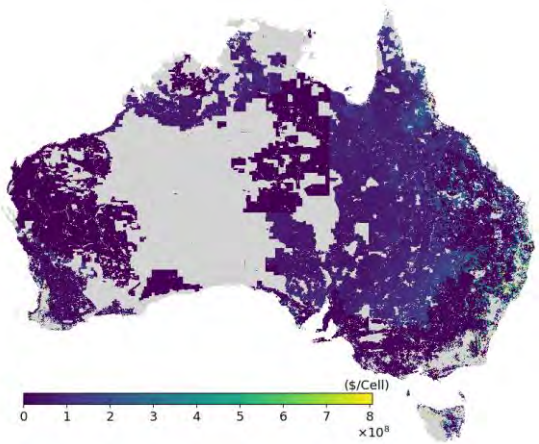

	

Figure 646 The non-irrigation-related raw transition costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under dryland management (AUD per ha)	Figure 647 The beef contributions in the transition costs for cells converted from land use in 2050 (Figure 393) to Sheep-Agroforestry under dryland management (AUD per ha)

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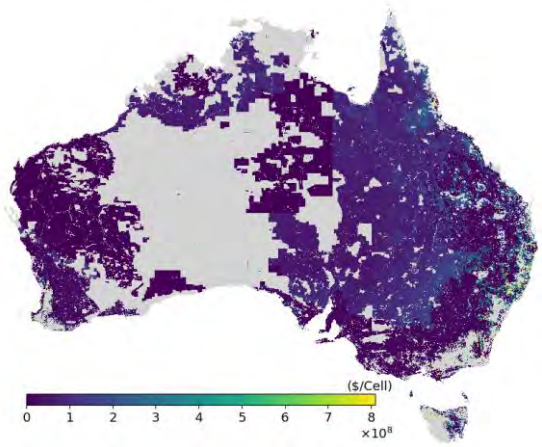	
Figure 648 The total transition costs for transitioning from agricultural land to Beef-Agroforestry plantings (AUD per ha)	

21.6. Transition Costs from Agricultural Land to Carbon Planting (Block)

21.6.1. Base Transition Cost from Agricultural Land to Carbon Planting (Block)

Let $\mathbf{RTCM}^{\text{AgToCPBlock}}$ be the raw transition cost matrix that represent the base cost of transition ($\$/\text{ha}$) from agricultural land uses to Carbon Planting (Block). It is defined as a matrix of size 1×28, where each element $\mathbf{RTCM}^{\text{AgToCPBlock}}_{\ell_i,\ell_j}$ denotes the cost of transition ($\$/\text{ha}$) from land-use class ℓ_i into ℓ_j. Here, $\ell_j = \text{CPBlock}$ and $\ell_i \in \mathcal{L}$, $\mathcal{L}$ is the set of all available land uses presented in Equation 1.

As per LUTO 2.0, $\mathbf{RTCM}^{\text{AgToCPBlock}}_{\ell_i,\ell_j} = \mathbf{RTCM}^{\text{AgToEP}}$; hence the values are equivalent to those shown in Figure 626.

Let $\mathbf{BTCM}^{\text{AgToCPBlock}}_{mr\ell}$ be the base transition cost matrix ($\$/\text{ha}$) from agriculture to Carbon Planting (Block) for each cell r, management practice $m \in \{0,1\}$ and land use $\ell \in \mathcal{L}$. Initially, the matrix $\mathbf{BTCM}^{\text{AgToCPBlock}}_{mr\ell}$ is initialized as zero:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell\ , \ell \in \mathcal{L}$	Equation 419
$\mathbf{BTCM}^{\text{AgToCPBlock}}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of land-use map cells in $\mathbf{LUM}^{\text{BYear}}$.
- N_k is the number of land management regimes $m \in \mathcal{M}$; hence $N_k = 2$ (see Equation 21).
- N_{lu} is the number of agricultural land-use classes; hence, $N_{lu} = 28$.

This tensor is updated using the values in $\mathbf{RTCM}^{\text{AgToCPBlock}}$ (Figure 649 and Figure 650), as follows:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 420
$\mathbf{BTCM}_{mr\ell}^{\text{AgToCPBlock}} = \begin{cases} \mathbf{RTCM}_{\ell}^{\text{AgToCPBlock}} & \text{if} \quad \ell \in \mathcal{L} \\ \mathbf{0} & \text{otherwise} \end{cases}$	

21.6.2. Amortized Base Cost of Transition from Agriculture to Carbon Planting (Block)

The computed base transition cost matrix $\mathbf{BTCM}_{mr\ell}^{\text{AgToCPBlock}}$ (from Equation 420) must be amortized using the general amortise formula (Equation 249), as follows:

$\mathbf{ABTCM}_{mr\ell}^{\text{AgToCPBlock}} = \dfrac{\mathbf{BTCM}_{mr\ell}^{\text{AgToCPBlock}} \times \text{DR} \times (1 + \text{DR})^{\text{NP}}}{(1 + \text{DR})^{\text{NP}} - 1}$	Equation 421

Where:

- $\mathbf{ABTCM}_{mr\ell}^{\text{AgToCPBlock}}$: Amortized base transition cost $\mathbf{BTCM}_{mr\ell}^{\text{AgToCPBlock}}$
- $\mathbf{BTCM}_{mr\ell}^{\text{AgToCPBlock}}$: Base Transition Cost from agricultural land to Carbon Planting (Block) (Equation 420)
- DR: Discount rate per period (LUTO 2.0 uses 7% or 0.07)
- NP: Number of periods (LUTO 2.0 assumes 30 years)

The amortized costs $\mathbf{ABTCM}_{mr\ell}^{\text{AgToCPBlock}}$ selected land-use classes are shown in Figure 651 and Figure 652.

21.6.3. Adjustment for Beginning-of-Period Payments

In LUTO 2.0, payments are assumed to be made at the beginning of each period. Therefore, the amortization must be adjusted accordingly:

$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToCPBlock}} = \mathbf{ABTCM}_{mr\ell}^{\text{AgToCPBlock}} \times \dfrac{1}{1 + DR}$	Equation 422

Substituting the general amortization formula (Equation 421):

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 423
$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToCPBlock}} = \dfrac{\mathbf{BTCM}_{mr\ell}^{\text{AgToCPBlock}} \times DR \times (1 + DR)^{NP}}{(1 + DR)^{NP} - 1} \times \dfrac{1}{1 + DR}$	

For a given year y, this simplifies to:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 424

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$$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToCPBlock}} = \frac{\mathbf{BTCM}_{mr\ell}^{\text{AgToCPBlock}} \times DR \times (1+DR)^{NP-1}}{(1+DR)^{NP}-1}$$	

For example, in the LUTO 2.0 model, with $DR = 0.07$ and $NP = 30$:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 425
$$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToEP}} = \frac{\mathbf{BTCM}_{mr\ell}^{\text{AgToEP}} \times 0.07 \times (1+0.07)^{30-1}}{(1+0.07)^{30}-1}$$	

Which can be simplified as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 426
$$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,AgToCPBlock}} = \frac{\mathbf{BTCM}_{mr\ell}^{\text{AgToCPBlock}} \times 0.07 \times (1+0.07)^{29}}{(1+0.07)^{30}-1}$$	

This formula yields the equivalent annual payment (EAP) over 30 years at a 7% discount rate, assuming upfront payments at the beginning of each year.

21.6.4. Total Transition Cost

To account for all relevant expenses, the total transition cost matrix for converting agricultural land to Carbon Planting (Block) includes both the amortized base transition cost and any pre-amortized costs related to water licensing and irrigation infrastructure:

$$\mathbf{TCM}_{mr\ell}^{\text{AgToCPBlock}}(y) = \mathbf{ABTCM}_{mr\ell}^{\text{AgToCPBlock}} + \mathbf{WLC}_{mr\ell}(y)$$	Equation 427

where,

- $\mathbf{TCM}_{mr\ell}^{\text{AgToCPBlock}}$**:** Total transition cost matrix ($/ha) from agriculture to Carbon Planting (Block)
- $\mathbf{ABTCM}_{mr\ell}^{\text{AgToCPBlock}}$: Amortized base transition cost (Equation 421)
- $\mathbf{WLC}_{mr\ell}(y)$: Amortized cost of water licenses and irrigation infrastructure (Equation 274)

The results are illustrated in Figure 653.

21.6.5. Total transition cost for each cell

To ensure that transition costs from agricultural land to Carbon Planting (Block) are only applied where appropriate, the matrix $\mathbf{TCM}_{mr\ell}^{\text{AgToCPBlock}}$ (from Equation 427) is multiplied by the Boolean tensor $\mathbf{BLuLmM}_{mr\ell}$**.** This tensor has a value of 1 for agricultural cells and 0 for non-agricultural ones, effectively filtering the valid land-use transitions based on land-use type ℓ, management states m, and cell r.

$$\mathbf{TCM}_{r}^{\text{AgToCPBlock}}(y) = \sum_{m,\ell} \left(\mathbf{TCM}_{mr\ell}^{\text{AgToCPBlock}}(y) \times \mathbf{BLuLmM}_{mr\ell} \right)$$	Equation 428

where,

- $\mathbf{BLuLmM}_{mr\ell}$: Boolean tensor that identifies agricultural cells (Equation 234)

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- $\mathbf{TCM}_{mr\ell}^{\mathrm{AgToCPBlock}}$: Total transition cost matrix ($/ha) from agriculture to Carbon Planting (Block) (Equation 427, see Figure 653)

21.6.6. Establishment Cost for Carbon Planting (Block)

The amortized establishment cost per hectare for Carbon Planting (Block), denoted by $\mathbf{AEstCost}_r^{\mathrm{CPBlockEP}}(y)$, is computed using the standard amortization formula:

$$\mathbf{AEstCost}_r^{\mathrm{CPBlock}}(y) = \frac{\mathbf{IEstCost}_r^{\mathrm{CPBlock}}(y) \times \mathrm{DR} \times (1+\mathrm{DR})^{\mathrm{NP}}}{(1+\mathrm{DR})^{\mathrm{NP}} - 1}$$	Equation 429

Where:

- $\mathbf{AEstCost}_r^{\mathrm{CPBlock}}$: Amortized establishment cost per hectare ($/ha) (see Figure 655)
- $\mathbf{IEstCost}_r^{\mathrm{CPBlock}}$: Initial establishment cost per hectare ($/ha) (Equation 403 and see Figure 654)
- DR: Discount rate per period (LUTO 2.0 considered the value of 7% or 0.07)
- NP: Number of periods (LUTO 2.0 considered the value of 30 years)

The initial establishment cost is calculated as:

$$\mathbf{IEstCost}_r^{\mathrm{CPBlock}}(y) = \mathbf{EstCostD}_r^{\mathrm{CPBlock}} \times ECMD(y)$$	Equation 430

where,

- $\mathbf{EstCostD}_r^{\mathrm{CPBlock}}$: Establishment Cost data per hectare provided by LUTO 2 (Figure 654)
- $ECMD(y)$**:** Establishment cost multiplier for year y.

21.6.7. Final Total Cost including Establishment

The total transition cost from agricultural land to Carbon Planting (Block), including both the transition and establishment costs, is calculated as:

$$\mathbf{TotTCM}_r^{\mathrm{AgToCPBlock}}(y) = \left(\mathbf{TCM}_r^{\mathrm{AgToCPBlock}}(y) + \mathbf{AEstCost}_r^{\mathrm{CPBlock}}(y)\right) \times \mathbf{RA}_r$$	Equation 431

where,

- $\mathbf{TotTCM}_r^{\mathrm{AgToCPBlock}}$: Total cost of transitioning from agriculture to Carbon Planting (Block)
- $\mathbf{TCM}_r^{\mathrm{AgToCPBlock}}$: Transition cost per hectare (Equation 428)
- $\mathbf{AEstCost}_r^{\mathrm{CPBlock}}$: Amortized establishment cost per hectare (Equation 429, and see Figure 655)
- $\mathbf{RA}_r$: The real area (Figure 5)

The computed total cost $\mathbf{TotTCM}_r^{\mathrm{AgToCPBlock}}$ is illustrated in Figure 656.

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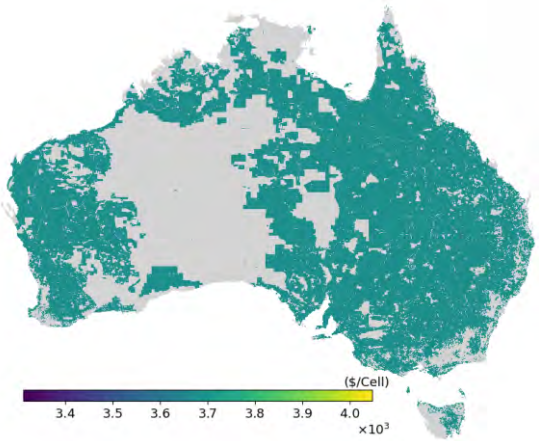

Figure 649 The transition costs for transitioning from Apple to Carbon Planting (Block), based on a sample $3680 transition cost

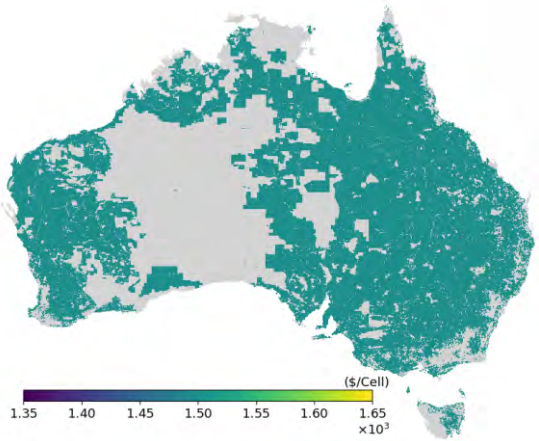

Figure 650 The transition costs for transitioning from Apple to Carbon Planting (Block), based on a sample $1500 transition cost

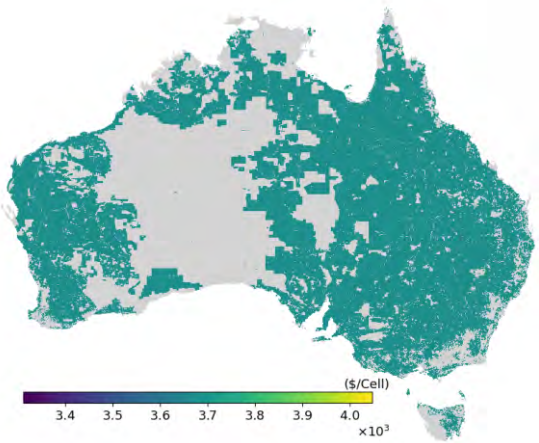

Figure 651 Amortised base transition costs for transitioning from Apple to Carbon Planting (Block), based on a $3680 transition cost

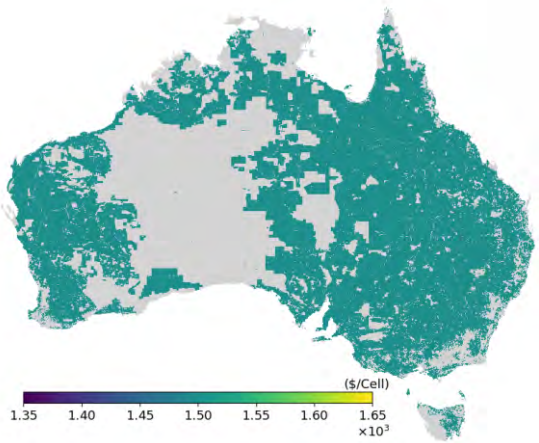

Figure 652 Amortised base transition costs for transitioning from Beef-Modified Land to Carbon Planting (Block)

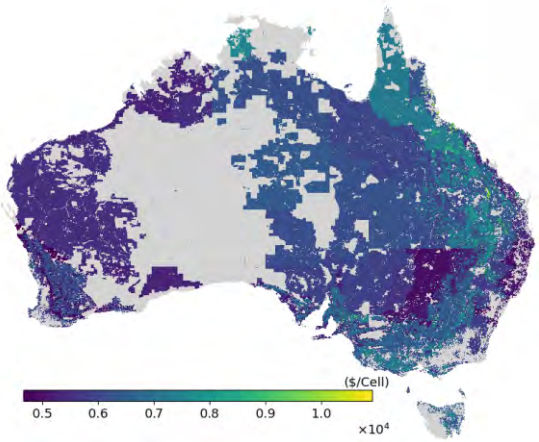

Figure 653 Total transition costs per cell for conversion to Carbon Planting (Block)

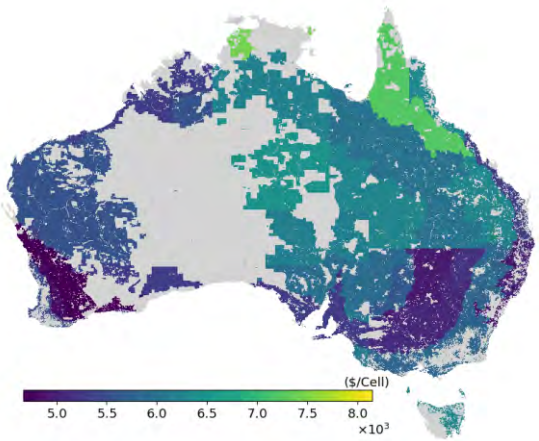

Figure 654 Establishment cost per hectare data for Carbon Planting (Block)

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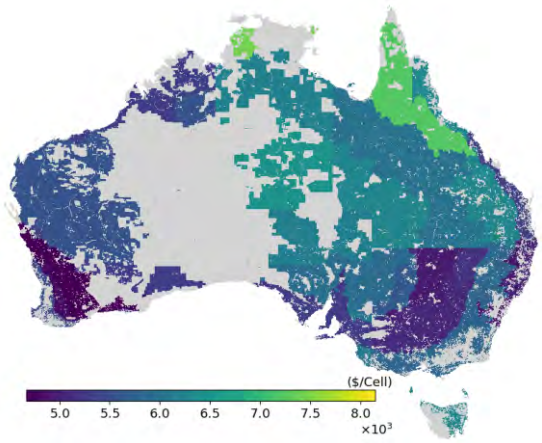	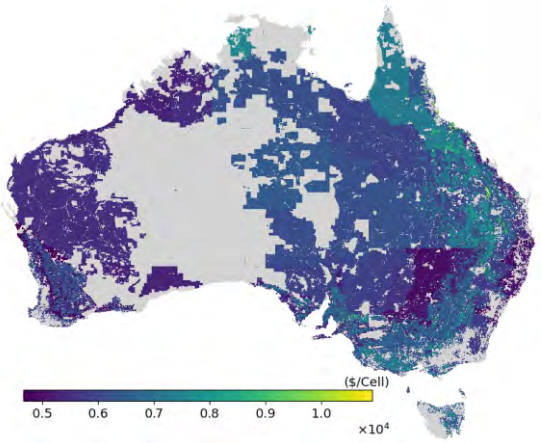
Figure 655 Amortised establishment cost per hectare for Carbon Planting (Block)	Figure 656 Total transition costs (including establishment) from agricultural land to Carbon Planting (Block)

21.7. Base Transition Costs from Agricultural Land to Carbon Plantings (Belt)

Let $\mathbf{TotTCM}_{mr\ell}^{\text{Base,AgToCPBelt}}(y)$ be the total transition cost matrix for converting agricultural land into carbon plantings (belt). It is calculated as:

$\mathbf{TotTCM}_{mr\ell}^{\text{Base,AgToCPBelt}}(y) = \mathbf{BTCM}_{r}^{\text{AgToCPBelt}} + \mathbf{FCM}_{r}^{\text{CPBelt}}$	Equation 432

where,

- $\mathbf{BTCM}_{r}^{\text{AgToCPBelt}}$ is the base cost for converting agricultural land into carbon plantings (belt)
- $\mathbf{FCM}_{r}^{\text{CPBelt}}$ is the fencing cost matrix for the transition

LUTO 2.0 assumes that the base transition cost for carbon planting (belt) $\mathbf{BTCM}_{r}^{\text{AgToCPBelt}}$ s the same as the cost for environmental plantings $\mathbf{TotTCM}_{r}^{\text{AgToEP}}$ (Equation 404):

$\mathbf{BTCM}_{r}^{\text{AgToCPBelt}} = \mathbf{TotTCM}_{r}^{\text{AgToEP}}$	Equation 433

The fencing cost $\mathbf{FCM}_{r}^{\text{CPBelt}}$ is calculated as:

$\mathbf{FCM}_{r}^{\text{CPBelt}} = \mathbf{FL}_{r}^{\text{CPBelt}} \times FCost \times FCMD(y) \times \mathbf{RA}_{r}$	Equation 434

where,

- $\mathbf{FL}_{r}^{\text{CPBelt}}$ is the fencing length (Equation 435, and Figure 657),
- $FCost = 5$ AUD per linear meter (assumed in LUTO 2.0),
- $FCMD(y)$ is the fencing cost multiplier for year y,
- $\mathbf{RA}_{r}$ is the real area (Figure 5).

The computed fencing cost $\mathbf{FCM}_{r}^{\text{CPBelt}}$ is illustrated in Figure 659.

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The fencing length $\mathbf{FL}_r^{\text{CPBelt}}$ is computed as:

$$\mathbf{FL}_r^{\text{CPBelt}} = \frac{20000}{\text{CPBelt}_{RW} + \text{CPBelt}_{RS}}$$	Equation 435
$$\mathbf{FL}_r^{\text{CPBelt}} = \frac{20000}{20 + 40} = 333.33$$	

where,

- $\text{CPBelt}_{RW} = 20m$ is the carbon plantings (belt) row width, a constant parameter in LUTO 2.0,
- $\text{CPBelt}_{RS} = 40m$ is the carbon plantings (belt) row spacing, a constant parameter in LUTO 2.0.

The total belt width is:

$$\text{CPBelt}_{Belt} = \text{CPBelt}_{RS} + \text{CPBelt}_{RW}$$	Equation 436
$$\text{CPBelt}_{Belt} = 20 + 40 = 60\ m$$	
$$NBH = \frac{100}{\text{CPBelt}_{Belt}} = \frac{100}{60} = 1.666$$	

where,

- NBH represents the number of belts per hectare

Therefore, from this, the number of belts per hectare is 1.666.

Using NBH, the fencing length can also be expressed as:

$$\mathbf{FL}_r^{\text{CPBelt}} = 100 \times NBH \times 2$$	Equation 437

Figure 657 illustrates the computation of $\mathbf{FL}_r^{\text{CPBelt}}$.

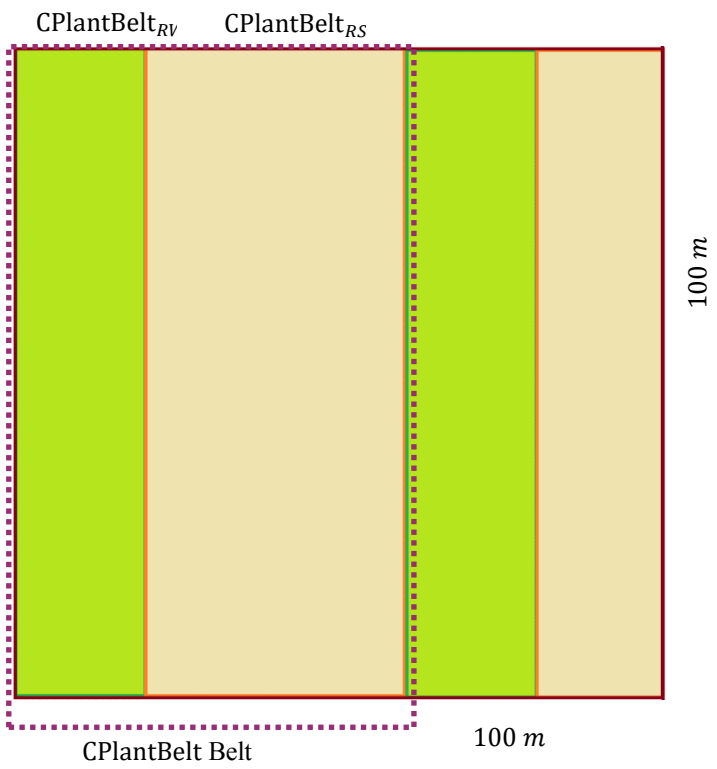

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Figure 657 The length of fence required for carbon plantings (belt), based on row width and spacing assumptions in LUTO 2.0.

21.8. Transition Costs from Agricultural Land to Sheep–Carbon Plantings (Belt)

The transition cost matrix for converting agricultural land into sheep-carbon plantings (belt) is calculated as:

$$\mathbf{TotTCM}_r^{Sheep,\text{CPBelt}}(y) = \left(\mathbf{TotTCM}_{mr\ell}^{\text{Base,AgToCPBelt}} \times \mathbf{XCM}_r^{CPBelt}\right) + \left[\mathbf{Cost}_r^{Sheep} \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$$	Equation 438

where,

- $\mathbf{TotTCM}_{mr\ell}^{\text{Base,AgToCPBelt}}$: Base transition cost matrix for converting agricultural land into carbon plantings (belt) (see Equation 432, and Figure 658)
- $\mathbf{Cost}_r^{Sheep}$: Non-irrigation-related raw transition costs for converting from land use in 2050 to sheep-modified land under dryland management (Equation 385 and Figure 642)
- $\mathbf{XCM}_r^{CPBelt}$: Exclusion matrix adjusted for the proportion of land allocated to carbon plantings (belt) (Equation 298)

In this equation,

- The first term, $\left(\mathbf{TotTCM}_{mr\ell}^{\text{Base,AgToCPBelt}} \times \mathbf{XCM}_r^{CPBelt}\right)$, represents the carbon plantings (belt) contribution (Figure 661).
- The second term $\mathbf{Cost}_r^{Sheep} \times (1 - \mathbf{XCM}_r^{CPBelt})$ reflects the **sheep grazing** contribution (Figure 643), with the complement of the exclusion matrix indicating the share of land not occupied by carbon plantings.

The raw transition costs for cells converted from land use in 2050 (see Figure 393) to sheep - modified land under dryland management, denoted as $\mathbf{Cost}_r^{Sheep}$, are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\text{BYear}}$	Equation 439
$\mathbf{Cost}_r^{Sheep} = \begin{cases} \mathbf{TotTranMatC}_{mr\ell}^{AG}(y) & \text{if} \quad \text{m} = 0 \ \wedge \ell \in \mathcal{L}_{\text{Sheep, modified}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{TotTranMatC}_{mr\ell}^{AG}(y)$ is the total costs associated with land-use transitions (as defined in Equation 216, and Figure 461-Figure 469)
- $\mathcal{L}_{\text{Sheep, modified}}$ is the set of sheep-modified land use classes introduced in Equation 5.

The computed $\mathbf{TotTCM}_r^{Sheep,CPBelt}$ is presented in Figure 645.

21.9. Transition Costs from Agricultural Land to Beef–Carbon Plantings (Belt)

The transition cost matrix for converting agricultural land into beef- carbon plantings (belt) is calculated as:

$$\mathbf{TotTCM}_r^{Beef,CPBelt}(y) = \left(\mathbf{TotTCM}_{mr\ell}^{\text{Base,AgToCPBelt}} \times \mathbf{XCM}_r^{CPBelt}\right) + \left[\mathbf{Cost}_r^{\text{Beef}} \times (1 - \mathbf{XCM}_r^{CPBelt})\right]$$	Equation 440

where,

- $\mathbf{TotTCM}_{mr\ell}^{\text{Base,AgToCPBelt}}$ is the base transition cost matrix for converting agricultural land into carbon plantings (belt) (Equation 432, and Figure 658)
- $\mathbf{Cost}_r^{\text{Beef}}$ is the non-irrigation-related raw transition cost for cells converted from 2050 land use to beef-modified land under dryland management (AUD/ha) (Equation 385, and Figure 646) $\mathbf{XCM}_r^{CPBelt}$ is the updated exclusion matrix considering the proportion of carbon plantings (belt) (Equation 298)

In this equation,

- The first term, $\left(\mathbf{TotTCM}_r^{\text{Base,AgToCPBelt}} \times \mathbf{XCM}_r^{CPBelt}\right)$ represents the contribution of carbon plantings (belt) (Figure 660).
- The second term $\mathbf{Cost}_r^{\text{Beef}} \times (1 - \mathbf{XCM}_r^{CPBelt})$, represents the contribution from *Beef* (Figure 662).

Here, $\mathbf{Cost}_r^{\text{Beef}}$ represents the non-irrigation-related raw transition cost (AUD per hectare) for cells converted from land use in 2050 (as defined in Equation 385, and Figure 646) to beef-modified land under dryland management. The term $(1 - \mathbf{XCM}_r^{CPBelt})$ denotes the remaining proportion of cell r not covered by carbon plantings (belt), thereby indicating the available area for beef production. This second term, therefore, captures the beef-related contribution to the total transition cost matrix under the Beef–Carbon Plantings (Belt) arrangement.

The raw transition costs for cells converted from land use in 2050 (Figure 393) to beef - modified land under dryland management $\mathbf{Cost}_r^{\text{Beef}}$ is computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\, \ell, \ell = \mathbf{LUM}_{mr}^{\text{BYear}}$	Equation 441
$\mathbf{Cost}_r^{\text{Beef}} = \begin{cases} \mathbf{TotTranMatC}_{mr\ell}^{AG}(y) & \text{if} \quad \text{m} = 0 \ \wedge \ell \in \mathcal{L}_{\text{Beef, modified}} \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{TotTranMatC}_{mr\ell}^{AG}(y)$ is the total costs associated with land-use transitions (Equation 216, and Figure 461-Figure 469)
- $\mathcal{L}_{\text{Beef, modified}}$ is defined in Figure 6

The computed $\mathbf{TotTCM}_r^{Beef,CPBelt}$ is presented in Figure 663.

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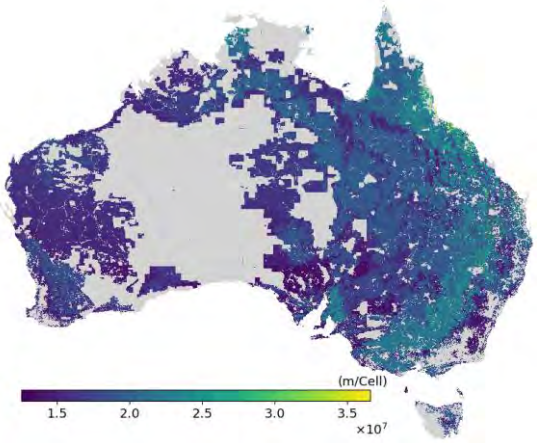


Figure 658 The total base transition costs for transitioning from agricultural land to carbon plantings (belt)

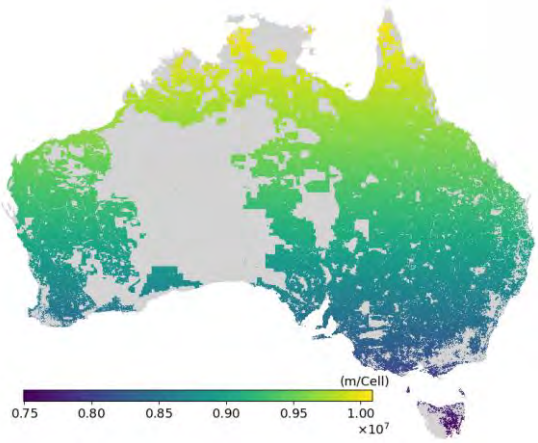


Figure 659 The fencing cost per cell for converting agricultural land to Carbon Plantings (Belt)

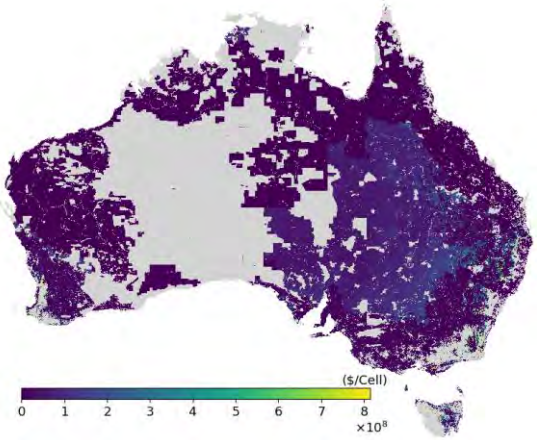


Figure 660 The sheep contribution in the transition costs for cells converted from 2050 land use (Figure 393) to Sheep–Carbon Plantings (Belt) under dryland management (AUD/ha)

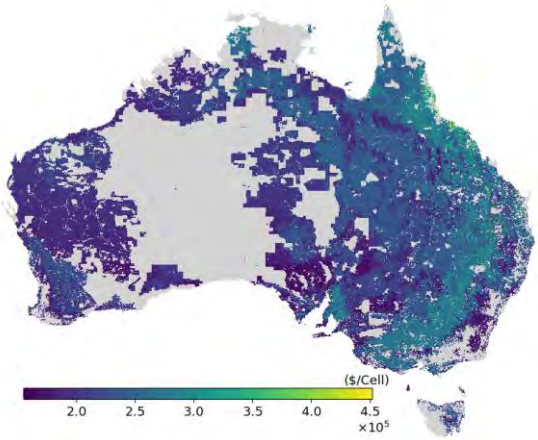
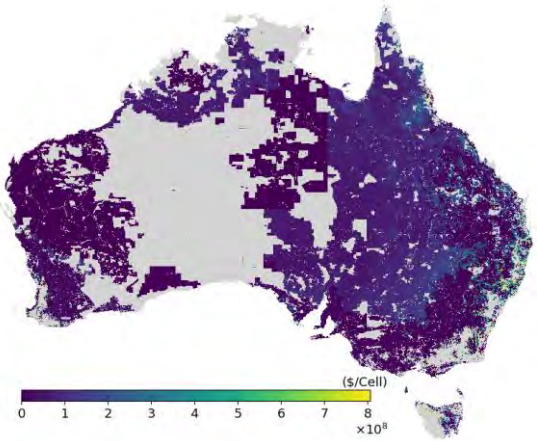


Figure 661 The Carbon Plantings (Belt) contribution in the transition costs for cells converted from 2050 land use (Figure 393) to Sheep–Carbon Plantings (Belt) under dryland management (AUD/ha)



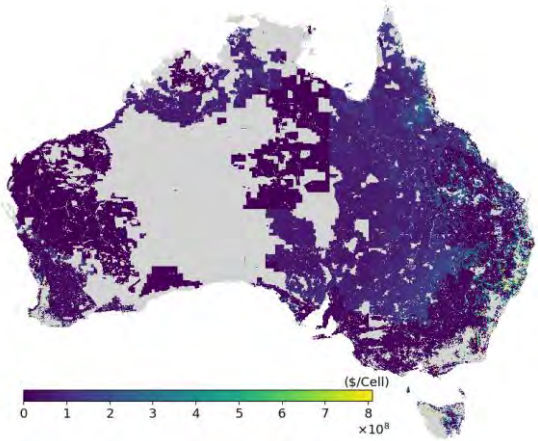


Figure 662 The beef contribution in the transition costs for cells converted from 2050 land use (Figure 393) to Beef–Carbon Plantings (Belt) under dryland management (AUD/ha)	Figure 663 The total transition costs for converting agricultural land to Beef–Carbon Plantings (Belt) (AUD/ha)

21.10. Transition Costs from Agricultural Land to Bioenergy with Carbon Capture and Storage (BECCS)

In LUTO 2.0, it is assumed that the total transition cost from agricultural land to BECCS $\mathbf{TotTCM}_r^{\text{AgToBECCS}}(y)$ is equal to the total transition cost to Environmental Plantings $\mathbf{TotTCM}_r^{\text{AgToEP}}(y)$, (Equation 404). Therefore:

$$\mathbf{TotTCM}_r^{\text{AgToBECCS}}(y) = \mathbf{TotTCM}_r^{\text{AgToEP}}(y)$$	Equation 442

where,

- $\mathbf{TotTCM}_{mr\ell}^{\text{AgToBECCS}}(y)$ is the total transition cost matrix for converting agricultural land to BECCS.
- $\mathbf{TotTCM}_r^{\text{AgToEP}}(y)$ is defined in Equation 404.

21.11. The Cost Matrix from Agricultural Land to All Non-Agricultural Land Uses

The general form of the transition cost matrix from agricultural land to all non-agricultural land uses, denoted as $\mathbf{TCM}_{r\ell}^{\text{AgToNonAg}}(y)$, where $\ell \in \mathcal{L}_{\text{NonAgrLand}}$ (as defined in Equation 13), is computed as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 443
$$\mathbf{TCM}_{r\ell}^{\text{AgToNonAg}}(y) = \text{concatenate}\begin{pmatrix} \mathbf{TotTCM}_{mr\ell}^{\text{AgToEP}}(y), \mathbf{TotTCM}_{mr\ell}^{\text{AgToRP}}(y), \mathbf{TotTCM}_r^{Sheep,AgFor}(y), \\ \mathbf{TotTCM}_r^{Beef,AgFor}(y), \mathbf{TotTCM}_r^{\text{AgToCPBlock}}(y), \mathbf{TotTCM}_r^{Sheep,\text{CPBelt}}(y), \\ \mathbf{TotTCM}_r^{Beef,CPBelt}(y), \mathbf{TotTCM}_r^{\text{AgToBECCS}}(y) \end{pmatrix}$$	

where,

- $\mathbf{TCM}_{r\ell}^{\text{AgToNonAg}}(y)$ is the aggregated transition cost matrix from agricultural land to each non-agricultural land use in cell r for year y.
- Concatenation refers to the process of assembling the individual land use transition cost vectors into one comprehensive matrix.

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22. The Transition Matrix from Non-Agricultural Land Uses to Agricultural Classes

22.1. Transition Cost from Environmental Planting to Agricultural Land

22.1.1. Base Transition Cost from environmental planting to agricultural land

Let $\mathbf{RTCM}^{\text{EPtoAG}}$ be the raw transition cost matrix representing the base cost of transitioning (\$/ha) from Environmental Planting (EP) to agricultural land uses. It is defined as a matrix of size 1×28, where each element $\mathbf{RTCM}^{\text{EPtoAG}}_{\ell_i,\ell_j}$ indicates the cost (\$/ha) of converting from class $\ell_i = \text{EP}$ to $\ell_j \in \mathcal{L}$, where $\mathcal{L}$ is the set of agricultural land use types (as defined in Equation 1).

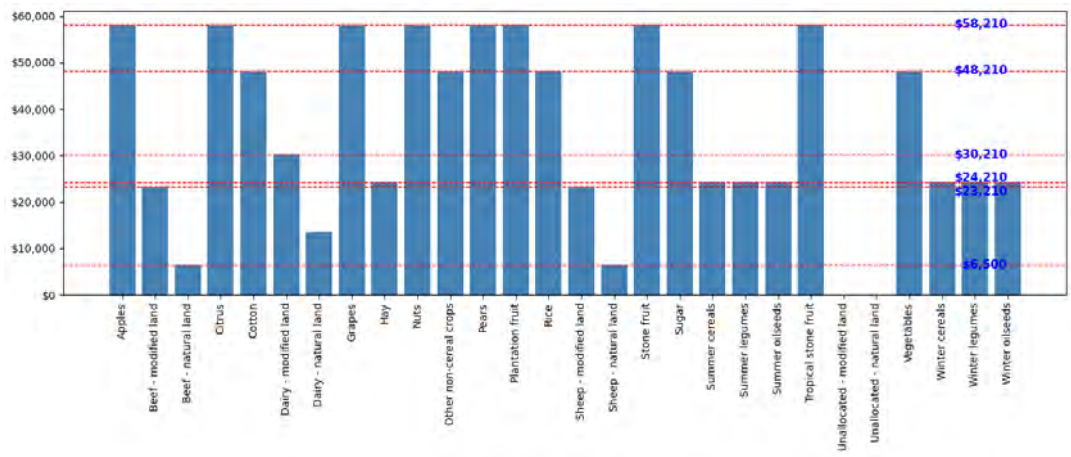

Figure 664 Associated Transition Cost from environmental planting to agricultural land

Let $\mathbf{BTCM}^{\text{EPtoAG}}_{mr\ell}$ be the base transition cost matrix that represent the cost of transition (\$/ha) from Environmental Planting (EP) to Agriculture land use for each cell r, under land management $m \in \{0,1\}$. Initially, $\mathbf{BTCM}^{\text{EPtoAG}}_{mr\ell}$ is defined as a zero matrix:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 444
$\mathbf{BTCM}^{\text{EPtoAG}}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$,
- $N_k = 2$ is the number of land management practices $m \in \mathcal{M}$ (Equation 21),
- $N_{lu} = 28$ is the number of agricultural land-use categories.

This matrix is then updated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 445
$\mathbf{BTCM}^{\text{EPtoAG}}_{mr\ell} = \begin{cases} \mathbf{RTCM}^{\text{EPtoAG}}_{\ell} \times TCMD(y) & \text{if} \quad \ell \in \mathcal{L} \\ \mathbf{0} & \text{otherwise} \end{cases}$	

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where,

- $\mathbf{RTCM}_{\ell}^{\mathrm{EPtoAG}}$ is the raw transition cost from the Environmental Planting (EP) to land use Agriculture
- $TCMD(y)$ is the transition cost multiplier for each year y, provided by LUTO 2.

Figure 665-Figure 668 illustrate examples of the computed $\mathbf{BTCM}_{mr\ell}^{\mathrm{EPtoAG}}$.

22.1.2. Amortized Transition Cost from environmental planting to agricultural land

The computed $\mathbf{BTCM}_{mr\ell}^{\mathrm{EPtoAG}}$, obtained using Equation 445 (as shown in Figure 665-Figure 668), must be amortized using the amortization formula provided in (Equation 249), as follows:

$$\mathbf{ABTCM}_{mr\ell}^{\mathrm{EPtoAG}} = \frac{\mathbf{BTCM}_{mr\ell}^{\mathrm{EPtoAG}} \times \mathrm{DR} \times (1+\mathrm{DR})^{\mathrm{NP}}}{(1+\mathrm{DR})^{\mathrm{NP}} - 1}$$	Equation 446

Where:

- $\mathbf{ABTCM}_{mr\ell}^{\mathrm{EPtoAG}}$ is amortized base transition cost of $\mathbf{BTCM}_{mr\ell}^{\mathrm{EPtoAG}}$
- $\mathbf{BTCM}_{mr\ell}^{\mathrm{EPtoAG}}$ is the Base Transition Cost from environmental plantings to agricultural land (Equation 445)
- DR is the discount rate per period (LUTO 2.0 considered the value of 7% or 0.07)
- NP is the number of periods (LUTO 2.0 considered the value of 30 years)

The computed $\mathbf{ABTCM}_{mr\ell}^{\mathrm{EPtoAG}}$ for selected land use classes is illustrated in Figure 669-Figure 672.

As outlined in Equation 251-Equation 255, and consistent with the LUTO 2.0 model assumption that payments are made at the beginning of each period, the amortized payment calculation is adjusted as follows:

$$\mathbf{ABTCM}_{mr\ell}^{\mathrm{Begin,EPtoAG}} = \mathbf{ABTCM}_{mr\ell}^{\mathrm{EPtoAG}} \times \frac{1}{1+DR}$$	Equation 447

Substituting the general amortization formula (Equation 394) into this adjustment yields:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 448
$$\mathbf{ABTCM}_{mr\ell}^{\mathrm{Begin,EPtoAG}} = \frac{\mathbf{BTCM}_{mr\ell}^{\mathrm{EPtoAG}} \times DR \times (1+DR)^{NP}}{(1+DR)^{NP} - 1} \times \frac{1}{1+DR}$$	

For a given year y, this simplifies to:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 449
$$\mathbf{ABTCM}_{mr\ell}^{\mathrm{Begin,EPtoAG}} = \frac{\mathbf{BTCM}_{mr\ell}^{\mathrm{EPtoAG}} \times DR \times (1+DR)^{NP-1}}{(1+DR)^{NP} - 1}$$	

This represents the amortized cost assuming payments occur at the start of each period, as per the LUTO 2.0 model. For example, in the LUTO 2.0 model, with $DR = 0.07$ and $NP = 30$:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 450

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$$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,EPtoAG}} = \frac{\mathbf{BTCM}_{mr\ell}^{\text{EPtoAG}} \times 0.07 \times (1+0.07)^{30-1}}{(1+0.07)^{30}-1}$$	

Which can be simplified as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	Equation 451
$$\mathbf{ABTCM}_{mr\ell}^{\text{Begin,EPtoAG}} = \frac{\mathbf{BTCM}_{mr\ell}^{\text{EPtoAG}} \times 0.07 \times (1+0.07)^{29}}{(1+0.07)^{30}-1}$$	

This equation represents a tensor of the equivalent annual payment (amortized value) of the computed $\mathbf{BTCM}_{mr\ell}^{\text{EPtoAG}}$, distributed over 30 years at a 7% discount rate, under the assumption that payments are made at the beginning of each period.

22.1.3. Total Transition Cost

Converting Environmental Planting to agricultural land requires accounting for the water license price and the costs associated with installing or removing irrigation, where applicable. These are captured in $\mathbf{WLC}_{mr\ell}(y)$, as defined in Equation 274. Therefore, the total transition cost is computed as:

$$\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAG}}(y) = \mathbf{ABTCM}_{mr\ell}^{\text{EPtoAG}} + \mathbf{WLC}_{mr\ell}(y)$$	Equation 452

where,

- $\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAG}}$ represents that total transition cost matrix ($/ha) to convert land use from Environmental Planting to Agriculture.
- $\mathbf{ABTCM}_{mr\ell}^{\text{EPtoAG}}$ is the amortized base transition cost (Equation 446).
- $\mathbf{WLC}_{mr\ell}(y)$ is the amortized cost of water license and irrigation setup/removal, where applicable (Equation 274)

22.1.4. Total transition cost for each cell

Since the transition from Environmental Planting to agriculture is only applicable for non-agricultural cells, the computed $\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAG}}$ (Equation 452) must be updated by multiplying it by $\mathbf{BLuLmM}_{mr\ell}^{NOT}$ (refer to Equation 236, and Figure 384-Figure 387). In this Boolean tensor ($\mathbf{BLuLmM}_{mr\ell}^{NOT}$), agricultural cells are assigned a value of 0, and non-agricultural cells are assigned 1, thus controlling where transitions are applicable.

The final total cost of transition from Environmental Planting to agricultural land is then calculated as:

$$\mathbf{TTotCM}_{mr\ell}^{\text{EPtoAG}}(y) = \left(\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAG}}(y) \times \mathbf{BLuLmM}_{mr\ell}^{NOT}\right) \times \mathbf{RA}_r$$	Equation 453

where,

- $\mathbf{BLuLmM}_{mr\ell}^{NOT}$ is the negated Boolean land-use and management matrix (Equation 236
- $\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAG}}$ is the total transition cost matrix from Environmental Planting to Agriculture (Equation 452)
- $\mathbf{RA}_r$ represents the real area (Figure 5)

The computed $\mathbf{TTotCM}_{mr\ell}^{\text{EPtoAG}}(y)$ value using Equation 453 are illustrated in Figure 673-Figure 676.

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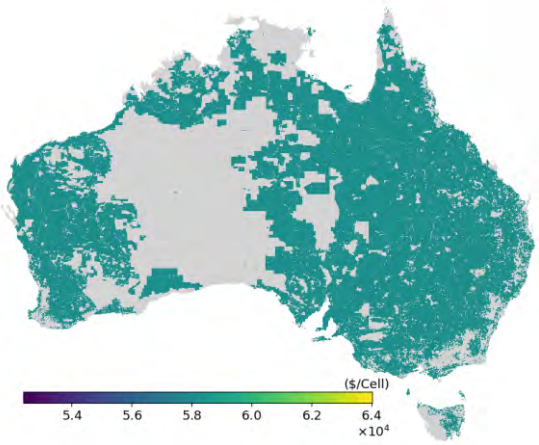

Figure 665 Transition costs for converting from Environmental Plantings to Apple – example with $58,200 transition cost

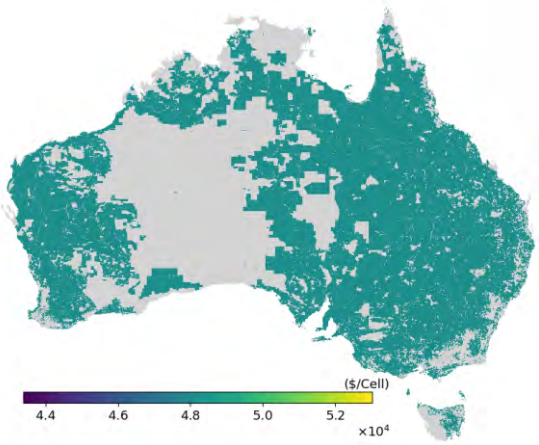

Figure 666 Transition costs for converting from Environmental Plantings to Other Non-Cereal Crops – example with $148,210 transition cost

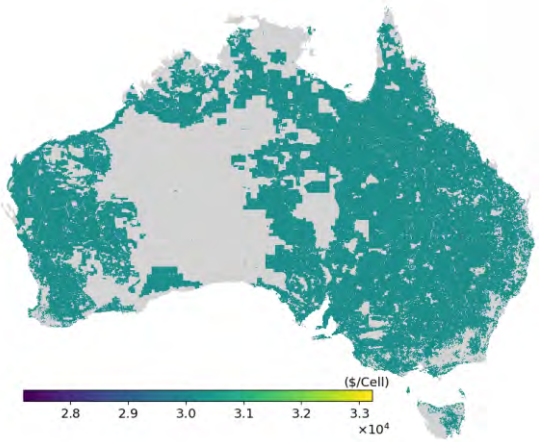

Figure 667 Transition costs for converting from Environmental Plantings to Dairy-Modified Land – example with $30,210 transition cost

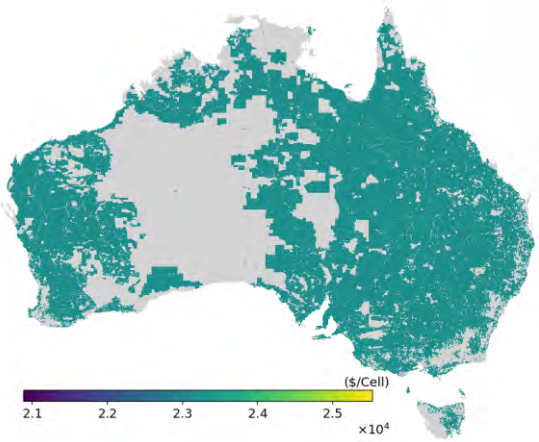

Figure 668 Transition costs for converting from Environmental Plantings to Beef-Modified Land – example with $23,210 transition cost

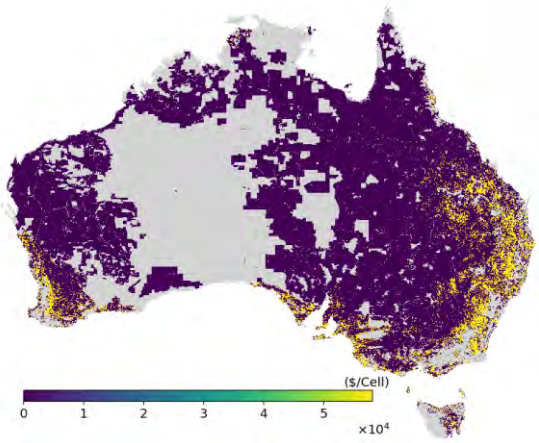

Figure 669 Amortized base transition costs for converting from Environmental Plantings to Apple – based on $58,200 transition cost

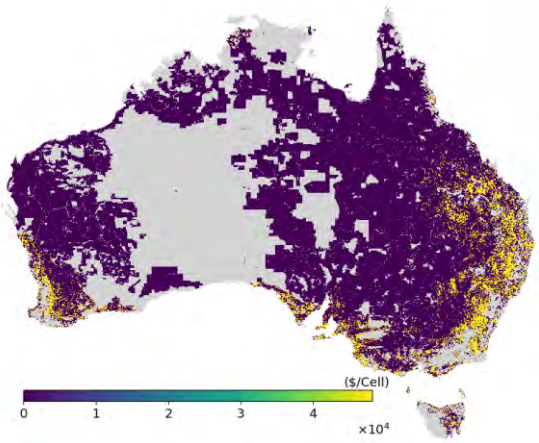

Figure 670 Amortized base transition costs for converting from Environmental Plantings to Other Non-Cereal Crops – based on $148,210 transition cost

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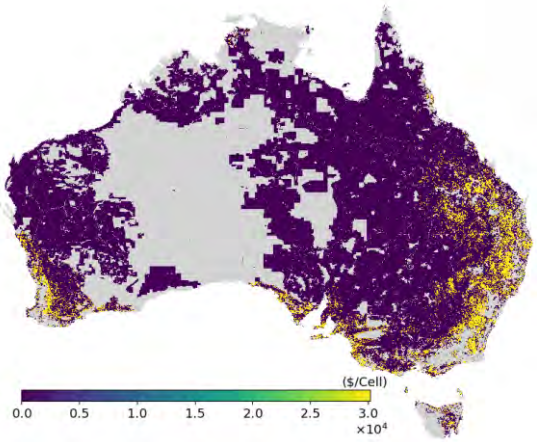

Figure 671 Amortized base transition costs for converting from Environmental Plantings to Dairy-Modified Land – based on $30,210 transition cost

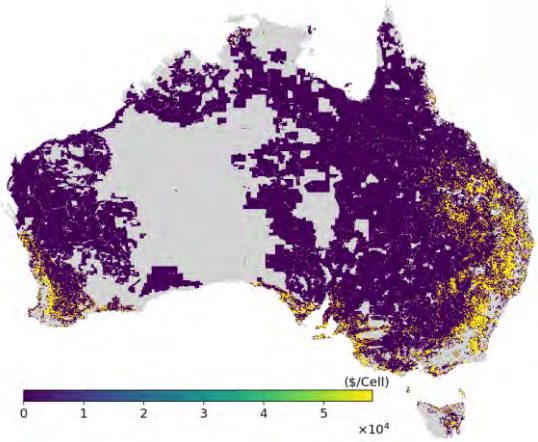

Figure 672 Amortized base transition costs for converting from Environmental Plantings to Beef-Modified Land – based on $23,210 transition cost

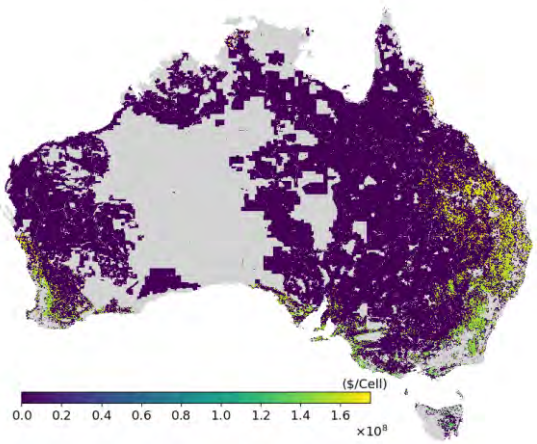

Figure 673 Total transition costs for converting from Environmental Plantings to Apple

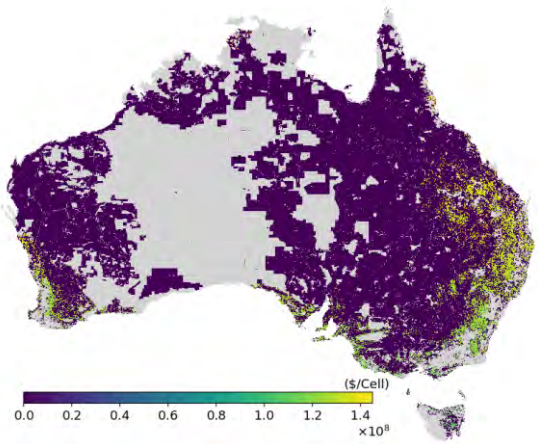

Figure 674 Total transition costs for converting from Environmental Plantings to Other Non-Cereal Crops

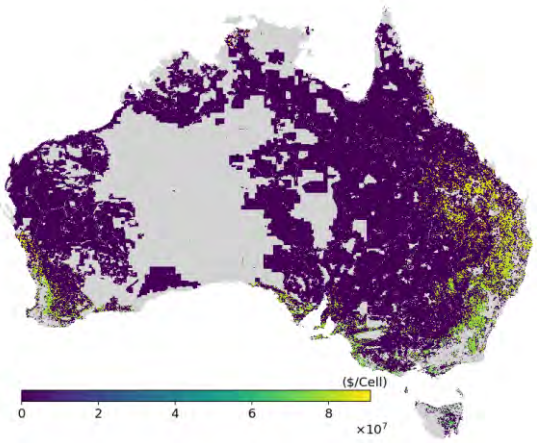

Figure 675 Total transition costs for converting from Environmental Plantings to Dairy-Modified Land

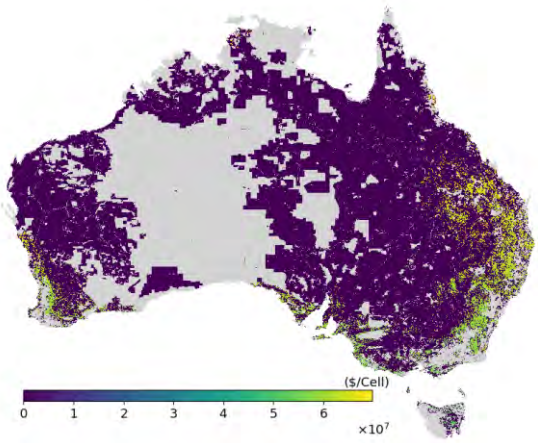

Figure 676 Total transition costs for converting from Environmental Plantings to Beef-Modified Land

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22.2. Transition Cost from Riparian Planting to Agricultural Land

The transition costs from riparian plantings to agricultural land use are assumed to be the same as those from environmental plantings to agricultural land. Therefore, the relationship is expressed as:

$\mathbf{TotTCM}_{mr\ell}^{\mathrm{RPtoAg}}(y) = \mathbf{TotTCM}_{mr\ell}^{\mathrm{EPtoAG}}(y)$	Equation 454

where,

- $\mathbf{TotTCM}_{mr\ell}^{\mathrm{RPtoAg}}(y)$ represents the final total Cost of transition from riparian planting to agricultural land
- $\mathbf{TotTCM}_{mr\ell}^{\mathrm{EPtoAg}}(y)$ represents the final total Cost of transition from environmental planting to agricultural land (Equation 453)

22.3. Transition Cost from Agroforestry Planting to Agricultural Land

Similarly, the transition costs from agroforestry planting to agricultural land use are assumed to be equivalent to those from environmental plantings. Thus, the cost is defined as:

$\mathbf{TotTCM}_{mr\ell}^{\mathrm{AFtoAg}}(y) = \mathbf{TotTCM}_{mr\ell}^{\mathrm{EPtoAg}}(y)$	Equation 455

where,

- $\mathbf{TotTCM}_{mr\ell}^{\mathrm{AFtoAg}}(y)$ represents the final total Cost of transition from agroforestry planting to agricultural land
- $\mathbf{TotTCM}_{mr\ell}^{\mathrm{EPtoAg}}(y)$ represents the final total cost of transition from environmental planting to agricultural land (Equation 453)

22.4. Sheep Contribution to Transition Costs to Agricultural Land Uses

22.4.1. Identifying Cells Under the Sheep-Modified Land Class

Let $\mathcal{L}_{\mathrm{Sheep,\ modified}}$ be the set of land-use classes defined in (Equation 6), and let $\mathbf{SheepLUM}_{mr\ell}$ be a 3D tensor representing the cells assigned to Sheep − modified land under both dryland and irrigated land management systems.

This tensor, ($\mathbf{SheepLUM}_{mr\ell}$), is initially populated with ones, and is mathematically expressed as:

$\forall\ r \in \{1, \dots, N_r\}$	Equation 456
$\mathbf{SheepLUM}_r = \mathrm{Ones}_{(1\times N_c)}$	

where,

- r is the index of a given cell,

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- N_c is the total number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.

The values of $\mathbf{SheepLUM}_r$ are updated based on the label value L_ℓ assigned to each land-use class ℓ. For all $\ell \in \mathcal{L}_{\text{Sheep, modified}}$, Luto 2 assigns a label value of 14 to represent the Sheep − modified land class. Therefore, we define: $L_{\text{Sheep-modified land}} = 14$.

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{Sheep, modified}}$	Equation 457
$\mathbf{SheepLUM}_r = \mathbf{SheepLUM}_r \times L_{\text{Sheep-modified land}}$	

By applying the updates from Equation 456 and Equation 457, the tensor $\mathbf{SheepLUM}_r$ is transformed to reflect the spatial allocation of cells designated as Sheep-modified land.

22.4.2. Boolean Land-Use and Land Management Matrix for Sheep

Define $\mathbf{BLuLmM}^{Sheep}_{mr\ell}$ as a 3D Boolean tensor that captures the presence of sheep-modified land across land uses and management systems:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 458
$\mathbf{BLuLmM}^{Sheep}_{mr\ell} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_k = 2$ is the number of agricultural management practices $m \in \mathcal{M}$ (dryland and irrigated, from Equation 21).
- $N_{lu} = 28$ is the number of agricultural land-use categories.

Update values in this matrix ($\mathbf{BLuLmM}^{Sheep}_{mr\ell}$) based on the presence of the Sheep-modified land class ($\mathbf{SheepLUM}_r$):

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \exists\, \ell, \ell \in \mathbf{LUM}^{\text{BYear}}$	Equation 459
$\mathbf{BLuLmM}^{Sheep}_{mr\ell} = \begin{cases} \text{True} & \text{If} \quad m = 0 \wedge \ell = L_{\text{Sheep-modified land}} \\ 0 & \text{otherwise} \end{cases}$	

To identify cells **not** assigned to Sheep − modified land ($\ell \notin \mathcal{L}_{\text{Sheep, modified}}$), compute the logical negation of the matrix:

$\mathbf{BLuLmM}^{NOT,Sheep}_{mr\ell} = \neg \mathbf{BLuLmM}^{Sheep}_{mr\ell}$	Equation 460

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where, the operation ¬ represents the logical NOT, which inverts each element in $\mathbf{BLuLmM}_{mr\ell}^{Sheep}$ — changing 'True' to 'False' and from 'False' to 'True'. Therefore, the negated Boolean matrix $\mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$ can be defined as:

$\mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep} = \begin{cases} \text{True} & \text{If } \mathbf{BLuLmM}_{mr\ell}^{Sheep} = \text{False} \\ \text{False} & \text{If } \mathbf{BLuLmM}_{mr\ell}^{Sheep} = \text{True} \end{cases}$	Equation 461

where, $\mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$ is the negation of the Boolean matrix $\mathbf{BLuLmM}_{mr\ell}^{Sheep}$. This means it identifies the cells not assigned to the Sheep-modified land class by inverting the True/False values of the original matrix.

22.4.3. Transition Cost Matrix

As mentioned in Section 13.5, let $\mathbf{RTCM}$ denote the raw transition cost matrix, defined as a square matrix of size $N_c \times N_c$, where each element $\mathbf{RTCM}_{\ell_i,\ell_j}$ represents the cost of transition ($/ha) from land use class ℓ_i to ℓ_j. Here, $\ell_i, \ell_j \in \mathcal{L}$, and $\mathcal{L}$ is the set of all land-use classes defined in Equation 1. The $\mathbf{RTCM}$ is scaled using an annual transition cost multiplier $TCM(y)$, specific to year y, as:

$\mathbf{RTCM}(y) = \mathbf{RTCM} \times TCM(y)$	Equation 462

22.4.4. Boolean Exclusion Matrix for Cells Assigned to Sheep-modified Land Class

Let $\mathbf{XCM}_{mr\ell}^{Sheep}$ denote the Boolean exclusion matrix for cells classified under land-use Sheep – modified land. Initially, it is assumed to be equal to the general exclusion matrix $\mathbf{XCM}_{mr\ell}$, as defined in Equation 244:

$\mathbf{XCM}_{mr\ell}^{Sheep} = \mathbf{XCM}_{mr\ell}$	Equation 463

To refine this matrix for Sheep-modified land, define a transition cost matrix $\mathbf{TCM}_{r\ell}^{Sheep}$ initialized as:

$\forall, r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	
$\mathbf{TCM}_{r\ell}^{Sheep} = \text{False}_{N_c \times N_{lu}}$	Equation 464

where,

- N_c is the number of spatial cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_{lu} = 28$ is the number of agricultural land-use classes.

Using the following variables:

- $\mathbf{SheepLUM}_r$ from Equation 457
- $\mathbf{AgCells}_r$ from Equation 238
- $\mathbf{NonAgCells}_r$ from Equation 239
- $\mathbf{LUM}_{mr}^{\text{BYear}}$

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- $\mathbf{RTCM}(y)$ from Equation 462

Update $\mathbf{TCM}_{r}^{Sheep}$ conditionally:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\} \; \exists \; \ell_r^{Sheep}, \ell_r \mid \ell_r = \mathbf{LUM}_{mr}^{\mathrm{BYear}}, \ell_r^{Sheep} = \mathbf{BLuLmM}_{mr\ell}^{Sheep}$	Equation 465
$\mathbf{TCM}_{r\ell}^{Sheep} = \begin{cases} \mathbf{RTCM}_{\ell_r}(y) & \text{If} \quad \ell_r^{Sheep} = \text{True} \\ 0 & \text{Otherwise} \end{cases}$	
$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\} \; \exists \; \ell_r^{NonSheep}, \ell_r \mid \ell_r = \mathbf{LUM}_{mr}^{\mathrm{BYear}}, \ell_r^{NonSheep} = \mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$	
$\mathbf{TCM}_{r\ell}^{Sheep} = \begin{cases} \mathbf{RTCM}_{\ell_r}(y) & \text{If} \quad \ell_r^{NonSheep} = \text{True}, \mathbf{TCM}_{r}^{Sheep} = 0 \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{RTCM}(y)$ refers to the transition cost multiplier data , as defined in Equation 462 and illustrated in Figure 392.

To identify NaN values in $\mathbf{TCM}_{r\ell}^{Sheep}$, which may indicate disallowed transitions between land uses, we apply Equation 466.

$\forall r \in \{1, \dots, N_r\} \; \exists \; \ell_r, \ell_r = \mathbf{TCM}_{r}^{Sheep}$	Equation 466
$\mathbf{TCM}_{r}^{Sheep} = \begin{cases} \mathbf{0} & \text{If} \quad \ell_r = \text{NaN} \\ 1 & \text{Otherwise} \end{cases}$	

Then exclude disallowed transitions by applying the following filter to the exclusion matrix $\mathbf{XCM}_{mr\ell}^{Sheep}$:

$\mathbf{XCM}_{mr\ell}^{Sheep} = \mathbf{XCM}_{mr\ell}^{Sheep} \times \mathbf{TCM}_{r}^{Sheep}$	Equation 467

22.4.5. Establishment Costs for All Agricultural Land Use and Land Management Systems, Including Amortized Upfront Costs

The initial establishment cost for agricultural lands, denoted as $\mathbf{IEstCost}^{Sheep}(y)$, is defined as a tensor of dimensions $N_c \times N_{lu}$ filled with zeros:

$\mathbf{IEstCost}^{Sheep} = 0_{(N_c \times N_{lu})}$	Equation 468

where,

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- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$
- N_{lu}: Number of agricultural land-use categories (i.e., $N_{lu} = 28$)

This tensor, shaped as $\mathbf{IEstCost}_{r\ell}^{Sheep}$, represents the establishment cost for transitioning from the current land use ℓ_r (Sheep − modified land) to an agricultural land class ℓ_j.

To update the values of $\mathbf{IEstCost}_{r\ell}^{Sheep}$, the first step is to extract the land use class ℓ_r of cell r from $\mathbf{SheepLUM}_r$:

$\forall r \in \{1, \dots, N_r\}$	Equation 469
$\ell_r = \mathbf{SheepLUM}_r$	

To confirm that the cell r belongs to the Sheep − modified land class, the following conditions in Equation 470 must be satisfied:

$\ell_r \in \mathcal{L}_{\text{Sheep, modified}}$	Equation 470
$\ell_r \geq 0$	

Then, for each cell r, the related transition costs are taken from $\mathbf{RTCM}(y)$ (Equation 462) based on ℓ_{mr}, or set to zero otherwise.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \exists\, \ell_r = \mathbf{SheepLUM}_r \mid \ell_r \geq 0, \ell_r \in \mathcal{L}_{\text{Sheep, modified}}$	Equation 471
$\mathbf{IEstCost}_{r\ell}^{Sheep}(y) = \begin{cases} \mathbf{RTCM}_{\ell_r}(y) & \text{If} \quad (m = 0) \wedge (\ell_r \geq 0) \\ 0 & \text{Otherwise} \end{cases}$	

The amortization formula (Equation 249) is then applied to compute the periodic payment required to amortize the present value ($\mathbf{IEstCost}_{r\ell}^{Sheep}$) over the project period:

$\mathbf{PMT}_{begin}^{Sheep}(y) = \dfrac{\mathbf{IEstCost}^{Sheep}(y) \times \text{DR} \times (1 + \text{DR})^{\text{NP}}}{(1 + \text{DR})^{\text{NP}} - 1}$	Equation 472

Where:

- PMT: Annual payment
- $\mathbf{IEstCost}^{Sheep}$: Present value or initial transition cost
- DR: Discount rate per period (e.g., 0.07)
- NP: Number of periods (e.g., 30 years)

The amortized establishment cost is then updated according to the binary parameter $AmUpCost$, which determines whether costs are amortized:

$\mathbf{IEstCost}^{Sheep}(y) = \begin{cases} -1 \times \mathbf{PMT}_{begin}^{Sheep}(y) & \text{If } AmUpCost = \text{True} \\ \mathbf{PMT}_{begin}^{Sheep}(y) & \text{If } AmUpCost = \text{False} \end{cases}$	Equation 473

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Finally, the establishment cost is scaled from dollars per hectare to dollars per cell using the real area $\mathbf{RA}_r$:

$\mathbf{IEstCost}^{Sheep}(y) = \mathbf{IEstCost}^{Sheep}(y) \times \mathbf{RA}_r$	Equation 474

where,

- $\mathbf{RA}_r$ represents the real area (Figure 5)

To compute establishment costs under both dry and irrigated land management systems, we define the 3D tensor:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell, \ell \in \mathcal{L}$	Equation 475
$\mathbf{EstCost}^{Sheep}_{mr\ell} = \mathbf{0}_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_k = 2$ is the number of land management types (dryland and irrigation) $m \in \mathcal{M}$ (Equation 21).
- $N_{lu} = 28$ is the number of agricultural land-use categories.

Finally, the establishment cost tensor $\mathbf{EstCost}^{Sheep}_{mr\ell}$ is updated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 476
$\mathbf{EstCost}^{Sheep}_{mr\ell} = \begin{cases} \mathbf{IEstCost}^{Sheep}_{r\ell}(y) & \text{If} \quad m = 0 \\ \mathbf{IEstCost}^{Sheep}_{r\ell}(y) & \text{If} \quad m = 1 \end{cases}$	

22.4.6. Update Establishment Cost with Exclude Matrices

The establishment cost for a given cell r with land-use class ℓ_r that remains unchanged (i.e., transitions from ℓ_r to ℓ_r) is considered zero. Therefore, the establishment cost tensor $\mathbf{EstCost}^{Sheep}_{mr\ell}(y)$, as defined in Equation 476, must be updated to reflect this rule using exclusion matrices.

Specifically:

- The Boolean exclusion matrix $\mathbf{XCM}^{Sheep}_{mr\ell}$ (defined in Equation 467) is used to exclude disallowed or invalid land-use transitions for Sheep-modified land.
- The Boolean mask $\mathbf{BLuLmM}^{NOT,Sheep}_{mr\ell}$ (defined in Equation 461) ensures that only the cells not assigned to the Sheep-modified land class (i.e., $\ell \notin \mathcal{L}_{\text{Sheep, modified}}$) are considered in the cost calculation.

Since all three tensors—$\mathbf{EstCost}^{Sheep}_{mr\ell}(y)$ (defined in Equation 476), $\mathbf{XCM}^{Sheep}_{mr\ell}$, and $\mathbf{BLuLmM}^{NOT,Sheep}_{mr\ell}$—share the same dimensions, they can be element-wise multiplied as follows:

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$\mathbf{EstCost}_{mr\ell}^{Sheep}(y) = \mathbf{EstCost}_{mr\ell}^{Sheep}(y) \times \mathbf{XCM}_{mr\ell}^{Sheep} \times \mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$	Equation 477

This operation ensures that the establishment costs:

- Are only assigned to valid transitions (as allowed by **XCM**),
- Do not apply to cells remaining under the same land use, and
- Exclude land uses already assigned to Sheep-modified land.

22.4.7. Update Water License Cost with Exclude Matrices

The water license cost for a given cell r with land-use class ℓ_r that remains unchanged (i.e., transitioning from ℓ_r to ℓ_r) is considered zero. Therefore, it is necessary to update the water license cost tensor $\mathbf{WLC}_{mr\ell}(y)$, as defined in Equation 275, by applying the exclusion matrix $\mathbf{XCM}_{mr\ell}^{Sheep}$ (Equation 467).

Additionally, the water license cost for cells **not assigned** to the Sheep − modified land class ($\ell \notin \mathcal{L}_{\text{Sheep, modified}}$) is maintained using the Boolean exclusion tensor $\mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$, computed in Equation 461.

Thus, the updated water license cost is computed as:

$\mathbf{WLC}_{mr\ell}^{Sheep}(y) = \mathbf{WLC}_{mr\ell}(y) \times \mathbf{XCM}_{mr\ell}^{Sheep} \times \mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$	Equation 478

22.4.8. Update Carbon Cost with Exclude Matrices

The updated carbon emission cost for the transition from natural land to modified land is calculated as:

$\mathbf{UCEP}_{mr\ell}^{\text{NLtoML}}(y) = \mathbf{CEP}_{mr\ell}^{\text{NLtoML}} \times CO2Price(y)$	Equation 479

where,

- $\mathbf{CEP}_{mr\ell}^{\text{NLtoML}}$ is the greenhouse gas emission associated with the land-use transition from natural to modified land (Equation 93)
- $CO2Price(y)$ is the market price of CO_2 Price (AUD per Tonne of CO_2) (Figure 349)

To compute the amortized cost over the planning horizon, the following payment function is applied:

$\mathbf{UCEP}_{begin}^{Sheep}(y) = \dfrac{\mathbf{UCEP}_{mr\ell}^{\text{NLtoML}}(y) \times \text{DR} \times (1+\text{DR})^{\text{NP}}}{(1+\text{DR})^{\text{NP}} - 1}$	Equation 480

Where:

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- PMT is the equivalent annual payment
- DR is the discount rate per period (0.07 in LUTO 2.0),
- NP is the number of periods (30 years).
- $\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}$ is the updated greenhouse gas emission associated with the transition of land-use (ℓ) cell r from natural land to modified (Equation 479)

To account for whether the carbon cost is treated as an amortized upfront payment ($AmUpCost$), we define:

$\mathbf{UCEP}^{Sheep}(y) = \begin{cases} -1 \times \mathbf{UCEP}_{begin}^{Sheep}(y) & \text{If } AmUpCost = \text{True} \\ \mathbf{UCEP}_{begin}^{Sheep}(y) & \text{If } AmUpCost = \text{False} \end{cases}$	Equation 481

Finally, the transition cost of a given cell r with land-use class ℓ_r that remains unchanged (i.e., a transition from ℓ_r to ℓ_r) is zero. Therefore, the updated greenhouse gas emission cost tensor $\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}(y)$ must be adjusted using the exclusion matrix $\mathbf{XCM}_{mr\ell}^{Sheep}$ (as defined in Equation 463).

In addition, for cells not assigned to the Sheep − modified land class ($\ell \notin \mathcal{L}_{\text{Sheep, modified}}$), the emissions cost must be filtered using the Boolean exclusion tensor $\mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$, as computed in Equation 460.

Since $\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}(y)$, $\mathbf{XCM}_{mr\ell}^{Sheep}$, and $\mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$ are tensors of the same dimensions, the filtered emission cost tensor can be computed element-wise as:

$\mathbf{CEP}_{mr\ell}^{Sheep}(y) = \mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}(y) \times \mathbf{XCM}_{mr\ell}^{Sheep} \times \mathbf{BLuLmM}_{mr\ell}^{NOT,Sheep}$	Equation 482

Note: As discussed in Section 3.4, the emission tensor $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$ is only defined for transitions originating from natural land uses. Consequently, for the Sheep − modified land ($\ell \in \mathcal{L}_{\text{Sheep, modified}}$), the values of $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$, $\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}$ and $\mathbf{CEP}_{mr\ell}^{Sheep}$ are all zero.

22.4.9. Ensure Transition Costs Are Zero for All Agricultural Cells

To ensure that the transition costs for agricultural cells $\mathbf{AgCells}_r$ (defined in Equation 238) transitioning either to the same or to other agricultural land-use classes are correctly set to zero, the following conditional logic must be applied to the establishment cost $\mathbf{EstCost}_{mr\ell}^{Sheep}$(defined in Equation 477), water license cost $\mathbf{WLC}_{mr\ell}^{Sheep}$ (defined in Equation 478), and carbon emission cost $\mathbf{CEP}_{mr\ell}^{Sheep}$ (defined in Equation 482) tensors:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \exists\, \ell, \ell = \mathbf{AgCells}_r$	
$\mathbf{EstCost}_{mr\ell}^{Sheep}(y) = \begin{cases} \mathbf{EstCost}_{mr\ell}^{Sheep}(y) & \text{if} \quad \ell = 0 \\ 0 & \text{otherwise} \end{cases}$	Equation 483
$\mathbf{WLC}_{mr\ell}^{Sheep}(y) = \begin{cases} \mathbf{WLC}_{mr\ell}^{Sheep}(y) & \text{if} \quad \ell = 0 \\ 0 & \text{otherwise} \end{cases}$	Equation 484

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$\mathbf{CEP}_{mr\ell}^{Sheep}(y) = \begin{cases} \mathbf{CEP}_{mr\ell}^{Sheep}(y) & \text{if} \quad \ell = 0 \\ 0 & \text{otherwise} \end{cases}$	Equation 485

22.4.10. Total transition costs

The total transition cost matrix $\mathbf{TotTCM}_{mr\ell}^{Sheep}(y)$ for sheep-modified land under both management regimes is then calculated as the sum of the updated tensors:

$\mathbf{TotTCM}_{mr\ell}^{Sheep}(y) = \mathbf{EstCost}_{mr\ell}^{Sheep}(y) + \mathbf{WLC}_{mr\ell}^{Sheep}(y) + \mathbf{CEP}_{mr\ell}^{Sheep}(y)$	Equation 486

Here, $\mathbf{EstCost}_{mr\ell}^{Sheep}$, $\mathbf{WLC}_{mr\ell}$, and $\mathbf{CEP}_{mr\ell}^{Sheep}$ are computed according to Equation 483-Equation 485, ensuring proper exclusion and zeroing for agricultural land cells.

22.5. Get beef contribution to transition costs to agricultural land uses

22.5.1. Identifying Cells Under the Beef-Modified Land Class

Let $\mathcal{L}_{\text{Beef, modified}}$ be the set of land-use classes defined in Equation 5, and $\mathbf{BeefLUM}_{mr\ell}$ be a 3D tensor that identifies cells managed under both dryland and irrigated systems and assigned to the Beef−modified land class. This tensor ($\mathbf{BeefLUM}_{mr\ell}$) is initially filled with ones and can be expressed as:

$\forall\ r \in \{1, \dots, N_r\}$	Equation 487
$\mathbf{BeefLUM}_r = \mathbf{Ones}_{(1 \times N_c)}$	

where,

- r is the index for cells.
- N_c is the number of cells in the base year land-use map $\mathbf{LUM}^{\text{BYear}}$.

The values of $\mathbf{BeefLUM}_r$ are then updated using the assigned land-use label L_ℓ for each class ℓ. In the LUTO 2.0 model, the label value for the Beef − modified land class is 1. Therefore, we define:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{Beef, modified}}$	Equation 488
$\mathbf{BeefLUM}_r = \mathbf{BeefLUM}_r \times L_{\text{Beef−modified land}}$	

By applying Equation 487 and Equation 488, we derive the updated values of the $\mathbf{BeefLUM}_r$ tensor, which identifies all cells currently allocated to Beef-modified land use.

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22.5.2. Boolean Land-Use and Land Management Matrix based on $\mathbf{BeefLUM}_r$

Let $\mathbf{BLuLmM}_{mr\ell}^{Beef}$ be a 3D Boolean tensor representing the land-use and land management matrix for cells under Beef-modified land use. It is initialized as a tensor filled with zeros:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 489
$\mathbf{BLuLmM}_{mr\ell}^{Beef} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the base land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_k = 2$ represents the two land management practices (dry and irrigated) $m \in \mathcal{M}$ (Equation 21).
- $N_{lu} = 28$ is the number of agricultural land-use categories.

The values in $\mathbf{BLuLmM}_{mr\ell}^{Beef}$ are updated based on the beef land-use $\mathbf{SheepLUM}_r$ assignment:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \exists\, \ell, \ell \in \mathbf{LUM}^{\mathrm{BYear}}$	Equation 490
$\mathbf{BLuLmM}_{mr\ell}^{Beef} = \begin{cases} \text{True} & \text{If} \quad m = 0 \wedge \ell = L_{\text{Beef-modified land}} \\ \mathbf{0} & \textbf{\textit{otherwise}} \end{cases}$	

To identify cells not assigned to Beef − modified land ($\ell \notin \mathcal{L}_{\text{Beef, modified}}$), compute the logical NOT of $\mathbf{BLuLmM}_{mr\ell}^{Beef}$:

$\mathbf{BLuLmM}_{mr\ell}^{NOT,Beef} = \neg \mathbf{BLuLmM}_{mr\ell}^{Beef}$	Equation 491

where,

The operation ¬ is the logical NOT, which flips each element in the Boolean matrix $\mathbf{BLuLmM}_{mr\ell}^{Beef}$:

- If an element is 'True', it becomes 'False'.
- If an element is 'False', it becomes 'True'.

Therefore, the negated matrix $\mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$ can be written element-wise as:

$\mathbf{BLuLmM}_{mr\ell}^{NOT,Beef} = \begin{cases} \text{True} & \text{If } \mathbf{BLuLmM}_{mr\ell}^{Beef} = \text{False} \\ \text{False} & \text{If } \mathbf{BLuLmM}_{mr\ell}^{Beef} = \text{True} \end{cases}$	Equation 492

where, $\mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$ is the negation of the Boolean matrix $\mathbf{BLuLmM}_{mr\ell}^{Beef}$.

This logical inversion is used to identify cells that are not currently assigned to the Beef-modified land class. It ensures that any subsequent calculations (e.g., for transition costs or carbon estimates) exclude these beef-assigned cells where necessary.

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22.5.3. Boolean Exclusion Matrix for Cells Assigned to Beef-Modified Land Class

Let $\mathbf{XCM}_{mr\ell}^{Beef}$ represent the Boolean exclusion matrix for cells that are assigned to the Beef − modified land use class. Initially, it is assumed that this matrix ($\mathbf{XCM}_{mr\ell}^{Beef}$) is identical to the general exclusion matrix $\mathbf{XCM}_{mr\ell}$ derived in Equation 244 , so we define:

$\mathbf{XCM}_{mr\ell}^{Beef} = \mathbf{XCM}_{mr\ell}$	Equation 493

Let $\mathbf{TCM}_{r\ell}^{Beef}$ be a matrix of size $N_c \times N_{lu}$ initialized with False, representing potential transitions for each cell r to any agricultural land-use class ℓ:

$\forall\, , r \in \{1, \dots, N_r\},\ \ell \in \mathcal{L}$	
$\mathbf{TCM}_{r\ell}^{Beef} = \text{False}_{N_c \times N_{lu}}$	Equation 494

where,

- N_c: Number of land-use cells in $\mathbf{LUM}^{\text{BYear}}$.
- $N_{lu} = 28$: Number of agricultural land-use categories (typically 28)

Using the land-use map $\mathbf{LUM}_{mr}^{\text{BYear}}$, and Boolean matrices $\mathbf{BLuLmM}_{mr\ell}^{Beef}$ and $\mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$, the transition cost matrix is updated with the raw transition cost matrix $\mathbf{RTCM}(y)$ as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists\ \ell_r^{Beef}, \ell_r \mid \ell_r = \mathbf{LUM}_{mr}^{\text{BYear}}, \ell_r^{Beef} = \mathbf{BLuLmM}_{mr\ell}^{Beef}$	Equation 495
$\mathbf{TCM}_{r\ell}^{Beef} = \begin{cases} \mathbf{RTCM}_{\ell_r}(y) & \text{If} \quad \ell_r^{Beef} = \text{True} \\ 0 & \text{Otherwise} \end{cases}$	
$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists\ \ell_r^{NonBeef}, \ell_r \mid \ell_r = \mathbf{LUM}_{mr}^{\text{BYear}}, \ell_r^{NonBeef} = \mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$	
$\mathbf{TCM}_{r\ell}^{Beef} = \begin{cases} \mathbf{RTCM}_{\ell_r}(y) & \text{If} \quad \ell_r^{NonBeef} = \text{True}, \mathbf{TCM}_r^{Beef} = 0 \\ 0 & \text{Otherwise} \end{cases}$	

where,

- $\mathbf{RTCM}(y)$: Yearly-adjusted raw transition cost matrix (Equation 462 and Figure 392)

If any value in $\mathbf{TCM}_{r\ell}^{Beef}$ is NaN, it is treated as a disallowed switch and set to 0 using:

$\forall r \in \{1, \dots, N_r\}\ \exists\ \ell_r, \ell_r = \mathbf{TCM}_r^{Beef}$	

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$\mathbf{TCM}_r^{Beef} = \begin{cases} \mathbf{0} & \text{If} \quad \ell_r = \text{NaN} \\ 1 & \text{Otherwise} \end{cases}$	Equation 496

Disallowed switches are excluded from the final Boolean exclusion matrix using element-wise multiplication:

$\mathbf{XCM}_{mr\ell}^{Beef} = \mathbf{XCM}_{mr\ell}^{Beef} \times \mathbf{TCM}_r^{Beef}$	Equation 497

Where:

- $\mathbf{XCM}_{mr\ell}^{Beef}$: Boolean exclusion matrix for Beef-modified land
- $\mathbf{TCM}_r^{Beef}$: Matrix indicating valid transition paths (0 for disallowed, 1 for allowed)

22.5.4. Establishment Costs for All Agricultural Land Use and Land Management Systems, Including Amortized Upfront Costs (Beef)

The initial establishment cost for agricultural lands, denoted as $\mathbf{IEstCost}^{Beef}(y)$ is defined as a tensor of dimensions $N_c \times N_{lu}$ filled with zeros:

$\mathbf{IEstCost}^{Beef} = 0_{(N_c \times N_{lu})}$	Equation 498

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_{lu} = 28$: is the number of agricultural land-use categories (28 categories in LUTO 2.0).

This tensor can be written as $\mathbf{IEstCost}_{r\ell}^{Beef}$ to represent the establishment cost for transitioning from current land use ℓ_r (Beef − modified land) to another agricultural class ℓ_j.

To update the values of $\mathbf{IEstCost}_{r\ell}^{Beef}$, the land use class of cell r is extracted from $\mathbf{BeefLUM}_r$:

$\forall r \in \{1, \dots, N_r\}$	Equation 499
$\ell_r = \mathbf{BeefLUM}_r$	

To confirm that cell r belongs to Beef − modified land, the value to $\mathbf{BLuLmM}_{mr\ell}^{Beef}$, the following condition must be satisfied (Equation 500):

$\ell_r \in \mathcal{L}_{\text{Beef, modified}}$	Equation 500
$\ell_r \geq 0$	

Then, the related establishment costs of cell r are extracted from $\mathbf{RTCM}(y)$ (Equation 462) based on ℓ_{mr}, or set to 0 otherwise.

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \exists\, \ell_r = \mathbf{BeefLUM}_r \mid \ell_r \geq 0, \ell_r \in \mathcal{L}_{\text{Beef, modified}}$	Equation 501
$\mathbf{IEstCost}_{r\ell}^{Beef}(y) = \begin{cases} \mathbf{RTCM}_{\ell_r}(y) & \text{If} \quad (m = 0) \wedge (\ell_r \geq 0) \\ 0 & \text{Otherwise} \end{cases}$	

Then, the amortization formula (Equation 249) is used to compute the periodic payment required to amortize the present value of the establishment cost, ($\mathbf{IEstCost}_{r\ell}^{Beef}$), over a given period is:

$\mathbf{PMT}_{begin}^{Beef}(y) = \dfrac{\mathbf{IEstCost}^{Beef}(y) \times \mathrm{DR} \times (1 + \mathrm{DR})^{\mathrm{NP}}}{(1 + \mathrm{DR})^{\mathrm{NP}} - 1}$	Equation 502

Where:

- PMT is the annual payment
- $\mathbf{IEstCost}^{Beef}$ is the present value or initial transition cost
- DR is the discount rate per period (0.07)
- NP is the number of periods (30 years)

To update the value of $\mathbf{IEstCost}^{Beef}$, the assigned binary flag $AmUpCost$ (which indicates whether upfront costs should be amortized) must be considered. Accordingly, the updated establishment cost is calculated as:

$\mathbf{IEstCost}^{Beef}(y) = \begin{cases} -1 \times \mathbf{PMT}_{begin}^{Beef}(y) & \text{If } AmUpCost = \text{True} \\ \mathbf{PMT}_{begin}^{Beef}(y) & \text{If } AmUpCost = \text{False} \end{cases}$	Equation 503

where:

- $\mathbf{PMT}_{begin}^{Beef}(y)$ is the annual amortized payment calculated in Equation 502
- $AmUpCost$ is a binary variable (True or False) provided by LUTO 2.0

Finally, the real area of each cell (denoted as $\mathbf{RA}_r$) is used to convert the establishment cost from a per-hectare basis to a per-cell basis. This is done by multiplying the cost by the real area:

$\mathbf{IEstCost}^{Beef}(y) = \mathbf{IEstCost}^{Beef}(y) \times \mathbf{RA}_r$	Equation 504

where,

- $\mathbf{RA}_r$ represents the real area (see Figure 5)

To compute the establishment cost across both dryland and irrigated management systems, we define a 3D tensor $\mathbf{EstCost}_{mr\ell}^{Beef}$:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}\ \exists \ell\ , \ell \in \mathcal{L}$	Equation 505
$\mathbf{EstCost}_{mr\ell}^{Beef} = 0_{(N_k \times N_c \times N_{lu})}$	

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where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_k = 2$ is the number of agricultural management types (dry and irrigated) $m \in \mathcal{M}$ (Equation 21).
- $N_{lu} = 28$ is the number of land-use categories.

Next, we update the tensor $\mathbf{EstCost}_{mr\ell}^{Beef}$ using the values from the amortized establishment cost:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 506
$\mathbf{EstCost}_{mr\ell}^{Beef} = \begin{cases} \mathbf{IEstCost}_{r\ell}^{Beef}(y) & \text{If} \quad m = 0 \\ \mathbf{IEstCost}_{r\ell}^{Beef}(y) & \text{If} \quad m = 1 \end{cases}$	

22.5.5. Update Establishment Cost with Exclusion Matrices

The transition cost of a given cell r with land-use class ℓ_r that remains the same (ℓ_r) must be set to 0. To achieve this, the establishment cost tensor $\mathbf{EstCost}_{mr\ell}^{Beef}(y)$ (Equation 506) is updated using the exclusion matrix $\mathbf{XCM}_{mr\ell}^{Beef}$ (Equation 497). Additionally, to ensure this applies only to cells not assigned to Beef – modified land ($\ell \in \mathcal{L}_{\text{Beef, modified}}$), the Boolean exclusion matrix $\mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$ (Equation 492) is incorporated. As all involved tensors have matching dimensions, the update is computed via element-wise multiplication:

$\mathbf{EstCost}_{mr\ell}^{Beef}(y) = \mathbf{EstCost}_{mr\ell}^{Beef}(y) \times \mathbf{XCM}_{mr\ell}^{Beef} \times \mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$	Equation 507

22.5.6. Update Water License Cost with Exclusion Matrices

The water license cost for a given cell r, where the land-use class ℓ_r does not change (i.e., $\ell_r \to \ell_r$), should be set to zero. To ensure this, the water license cost tensor $\mathbf{WLC}_{mr\ell}(y)$ (defined in Equation 275) must be filtered using two components:

- The Boolean exclusion matrix $\mathbf{XCM}_{mr\ell}^{Beef}$ (Equation 497), which restricts transitions to allowable land-use changes based on spatial exclusions and transition feasibility.
- The negation of the land-use and management matrix $\mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$ (Equation 492), which ensures that the calculation only applies to cells not assigned to Beef-modified land.

Given that these tensors share the same dimensions, the updated water license cost tensor is computed via element-wise multiplication:

$\mathbf{WLC}_{mr\ell}^{Beef}(y) = \mathbf{WLC}_{mr\ell}(y) \times \mathbf{XCM}_{mr\ell}^{Beef} \times \mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$	Equation 508

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22.5.7. Update Carbon Cost with Exclude Matrices

The updated carbon cost $\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}(y)$ for a land-use transition from natural land to modified land is computed by multiplying the base carbon emission cost with the CO_2 market price for a given year y:

$\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}(y) = \mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}} \times CO2Price(y)$	Equation 509

where,

- $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$ represents the greenhouse gas emissions (in tonnes of CO_2 per hectare) associated with transitioning a land-use class ℓ in cell r from natural land to modified land, as defined in Equation 93.
- $CO2Price(y)$ is the market price of carbon dioxide in AUD per tonne of CO_2 for the year y, provided in Figure 349.

To convert the $\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}$ into an equivalent annual payment, the amortization formula (Equation 249) is applied:

$\mathbf{UCEP}_{begin}^{Beef}(y) = \dfrac{\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}(y) \times \mathrm{DR} \times (1+\mathrm{DR})^{\mathrm{NP}}}{(1+\mathrm{DR})^{\mathrm{NP}} - 1}$	Equation 510

Where:

- DR: Discount rate per year (LUTO 2.0 assumes 7% or 0.07),
- NP: Number of periods (LUTO 2.0 assumes 30 years),
- $\mathbf{UCEP}_{begin}^{Beef}(y)$: Annualized carbon cost for the Beef-modified class in year y.

Depending on whether upfront costs are to be amortized, the carbon cost is adjusted as:

$\mathbf{UCEP}^{Beef}(y) = \begin{cases} -1 \times \mathbf{UCEP}_{begin}^{Beef}(y) & \text{If } AmUpCost = \text{True} \\ \mathbf{UCEP}_{begin}^{Beef}(y) & \text{If } AmUpCost = \text{False} \end{cases}$	Equation 511

To ensure that the carbon cost is correctly applied:

- Set the cost to zero for transitions where the land use does not change ($\ell_r = \ell_j$),
- Exclude transitions involving Beef-modified cells ($\ell \notin \mathcal{L}_{\text{Beef, modified}}$).

This is achieved by filtering using:

- The exclusion matrix $\mathbf{XCM}_{mr\ell}^{Beef}$ (Equation 497),
- The Boolean land-use mask for non-Beef cells $\mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$ (Equation 492).

Thus, the final carbon cost tensor becomes:

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$\mathbf{CEP}_{mr\ell}^{Beef}(y) = \mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}(y) \times \mathbf{XCM}_{mr\ell}^{Beef} \times \mathbf{BLuLmM}_{mr\ell}^{NOT,Beef}$	Equation 512

Note: As outlined in Section 3.4, $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$ is only computed for cells classified as natural land use. Since Beef − modified land does not fall under this category, its related emissions $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}$, and therefore $\mathbf{UCEP}_{mr\ell}^{\mathrm{NLtoML}}$ and $\mathbf{CEP}_{mr\ell}^{Beef}(y)$, will always be zero.

22.5.8. Ensure Transition Costs Are Zero for All Agricultural Cells

To ensure that the transition costs for agricultural cells $\mathbf{AgCells}_r$ (as defined in Equation 238) transitioning to the same or other agricultural land-use classes are zero, the following equations must be applied to the transition components:

This applies to:

- $\mathbf{EstCost}_{mr\ell}^{Beef}(y)$ from Equation 507
- $\mathbf{WLC}_{mr\ell}^{Beef}(y)$ from Equation 508
- $\mathbf{CEP}_{mr\ell}^{Beef}(y)$ from Equation 512

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \exists\, \ell, \ell = \mathbf{AgCells}_r$	
$\mathbf{EstCost}_{mr\ell}^{Beef}(y) = \begin{cases} \mathbf{EstCost}_{mr\ell}^{Beef}(y) & \text{if} \quad \ell = 0 \\ 0 & \text{otherwise} \end{cases}$	Equation 513
$\mathbf{WLC}_{mr\ell}^{Beef}(y) = \begin{cases} \mathbf{WLC}_{mr\ell}^{Beef}(y) & \text{if} \quad \ell = 0 \\ 0 & \text{otherwise} \end{cases}$	Equation 514
$\mathbf{CEP}_{mr\ell}^{Beef}(y) = \begin{cases} \mathbf{CEP}_{mr\ell}^{Beef}(y) & \text{if} \quad \ell = 0 \\ 0 & \text{otherwise} \end{cases}$	Equation 515

22.5.9. Total transition costs

The total transition cost matrix for converting Beef − modified land to agricultural classes is then computed as:

$\mathbf{TotTCM}_{mr\ell}^{Beef}(y) = \mathbf{EstCost}_{mr\ell}^{Beef}(y) + \mathbf{WLC}_{mr\ell}^{Beef}(y) + \mathbf{CEP}_{mr\ell}^{Beef}(y)$	Equation 516

where, $\mathbf{EstCost}_{mr\ell}^{Sheep}$, $\mathbf{WLC}_{mr\ell}^{Beef}$, and $\mathbf{CEP}_{mr\ell}^{Sheep}$ are computed in Equation 513-Equation 515.

22.6. Transition Costs from Sheep-Agroforestry to All Agricultural Land Uses

The total transition cost for converting land from Sheep-Agroforestry to all agricultural land-use classes is calculated as:

$\mathbf{TotTCM}_{mr\ell}^{Sheep,\mathrm{AFtoAg}}(y) = \left[\left(1 - \mathbf{XCM}_r^{AgFor}\right) \times \mathbf{TotTCM}_{mr\ell}^{Sheep}(y)\right] + \left(\mathbf{XCM}_r^{AgFor} \times \mathbf{TotTCM}_{mr\ell}^{\mathrm{AFtoAg}}(y)\right)$	Equation 517

where,

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- $\mathbf{TotTCM}_{mr\ell}^{Sheep,\mathrm{AFtoAg}}$: Total transition cost matrix for converting Sheep-Agroforestry to agricultural land uses.
- $\mathbf{XCM}_{r}^{AgFor}$: Exclusion matrix representing the proportion of land used for agroforestry (from Equation 298).
- $\mathbf{TotTCM}_{mr\ell}^{Sheep}(y)$: Transition cost contribution from the Sheep portion of the cell to other agricultural land uses (Equation 486).
- $\mathbf{TotTCM}_{mr\ell}^{\mathrm{AFtoAg}}(y)$: Transition cost from Agroforestry to other agricultural land uses (Equation 455).

This formulation ensures that the final transition cost accounts for both components of the Sheep-Agroforestry system, proportionally weighted by the exclusion matrix.

22.7. Transition Costs from Beef-Agroforestry to All Agricultural Land Uses

The total transition cost for converting land from Beef-Agroforestry to all agricultural land-use classes is calculated as:

$\mathbf{TotTCM}_{mr\ell}^{Beef,\mathrm{AFtoAg}}(y) = \left[\left(\mathbf{1} - \mathbf{XCM}_{r}^{AgFor}\right) \times \mathbf{TotTCM}_{mr\ell}^{Beef}(y)\right] + \left(\mathbf{XCM}_{r}^{AgFor} \times \mathbf{TotTCM}_{mr\ell}^{\mathrm{AFtoAg}}(y)\right)$	Equation 518

where,

- $\mathbf{TotTCM}_{mr\ell}^{Beef,\mathrm{AFtoAg}}$: Total transition cost matrix for converting Beef-Agroforestry to agricultural land uses.
- $\mathbf{XCM}_{r}^{AgFor}$: Exclusion matrix representing the proportion of land used for agroforestry (Equation 214)
- $\mathbf{TotTCM}_{mr\ell}^{Beef}(y)$: Transition cost contribution from the **Beef** portion of the cell to other agricultural land uses (Equation 516)
- $\mathbf{TotTCM}_{mr\ell}^{\mathrm{AFtoAg}}(y)$: Transition cost from Agroforestry to other agricultural land uses (Equation 455)

This equation ensures that the cost components from both Beef and Agroforestry sections of the mixed land use are appropriately weighted according to their respective proportions.

22.8. Transition Costs from Carbon Plantings (Block) to Agricultural Land

The transition cost from Carbon Plantings (Block) to agricultural land uses is assumed to be the same as the cost for converting Environmental Plantings to agricultural land. Therefore, it is expressed as:

$\mathbf{TotTCM}_{mr\ell}^{\mathrm{CPBlockToAg}}(y) = \mathbf{TotTCM}_{mr\ell}^{\mathrm{EPtoAg}}(y)$	Equation 519

where,

- $\mathbf{TotTCM}_{mr\ell}^{\mathrm{CPBlockToAg}}(y)$: Final total transition cost matrix ($/ha) for converting Carbon Plantings (Block) to agricultural land.
- $\mathbf{TotTCM}_{mr\ell}^{\mathrm{EPtoAg}}(y)$: Final total transition cost matrix ($/ha) for converting Environmental Plantings to agricultural land (Equation 453)

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This assumption ensures consistency in transition logic between similar vegetation-based land uses.

22.9. Transition costs from carbon plantings (Belt) to agricultural land

The transition cost from Carbon Plantings (Belt) to agricultural land uses is assumed to be the same as the cost for converting Environmental Plantings to agricultural land. Therefore, it is expressed as:

$\mathbf{TotTCM}_{mr\ell}^{\text{CPBeltToAg}}(y) = \mathbf{TotTCM}_{mr\ell}^{\text{EPtoAg}}(y)$	Equation 520

where,

- $\mathbf{TotTCM}_{mr\ell}^{\text{CPBeltToAg}}(y)$: Final total transition cost matrix ($/ha) for converting Carbon Plantings (Belt) to agricultural land.
- $\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAg}}(y)$: Final total transition cost matrix ($/ha) for converting Environmental Plantings to agricultural land (Equation 453).

22.10. Transition Costs of Sheep Carbon Plantings (Belt) to All Agricultural Land Uses

The total transition cost from Sheep Carbon Plantings (Belt) to all agricultural land uses is calculated as a weighted combination of the sheep and carbon planting components, based on the exclusion matrix that determines the proportion of land under carbon plantings (Belt):

$\mathbf{TotTCM}_{mr\ell}^{Sheep,\text{CPBeltToAg}}(y) = \left[(\mathbf{1} - \mathbf{XCM}_r^{CPBelt}) \times \mathbf{TotTCM}_{mr\ell}^{Sheep}(y)\right] + \left(\mathbf{XCM}_r^{CPBelt} \times \mathbf{TotTCM}_{mr\ell}^{\text{CPBeltToAg}}(y)\right)$	Equation 521

where,

- $\mathbf{TotTCM}_{mr\ell}^{Sheep,\text{CPBeltToAg}}$**:** Total transition cost ($/ha) for converting Sheep–Carbon Plantings (Belt) to agricultural land.
- $\mathbf{XCM}_r^{CPBelt}$**:** Exclusion matrix indicating the proportion of land in cell r used for Carbon Plantings (Belt) (see Equation 307).
- $\mathbf{TotTCM}_{mr\ell}^{Sheep}(y)$: Transition cost contribution from Sheep component to agricultural land (see Equation 486).
- $\mathbf{TotTCM}_{mr\ell}^{\text{CPBeltToAg}}(y)$: Transition cost for converting Carbon Plantings (Belt) to agricultural land (see Equation 520).

22.11. Transition Costs of Beef Carbon Plantings (Belt) to All Agricultural Land Uses

The total transition cost from Beef Carbon Plantings (Belt) to all agricultural land uses is calculated by combining the transition cost contributions of beef and carbon plantings (belt), weighted by the proportion of land allocated to each:

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$$\mathbf{TotTCM}_{mr\ell}^{Beef,\text{CPBeltToAg}}(y) = \left[(\mathbf{1} - \mathbf{XCM}_{r}^{CPBelt}) \times \mathbf{TotTCM}_{mr\ell}^{Beef}(y)\right] + \left(\mathbf{XCM}_{r}^{CPBelt} \times \mathbf{TotTCM}_{mr\ell}^{\text{CPBeltToAg}}(y)\right)$$	Equation 522

where,

- $\mathbf{TotTCM}_{mr\ell}^{Beef,\text{CPBeltToAg}}$: Total transition cost ($/ha) for converting Beef–Carbon Plantings (Belt) to agricultural land.
- $\mathbf{XCM}_{r}^{CPBelt}$: Exclusion matrix indicating the **proportion of land** in cell rrr used for **Carbon Plantings (Belt)** (see Equation 307)
- $\mathbf{TotTCM}_{mr\ell}^{Beef}(y)$: Transition cost contribution from **Beef** component to agricultural land (see Equation 516)
- $\mathbf{TotTCM}_{mr\ell}^{\text{CPBeltToAg}}(y)$: Transition cost for converting Carbon Plantings (Belt) to agricultural land (see Equation 520)

22.12. Transition Costs from BEEC to Agricultural Land Uses

The transition costs associated with converting land from Bioenergy with Enhanced Environmental Co-benefits (BEEC) to agricultural land uses are assumed to be the same as those for converting from Environmental Plantings (EP) to agricultural land. Therefore, it can be expressed as:

$$\mathbf{TotTCM}_{mr\ell}^{\text{BEECtoAg}}(y) = \mathbf{TotTCM}_{mr\ell}^{\text{EPtoAg}}(y)$$	Equation 523

where,

- $\mathbf{TotTCM}_{mr\ell}^{\text{BEECtoAg}}(y)$: Total transition cost matrix for converting BEEC land to agricultural land uses in cell r, management state mmm, and land use type ℓ for year y.
- $\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAg}}(y)$: Total transition cost matrix for converting Environmental Plantings to agricultural land (see Equation 453)

22.13. Total Transition Costs from Non-Agricultural to Agricultural Land Uses

This section describes the aggregation of transition costs from various non-agricultural land uses (e.g., Environmental Plantings, Riparian Plantings, Agroforestry, BECCS, etc.) into agricultural land uses.

The general form of the total transition cost matrix from non-agricultural land uses to agricultural land uses for each cell r, land management type m, and land use class $\ell \in \mathcal{L}_{\text{NonAgrLand}}$, is defined as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 524
$\mathbf{TCM}_{mr\ell}^{\text{NonAgToAg}}(y) = \text{concatenate}\left(\begin{array}{c}\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAg}}(y), \mathbf{TotTCM}_{mr\ell}^{\text{RPtoAg}}(y), \mathbf{TotTCM}_{r}^{Sheep,\text{AFtoAg}}(y), \\ \mathbf{TotTCM}_{r}^{Beef,\text{AFtoAg}}(y), \mathbf{TotTCM}_{r}^{\text{CPBlockToAg}}(y), \mathbf{TotTCM}_{r}^{Sheep,\text{CPBeltToAg}}(y \\ \mathbf{TotTCM}_{r}^{Beef,\text{CPBeltToAg}}(y), \mathbf{TotTCM}_{r}^{\text{BEECtoAg}}(y)\end{array}\right.$	

where,

- $\mathbf{TCM}_{r\ell}^{\text{NonAgToAg}}(y)$ is the aggregated transition cost matrix (in AUD/ha) for year y, representing the cost of converting non-agricultural land uses to agricultural uses for each cell r, management regime m, and target agricultural class ℓ.
- Each $\mathbf{TotTCM}_{mr\ell}^{X}(y)$ denotes the total transition cost matrix from the corresponding non-agricultural use X to agriculture, including:
    - EPtoAg: Environmental Planting
    - RPtoAg: Riparian Planting
    - $Sheep$, AFtoAg: Sheep Agroforestry
    - $Beef$, AFtoAg: Beef Agroforestry
    - CPBlockToAg: Carbon Planting (Block)
    - $Sheep$, CPBeltToAg: Sheep Carbon Planting (Belt)
    - $Beef$, CPBeltToAg: Sheep Carbon Planting (Belt)
    - BEECtoAg: BEEC

Note: "concatenate" in this context refers to combining these individual cost tensors across all relevant land use transitions into a unified matrix structure.

Equation 524 can be summarized using summation notation over all non-agricultural land-use types LU:

$\mathbf{TotTCM}_{mr\ell}^{\text{NonAgToAg}}(y) = \sum_{LU \in \mathcal{L}_{\text{NonAgrLand}}} \mathbf{TotTCM}_{mr\ell}^{LU2AG}(y)$	Equation 525

where,

- $\mathcal{L}_{\text{NonAgrLand}}$ is the set of all non-agricultural land use types.
- $\mathbf{TotTCM}_{mr\ell}^{LU2AG}(y)$represents the total cost of transition from non-agricultural land use LU to agriculture.
- LU refers to each non-agricultural land use type, specifically:
    - Environmental Plantings (EP)
    - Riparian Plantings (RP)
    - Sheep Agroforestry
    - Beef Agroforestry
    - Carbon Plantings (Block)
    - Sheep Carbon Plantings (Belt)
    - Beef Carbon Plantings (Belt)
    - Bioenergy with Carbon Capture and Storage (BECCS)

These categories are all included in the set $\mathcal{L}_{\text{NonAgrLand}}$ and contribute to the aggregated transition cost matrix from non-agricultural to agricultural land uses as defined in Equation 525.

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To demonstrate the structure of the final aggregated transition cost matrix $\mathbf{TotTCM}_{mr\ell}^{\text{NonAgToAg}}$, assume the following:

- There are 2 land management practices ($m = 1,2$)
- There are 4 spatial cells ($r = 1,2,3,4$)
- There are 3 agricultural land use types ($\ell = 1,2,3$)

Let the individual transition cost matrices from selected non-agricultural land uses to agriculture be:

$\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAg}}(y) = \left(\begin{bmatrix} a_{111} & a_{112} & a_{113} \\ a_{121} & a_{122} & a_{123} \\ a_{131} & a_{132} & a_{133} \\ a_{141} & a_{142} & a_{143} \end{bmatrix}, \begin{bmatrix} a_{211} & a_{212} & a_{213} \\ a_{221} & a_{222} & a_{223} \\ a_{231} & a_{232} & a_{233} \\ a_{241} & a_{242} & a_{243} \end{bmatrix} \right)$	Equation 526
$\mathbf{TotTCM}_{mr\ell}^{\text{RPtoAg}}(y) = \left(\begin{bmatrix} b_{111} & b_{112} & b_{113} \\ b_{121} & b_{122} & b_{123} \\ b_{131} & b_{132} & b_{133} \\ b_{141} & b_{142} & b_{143} \end{bmatrix}, \begin{bmatrix} b_{211} & b_{212} & b_{213} \\ b_{221} & b_{222} & b_{223} \\ b_{231} & b_{232} & b_{233} \\ b_{241} & b_{242} & b_{243} \end{bmatrix} \right)$	
$\mathbf{TotTCM}_{mr\ell}^{Sheep,\text{AFtoAg}}(y) = \left(\begin{bmatrix} c_{111} & c_{112} & c_{113} \\ c_{121} & c_{122} & c_{123} \\ c_{131} & c_{132} & c_{133} \\ c_{141} & c_{142} & c_{143} \end{bmatrix}, \begin{bmatrix} c_{211} & c_{212} & c_{213} \\ c_{221} & c_{222} & c_{223} \\ c_{231} & c_{232} & c_{233} \\ c_{241} & c_{242} & c_{243} \end{bmatrix} \right)$	
$\mathbf{TotTCM}_{mr\ell}^{\text{NonAgToAg}}(y) = \left(\begin{bmatrix} a_{111}+b_{111}+c_{111} & a_{112}+b_{112}+c_{112} & a_{113}+b_{113}+c_{113} \\ a_{121}+b_{121}+c_{121} & a_{122}+b_{122}+c_{122} & a_{123}+b_{123}+c_{123} \\ a_{131}+b_{131}+c_{131} & a_{132}+b_{132}+c_{132} & a_{133}+b_{133}+c_{133} \\ a_{141}+b_{141}+c_{141} & a_{142}+b_{142}+c_{142} & a_{143}+b_{143}+c_{143} \end{bmatrix}, \begin{bmatrix} a_{211}+b_{211}+c_{211} & a_{212}+b_{212}+c_{212} & a_{213}+b_{213}+c_{213} \\ a_{221}+b_{221}+c_{221} & a_{222}+b_{222}+c_{222} & a_{223}+b_{223}+c_{223} \\ a_{231}+b_{231}+c_{231} & a_{232}+b_{232}+c_{232} & a_{233}+b_{233}+c_{233} \\ a_{241}+b_{241}+c_{241} & a_{242}+b_{242}+c_{242} & a_{243}+b_{243}+c_{243} \end{bmatrix} \right)$	

The total aggregated transition cost matrix $\mathbf{TotTCM}_{mr\ell}^{\text{NonAgToAg}}(y)$ is computed by summing corresponding elements from the above matrices $\mathbf{TotTCM}_{mr\ell}^{\text{EPtoAg}}(y)$, $\mathbf{TotTCM}_{mr\ell}^{\text{RPtoAg}}(y)$, and $\mathbf{TotTCM}_{mr\ell}^{Sheep,\text{AFtoAg}}(y)$. Each matrix corresponds to one of the two land management practices (e.g., dryland and irrigation), and each element gives the total transition cost from a non-agricultural land use to a specific agricultural land class for a particular cell and management type.

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23. Exclusion Criteria for Agricultural Land Use Transitions to Non-Agricultural Classes

23.1. Transition Costs for Non-Agricultural Land Uses

This section defines the transition costs for non-agricultural land-use classes, denoted as $\mathcal{L}_{\text{NonAgrLand}}$ (see Equation 13). In the LUTO 2.0 framework, transitions into non-agricultural land uses from agricultural classes are accounted for, but transitions from non-agricultural land uses are not permitted. Therefore, a transition cost matrix filled with zeros is defined to represent that no transitions are allowed from non-agricultural land-use types:

$\forall r \in \{1, \dots, N_r\}, \forall\, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	
$\mathbf{TotTCM}_{r\ell}^{\text{NonAG}} = 0_{(N_c \times N_{lu})}$	Equation 527

where,

- $\mathbf{TotTCM}_{r\ell}^{\text{NonAG}}$ is the total transition cost from non-agricultural land use ℓ in cell r,
- N_c is the number of spatial cells in the baseline land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_{lu} is the number of non-agricultural land-use types in the $\mathcal{L}_{NonAG}$.

23.2. Exclusion Matrix for Agricultural Land Use Transitions to Environmental Plantings

As mentioned in Section 21.1, let $\mathbf{RTCM}^{\text{AgToEP}}$ be the raw transition matrix with dimensions 1×28, that representing the base cost of transition ($/ha) from various agricultural land-use classes ℓ_i to Environmental Planting ℓ_j (see Figure 626).

Given that transitions from Environmental Planting to natural agricultural land are not allowed in the LUTO 2.0 model, the values in $\mathbf{RTCM}^{\text{AgToEP}}$ for land-use classes belonging to the set $\mathcal{L}_{\text{NatAgLu}}$ (see Equation 18) — including 'Beef-natural land', 'Dairy-natural land', 'Sheep-natural land', and 'Unallocated-natural land' — are assigned the value NaN.

To implement this restriction in model calculations, we define an exclusion matrix $\mathbf{XCM}_r^{EP}$, initially populated with ones:

$\mathbf{XCM}_r^{EP} = 1_{(N_c \times 1)}$	Equation 528

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.

We then update the values of $\mathbf{XCM}_r^{EP}$ based on the land-use class ℓ_r assigned to each cell r, using the rule:

$\forall r \in \{1, \dots, N_r\}\ \exists\, \ell_r, \ell_r = \mathbf{LUM}_r^{\text{BYear}}$	

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$$\mathbf{XCM}_r^{EP} = \begin{cases} \mathbf{0} & \text{if } \ell_r \in \mathcal{L}_{\text{NatAgLu}} \\ \mathbf{0} & \text{if } \ell_r \in \mathcal{L}_{\text{NonAgrLand}} \\ \mathbf{1} & \text{if } \ell_r = \ell_{EP} \end{cases}$$	Equation 529

Where,

- ℓ_{EP} is the land-use class label for Environmental Planting; in LUTO 2.0, $\ell_{EP} = 100$.

Interpretation:

- The first condition ensures that cells currently classified as natural agricultural land cannot be transitioned into environmental planting.
- The second condition ensures that other non-agricultural land-use classes (excluding environmental planting itself) are also excluded from such transitions.
- The third condition allows environmental planting cells to remain as environmental planting in future timesteps.

The resulting matrix $\mathbf{XCM}_r^{EP}$ is used to control land-use transitions and is visually represented in Figure 677.

23.3. Exclusion Criteria for Agricultural Land Use Transitions to Riparian Plantings

This section outlines the calculation of the exclusion matrix $\mathbf{XCM}_r^{RP}$, which determines the proportion of each cell that can be allocated to Riparian Plantings (RP).

Step 1: Compute Riparian Planting Proportion

Let RP_r^{Prop} represent the proportion of cell r that can be utilized for Riparian Plantings. It is computed using:

$$\text{RP}_r^{Prop} = \frac{2 \times \text{RP}_{RW} \times SL_r}{10000 \times \mathbf{RA}_r}$$	Equation 530

where,

- RP_{RW} is the Riparian Planting buffer width, fixed in LUTO 2.0 as 30 meters ($\text{RP}_{RW} = 30$).
- SL_r is the stream length within cell r (see Figure 679)
- $\mathbf{RA}_r$ is the **real area** of cell r (see Figure 5)

The resulting RP_r^{Prop} expresses what fraction of the cell is available for RP (see Figure 680).

Step 2: Initialize Exclusion Matrix

An exclusion matrix $\mathbf{XCM}_r^{RP}$ is created with dimensions $N_c \times 1$, where all values are initially set to one:

$$\mathbf{XCM}_r^{RP} = 1_{(N_c \times 1)}$$	Equation 531

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.

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Step 3: Update Exclusion Matrix Based on Land Use Class

We now update the values of $\mathbf{XCM}_r^{RP}$ based on the land-use class ℓ_r for each cell r, using the following conditions:

$\forall r \in \{1, \dots, N_r\} \; \exists \; \ell_r, \ell_r = \mathbf{LUM}_r^{\mathrm{BYear}}$	Equation 532
$\mathbf{XCM}_r^{RP} = \begin{cases} \mathbf{0} & \text{if } \ell_r \in \mathcal{L}_{\mathrm{NatAgLu}} \\ \mathbf{0} & \text{if } \ell_r \in \mathcal{L}_{\mathrm{NonAgrLand}} \\ \mathbf{1} & \ell_r = \ell_{RP} \end{cases}$	

where:

- $\mathcal{L}_{\mathrm{NatAgLu}}$ is the set of natural agricultural land uses (Equation 18).
- $\mathcal{L}_{\mathrm{NonAgrLand}}$ is the set of non-agricultural land uses (Equation 13).
- ℓ_{RP} is the code representing Riparian Planting, fixed at 101 ($\ell_{RP} = 101$) in LUTO 2.0.

This structure ensures that:

- Transitions from **natural agricultural** and **non-agricultural** land uses to RP are disallowed.
- Cells already under RP can continue to remain RP in the following time step.

Step 4: Scale the Exclusion Matrix by Proportional Area

Finally, the values of $\mathbf{XCM}_r^{RP}$ are scaled by RP_r^{Prop} to reflect the actual usable portion of each cell:

$\mathbf{XCM}_r^{RP} = \mathbf{XCM}_r^{RP} \times \mathrm{RP}_r^{Prop}$	Equation 533

This yields the final exclusion matrix for Riparian Plantings, shown in Figure 678.

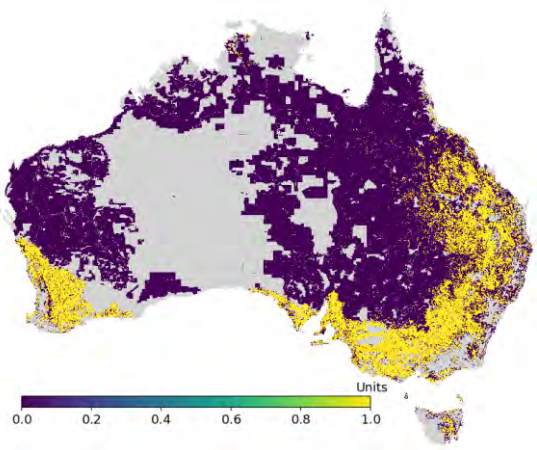

Figure 677 The exclusion matrix for the Environmental Plantings land use.

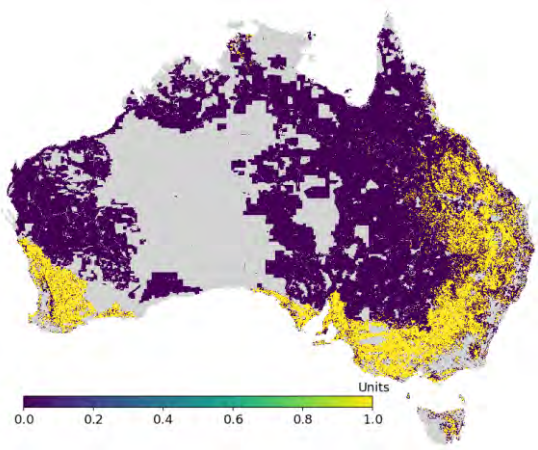

Figure 678 The exclusion matrix for the Riparian Plantings land use.

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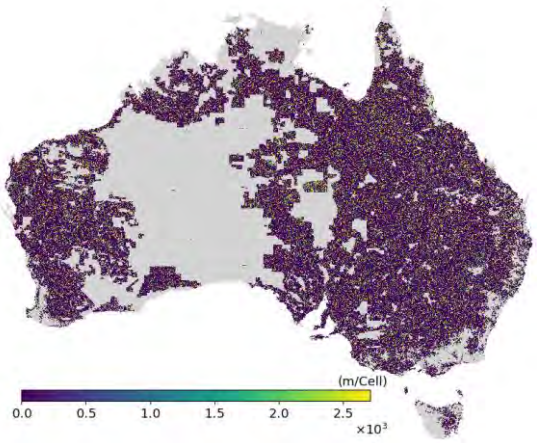	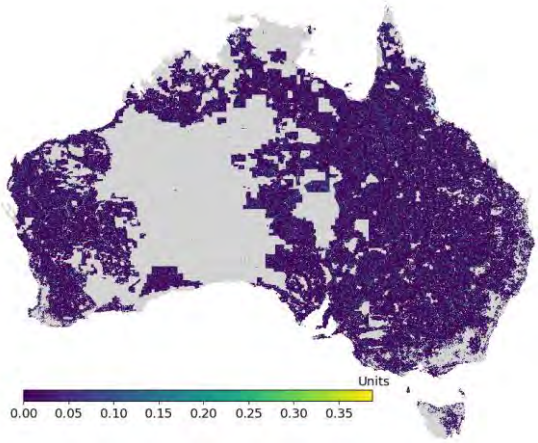
Figure 679 The stream length for the Riparian Plantings land use.	Figure 680 The Riparian Planting proportion per cell.

23.4. Exclusion Criteria for Agricultural Land Use Transitions to Sheep-Agroforestry

To compute the exclusion matrix for the Sheep-Agroforestry land use classes under the **dryland management system**, the Boolean exclusion matrix for subsequent years—denoted as $\mathbf{XCM}_{mr\ell}$, (Equation 244)—is used as follows:

$\forall r \in \{1, \dots, N_r\}, m = 0 \; \exists \; \ell = \text{Sheep} - \text{modified land}$	Equation 534
$\mathbf{XCM}_r^{Sheep} = \begin{cases} 1 & \text{if} \quad \mathbf{XCM}_{mr\ell} = \text{True} \\ 0 & \text{if} \quad \mathbf{XCM}_{mr\ell} = \text{False} \end{cases}$	

The computed $\mathbf{XCM}_r^{Sheep}$ is illustrated in Figure 681.

To define the set of cells where both sheep land use and agroforestry are present, the exclusion matrix for agroforestry, $\mathbf{XCM}_r^{AgFor}$, is required. As introduced in Equation 295, this matrix indicates the proportion of land used for agroforestry and is shown in Figure 682.

The Sheep-Agroforestry exclusion matrix is computed as the **intersection** of the non-zero values in both matrices $\mathbf{XCM}_r^{Sheep}$ and $\mathbf{XCM}_r^{AgFor}$, as:

$\forall r \in \{1, \dots, N_r\}$	Equation 535
$\mathbf{XCM}_r^{Sheep,AgFor} = \begin{cases} 1 & \text{if} \quad \left(\mathbf{XCM}_r^{Sheep} \neq 0\right) \cap \left(\mathbf{XCM}_r^{AgFor} \neq \mathbf{0}\right) \\ 0 & \text{otherwise} \end{cases}$	

The resulting Sheep-Agroforestry exclusion matrix, $\mathbf{XCM}_r^{Sheep,AgFor}$, is presented in Figure.

23.5. Exclusion Criteria for Agricultural Land Use Transitions to Beef-Agroforestry

To compute the exclusion matrix for the Beef-Agroforestry land use classes under the dryland management system, the Boolean exclusion matrix for subsequent years—denoted as $\mathbf{XCM}_{mr\ell}$ (Equation 244)—is employed as follows:

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$\forall r \in \{1, \dots, N_r\}, m = 0 \; \exists \; \ell = \text{Beef} - \text{modified land}$	Equation 536
$\mathbf{XCM}_r^{Beef} = \begin{cases} 1 & \text{if} \quad \mathbf{XCM}_{mr\ell} = \text{True} \\ 0 & \text{if} \quad \mathbf{XCM}_{mr\ell} = \text{False} \end{cases}$	

The computed $\mathbf{XCM}_r^{Beef}$ is illustrated in Figure 684.

To identify the cells where both Beef land use and Agroforestry coexist, the exclusion matrix for agroforestry $\mathbf{XCM}_r^{AgFor}$ is required. As introduced in Equation 295, $\mathbf{XCM}_r^{AgFor}$ also represents the proportion of land used for agroforestry (illustrated in Figure 682).

The Beef-Agroforestry exclusion matrix is computed as the intersection of non-zero values from both matrices $\mathbf{XCM}_r^{Beef}$ and $\mathbf{XCM}_r^{AgFor}$:

$\forall r \in \{1, \dots, N_r\}$	Equation 537
$\mathbf{XCM}_r^{Beef,AgFor} = \begin{cases} 1 & \text{if} \quad \left(\mathbf{XCM}_r^{Beef} \neq 0\right) \cap \left(\mathbf{XCM}_r^{AgFor} \neq \mathbf{0}\right) \\ 0 & \text{otherwise} \end{cases}$	

The resulting Beef-Agroforestry exclusion matrix, $\mathbf{XCM}_r^{Beef,AgFor}$, is presented in Figure 685.

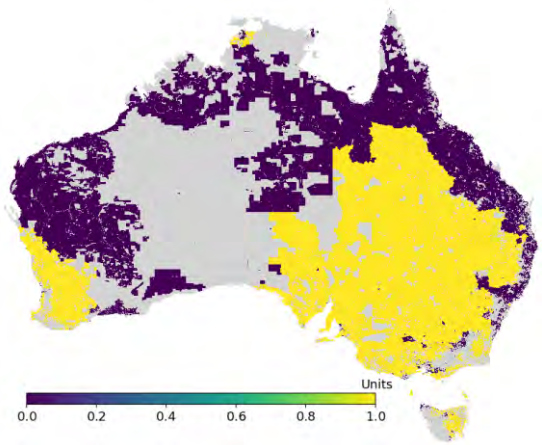

Figure 681 The exclusion matrix for the *Sheep-modified land* under dryland management system

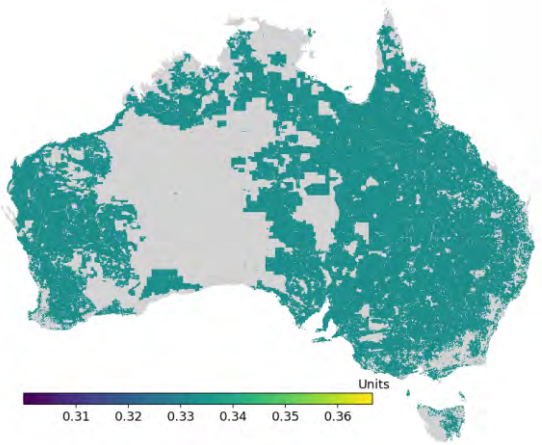

Figure 682 The exclusion matrix for the *Agroforestry Plantings* land use

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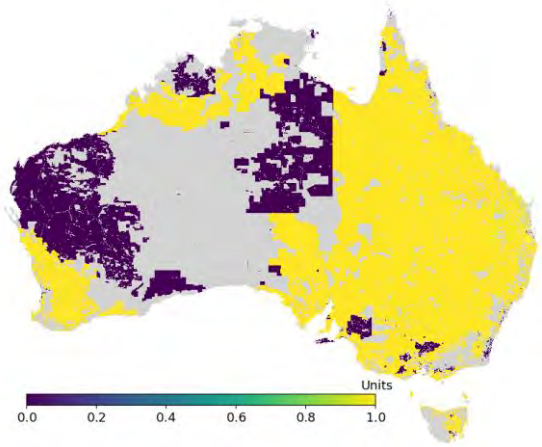	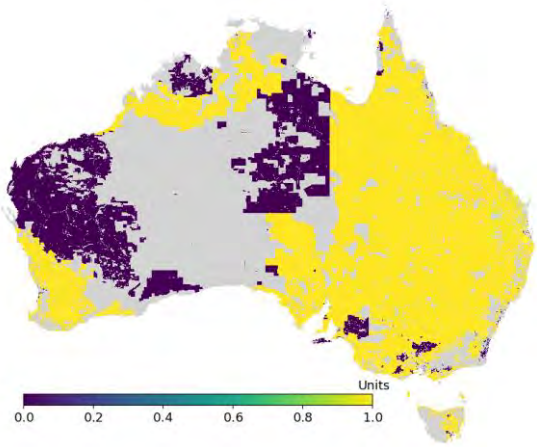
Figure 683 The exclusion matrix for the *Sheep-Agroforestry* land use	Figure 684 The exclusion matrix for the *Beef-modified land* under dryland management system
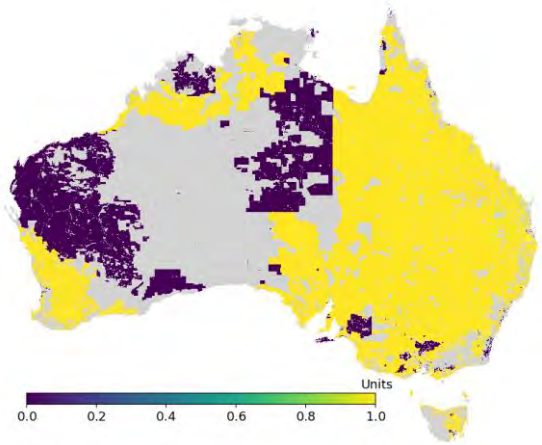	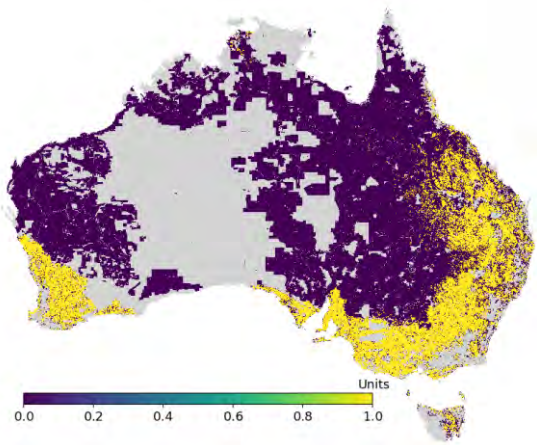
Figure 685 The exclusion matrix for the *Beef-Agroforestry* land use	Figure 686 The exclusion matrix for the *Carbon Plantings (Block)* land use

23.6. Exclusion Criteria for Agricultural Land Use Transitions to Carbon Plantings (Block)

This section calculates the exclusion matrix $\mathbf{XCM}_r^{CPBlock}$, which represents the extent to which the Carbon Plantings (Block) land use can be utilized. First, define an exclusion matrix with N_c rows and one column, initialized with ones:

$\mathbf{XCM}_r^{CPBlock} = \mathbf{One}_{(N_c \times 1)}$	Equation 538

where,

- N_c: Number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.

The values of $\mathbf{XCM}_r^{CPBlock}$ are updated based on land use classes defined in $\mathcal{L}_{\mathrm{NatAgLu}}$, as follows:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists\ \ell_r, \ell_r = \mathbf{LUM}_r^{\mathrm{BYear}}$	Equation 539
$\mathbf{XCM}_r^{CPBlock} = \begin{cases} \mathbf{0} & \text{if } \ell_r \in \mathcal{L}_{\mathrm{NatAgLu}} \\ \mathbf{0} & \text{if } \ell_r \in \mathcal{L}_{\mathrm{NonAgrLand}} \\ \mathbf{1} & \text{otherwise} \end{cases}$	

This matrix ensures that all cells classified as natural agricultural land (from $\mathcal{L}_{\mathrm{NatAgLu}}$) and non-agricultural land uses (from $\mathcal{L}_{\mathrm{NonAgrLand}}$) are excluded from transitioning into Carbon Plantings (Block). Since Carbon Plantings (Block) is itself part of $\mathcal{L}_{\mathrm{NonAgrLand}}$, the second condition in Equation 539 excludes it from transitioning. However, a Carbon Plantings (Block) cell may remain unchanged in the following year, which is accounted for in the third condition, setting the value to 1.

The computed exclusion matrix $\mathbf{XCM}_r^{CPBlock}$ is illustrated in Figure 686.

23.7. Exclusion Criteria for Agricultural Land Use Transitions to Sheep and Carbon Planting (Belt)

To determine the set of cells where both Sheep-modified land and Carbon Planting (Belt) are present, the exclusion matrices for Sheep-modified land $\mathbf{XCM}_r^{Sheep}$ (defined in Equation 534 and illustrated in Figure 681) and for Carbon Planting (Belt) $\mathbf{XCM}_r^{CPBelt}$ (defined in Equation 307 and illustrated in Figure 487)) are required.

The combined Sheep–Carbon Planting (Belt) exclusion matrix, denoted as $\mathbf{XCM}_r^{Sheep,CPBelt}$, is constructed as the intersection of non-zero values in both $\mathbf{XCM}_r^{Sheep}$ and $\mathbf{XCM}_r^{CPBelt}$, and is computed as:

$\forall r \in \{1, \dots, N_r\}$	Equation 540
$\mathbf{XCM}_r^{Sheep,CPBelt} = \begin{cases} 1 & \text{if } \left(\mathbf{XCM}_r^{Sheep} \neq 0\right) \cap \left(\mathbf{XCM}_r^{CPBelt} \neq \mathbf{0}\right) \\ 0 & \text{otherwise} \end{cases}$	

This ensures that only cells eligible under both Sheep-modified land and Carbon Planting (Belt) constraints are retained.

The computed exclusion matrix $\mathbf{XCM}_r^{Sheep,CPBelt}$ is presented in Figure 687.

23.1. Exclusion Criteria for Agricultural Land Use Transitions to Beef and Carbon Planting (Belt)

To determine the set of cells where both Beef-modified land and Carbon Planting (Belt) are present, the exclusion matrices for Beef-modified land $\mathbf{XCM}_r^{Beef}$ (defined in Equation 536 and shown in Figure 684) and for Carbon Planting (Belt) $\mathbf{XCM}_r^{CPBelt}$ (defined in Equation 307 and shown in Figure 487) are required.

The combined Beef–Carbon Planting (Belt) exclusion matrix, denoted as $\mathbf{XCM}_r^{Beef,CPBelt}$, is formed as the intersection of non-zero values in both $\mathbf{XCM}_r^{Beef}$ and $\mathbf{XCM}_r^{CPBelt}$, and is computed as:

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$\forall r \in \{1, \dots, N_r\}$	Equation 541
$\mathbf{XCM}_r^{Beef,CPBelt} = \begin{cases} 1 & \text{if} \quad \left(\mathbf{XCM}_r^{Beef} \neq 0\right) \cap \left(\mathbf{XCM}_r^{CPBelt} \neq 0\right) \\ 0 & \text{otherwise} \end{cases}$	

This matrix ensures that only the cells eligible under both Beef-modified land and Carbon Planting (Belt) constraints are considered valid.

The computed exclusion matrix $\mathbf{XCM}_r^{Beef,CPBelt}$ is presented in Figure 688.

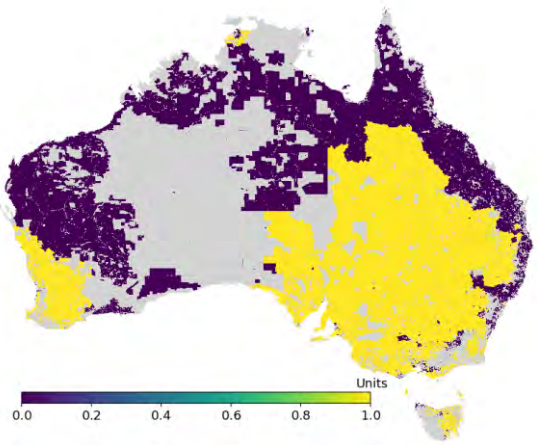	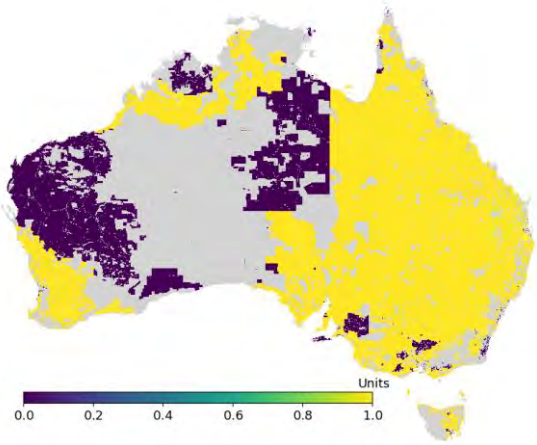
Figure 687 The exclusion matrix for the Sheep–Carbon Planting (Belt) land use	Figure 688 The exclusion matrix for the Beef–Carbon Planting (Belt) land use

23.2. Exclusion Criteria for Agricultural Land Use Transitions to BECCS

This section calculates the exclusion matrix $\mathbf{XCM}_r^{BECCS}$, which represents the proportion of each cell r that can be allocated to Bioenergy with Carbon Capture and Storage (BECCS) land use.

We first initialize the matrix as follows:

$\mathbf{XCM}_r^{BECCS} = \mathbf{One}_{(N_c \times 1)}$	Equation 542

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.

To ensure only cells with a defined BECCS cost are eligible, the matrix $\mathbf{XCM}_r^{BECCS}$ is conditionally updated based on the cost data:

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$\forall r \in \{1, \dots, N_r\} \; \exists \; \ell_r, \ell_r = \mathbf{Cost}_r^{BECCS}$	Equation 543
$\mathbf{XCM}_r^{BECCS} = \begin{cases} \mathbf{1} & \text{if} \quad \ell_r \neq \text{NaN} \\ \mathbf{0} & \text{otherwise} \end{cases}$	

where,

- $\mathbf{Cost}_r^{BECCS}(y)$ represents the cost of BECCS per hectare for each year y.

Further filtering is applied to exclude transitions from natural agricultural ($\mathcal{L}_{\text{NatAgLu}}$) and non-agricultural ($\mathcal{L}_{\text{NonAgrLand}}$) land uses:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists \; \ell_r, \ell_r = \mathbf{LUM}_r^{\text{BYear}}$	Equation 544
$\mathbf{XCM}_r^{BECCS} = \begin{cases} \mathbf{0} & \text{if} \;\; \ell_r \in \mathcal{L}_{\text{NatAgLu}} \\ \mathbf{0} & \text{if} \;\; \ell_r \in \mathcal{L}_{\text{NonAgrLand}} \\ \mathbf{XCM}_r^{BECCS} & \text{otherwise} \end{cases}$	

where:

- ℓ_r is the land-use class for cell r,
- $\mathcal{L}_{\text{NatAgLu}}$ is the set of natural agricultural land-use classes,
- $\mathcal{L}_{\text{NonAgrLand}}$ is the set of all non-agricultural land-use classes.

Since BECCS is included in the set $\mathcal{L}_{\text{NonAgrLand}}$, the second condition in Equation 544 appropriately excludes cells classified as BECCS from transitioning into BECCS again (i.e., from being reallocated to it). However, in practice, a BECCS cell may retain its classification in the next period.

Therefore, for each cell r currently assigned to the BECCS class, the exclusion matrix $\mathbf{XCM}_r^{BECCS}$ must be updated to 1, overriding any previous exclusion, to allow this continuity:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \exists \; \ell_r, \ell_r = \mathbf{LUM}_r^{\text{BYear}}$	
$\mathbf{XCM}_r^{BECCS} = \begin{cases} \mathbf{XCM}_r^{BECCS} & \text{if} \;\; \ell_r \in \mathcal{L}_{\text{NotAgLu}} \\ \mathbf{XCM}_r^{BECCS} & \text{if} \;\; \ell_r \in \mathcal{L}_{\text{NonAgrLand}} \\ 1 & \text{if} \;\; \ell_r = \ell_{\text{BECCS}} \end{cases}$	

where,

- ℓ_{BECCS} is the land-use class label assigned to BECCS in LUTO 2.0 (typically $\ell_{\text{BECCS}} = 107$).

This ensures that BECCS-designated cells are permitted to remain in BECCS in the following year, while all invalid or ineligible transitions remain excluded. The computed $\mathbf{XCM}_r^{BECCS}$ is illustrated in Figure 689.

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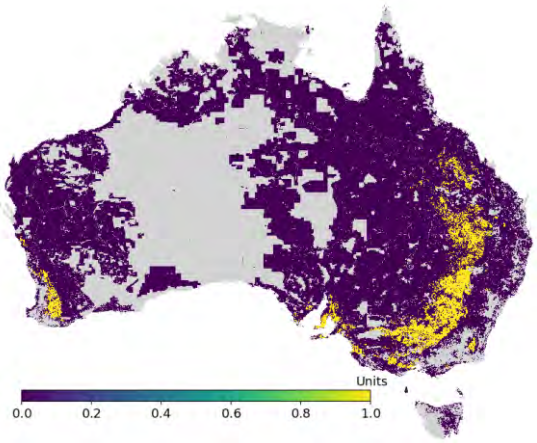	
Figure 689 The exclusion matrix for the BECCS land use	

23.3. The Non-Agricultural Exclusions Matrix

In this section, a unified exclusion matrix is constructed by combining the individual exclusion matrices for each non-agricultural land use. This matrix identifies which land use transitions into agricultural classes are permitted across all non-agricultural land use types.

Let:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 545
$\mathbf{XCM}_{r\ell}^{\text{NonAgToAg}} = \text{concatenate}\left(\mathbf{XCM}_r^{EP}, \mathbf{XCM}_r^{RP}, \mathbf{XCM}_r^{Sheep,AgFor}, \mathbf{XCM}_r^{Beef,AgFor}, \mathbf{XCM}_r^{CPBlock}, \mathbf{XCM}_r^{Sheep,CPBelt}, \mathbf{XCM}_r^{Beef,CPBelt}, \mathbf{XCM}_r^{BECCS}\right)$	

where,

- $\mathbf{XCM}_{r\ell}^{\text{NonAgToAg}}$ is the final aggregated transition cost matrix for transitions from all non-agricultural land uses to agricultural land uses, for cell r and land use class ℓ.
- $\mathbf{XCM}_r^{EP}$ is the exclusion matrix for Environmental Planting.
- $\mathbf{XCM}_r^{RP}$ is the exclusion matrix for Riparian Planting.
- $\mathbf{XCM}_r^{Sheep,AgFor}$ is the exclusion matrix for Sheep Agroforestry.
- $\mathbf{XCM}_r^{Beef,AgFor}$ is the exclusion matrix for Beef Agroforestry.
- $\mathbf{XCM}_r^{CPBlock}$ is the exclusion matrix for Carbon Planting (Block).
- $\mathbf{XCM}_r^{Sheep,CPBelt}$ is the exclusion matrix for Sheep Carbon Planting (Belt).
- $\mathbf{XCM}_r^{Beef,CPBelt}$ is the exclusion matrix for Beef Carbon Planting (Belt).
- $\mathbf{XCM}_r^{BECCS}$ is the exclusion matrix for BECCS.

Note: The concatenate operation combines these vectors into a comprehensive matrix

23.4. Computation of Lower Bound Matrix of Non-Agricultural Land Uses for Base Year Optimization

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This section explains how to compute the lower bound matrix $\mathbf{LB}_{r\ell}^{\text{NonAg}}$ for non-agricultural land uses during optimization for the base year. This matrix provides constraints on the minimum land allocation for each non-agricultural land use type in each spatial cell under different management systems.

Initialization

First, the lower bound matrix $\mathbf{LB}_{r\ell}^{\text{NonAg}}$ is initialized as a zero matrix:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 546
$\mathbf{LB}_{r\ell}^{\text{NonAg}} = 0_{(N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_k = 2$ is the number of agricultural management practices (e.g., dryland, irrigated) $m \in \mathcal{M}$.
- $N_{lu} = 8$ is the number of non-agricultural land-use classes.

Case 1: Base Year = Calibration Year (or data unavailable)

If the base year corresponds to the calibration year, or if base year data is unavailable in the non-agricultural decision variables, then the lower bound matrix remains a **zero matrix**, as in Equation 286.

Case 2: Case 2: Base Year ≠ Calibration Year

If the base year different from the calibration year, the lower bound matrix for each $\ell \in \mathcal{L}_{\text{NonAgrLand}}$ (Equation 13) is calculated as:

If the base year is different from the calibration year, the lower bound matrix $\mathbf{LB}_{r\ell}^{\text{NonAg}}$ is calculated from the non-agricultural management decision variable $\boldsymbol{D}_{r\ell}^{NonAgManag}(y)$, which indicates the base-year allocation for each land use class.

The formula is as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 547
$\mathbf{LB}_{r\ell}^{\text{NonAg}} = \frac{\lfloor \boldsymbol{D}_{r\ell}^{NonAgManag}(y) \times 10^d \rfloor}{10^d}$	

where,

agricultural management decision variables

- $\mathbf{D}_{r\ell}^{NonAgManag}(y)$ is the share of cell r allocated to land use $\ell \in \mathcal{L}_{\text{NonAgrLand}}$ in year y
- d is the number of decimal places used for rounding (as defined by the model, typically $d = 6$)
- $\lfloor . \rfloor$ is the **floor function**, applied element-wise to round down and maintain consistency in numeric representation

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24.Solver in LUTO

24.1. Model Parameter

24.1.1. The Gurobi Environment

The Gurobi environment is initialized with a log file (gurobi.log) to document output details. Parameters are set using "empty=True", allowing them to be adjusted flexibly before the solver starts. This approach is advantageous for large-scale optimization models, where parameter tuning can significantly impact performance.

24.2. Gurobi Parameters in LUTO Solver

The following sections explain each Gurobi parameter configured in the LUTO solver, emphasizing its role in performance optimization and solution quality.

24.2.1. Method

The `Method` parameter in Gurobi specifies the algorithm for solving continuous models and the root relaxation of Mixed Integer Programming (MIP) models:

- -1 (Automatic): Gurobi selects the optimal method based on model type, often choosing concurrent (3) for LP, barrier (2) for QP/QCP, and dual simplex (1) for MIP root relaxations. For very large relaxations, deterministic concurrent (4) may be used.
- 0 (Primal Simplex): Suitable for smaller models, with warm-start capabilities useful for multiobjective optimization.
- 1 (Dual Simplex): Fast for large models, ideal for MIP and low-memory situations.
- 2 (Barrier): Efficient for large, continuous models with dense constraints, following an interior-point path.
- 3 (Concurrent): Runs multiple methods on separate threads, selecting the fastest result.
- 4 (Deterministic Concurrent): Like concurrent but deterministic, ensuring consistent results across runs.
- 5 (Deterministic Concurrent Simplex): Deprecated; traditionally ensured consistent simplex-based results.

In the LUTO 2.0 model, the Barrier method (2) is selected for its ability to:

- Efficiently handle complex constraints in high-dimensional land-use optimization,
- Balance speed and stability for dense constraint matrices,
- Converge to the optimal solution by iteratively relaxing boundary constraints.

Chosen strategically, the Barrier method enables LUTO to manage complex models with precision and efficiency.

24.2.2. OutputFlag

The 'OutputFlag' parameter, controlled by the VERBOSE setting in settings, determines the verbosity level of the Gurobi solver's output.
In **LUTO 2.0**, OutputFlag is set to 1, which enables detailed reporting of the solver's progress in the console. This output includes information on initialization steps, iteration progress, convergence status, and other diagnostic messages.
Such detailed logging is valuable for monitoring solver behavior, diagnosing potential issues during optimization, and ensuring transparency during model execution.

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24.2.3. Presolve

The 'Presolve' parameter in Gurobi controls the level of model simplification applied before solving. Presolve can significantly reduce the model's size and complexity, leading to faster solution times. The available options are:

- **None (0):** Disables presolve entirely, keeping the model exactly as defined. Useful when numerical stability is a concern.
- **Conservative (1):** Applies basic simplifications cautiously, improving efficiency while preserving model stability.
- **Aggressive (2):** Applies extensive simplifications that can result in a much smaller, tighter model. This may increase initial presolve time but often reduces total solution time.
- **Automatic (-1):** Gurobi automatically selects the most appropriate presolve level based on the model characteristics.

In LUTO 2.0, Presolve is set to 1 (Conservative). This configuration balances computational efficiency and numerical stability, ensuring a reliable solution process without overly aggressive model reductions.

24.2.4. Aggregate

The 'Aggregate' parameter controls variable aggregation during the presolve phase, with three settings:

- **0 (Off):** No aggregation is performed, preserving the original model structure.
- **1 (Moderate):** Applies moderate aggregation to reduce model size.
- **2 (Aggressive):** Applies aggressive aggregation, which can substantially simplify the model but may introduce numerical issues.

In **LUTO 2.0**, the Aggregate parameter is set to **0**, meaning no aggregation is performed. This choice helps maintain the model's original structure and avoids potential numerical errors, which is crucial for large, high-dimensional models like LUTO.

24.2.5. Optimality Tolerance

The ' OptimalityTol' parameter defines the allowable tolerance for dual feasibility when determining optimality.

- **Default:** 1×10^{-6}
- **In LUTO 2.0:** Set to the maximum value 1×10^{-2}.

This adjustment allows faster solution times by slightly relaxing the strictness of optimality conditions, which is acceptable in scenarios prioritizing computational speed over precision.

24.2.6. Feasibility Tolerance

The 'FeasibilityTol' parameter specifies the allowable tolerance for primal feasibility, meaning slight constraint violations are permitted.

- **Default:** 1×10^{-6}
- **In LUTO 2.0:** Set to 1×10^{-2}.

Increasing this tolerance similarly accelerates the solution process, sacrificing minimal precision for significant gains in computational efficiency.

24.2.7. Barrier Convergence Tolerance

The 'BarConvTol' parameter is specific to the barrier method and controls the stopping criteria based on the relative difference between the primal and dual objectives.

- **In LUTO 2.0:** Set to 1×10^{-5}.

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By using this stricter convergence threshold, LUTO ensures that the optimization terminates once a sufficiently accurate solution is reached without unnecessary additional iterations.

24.2.8. Scale Flag

The 'ScaleFlag' is a parameter controls the scaling behavior of the model's constraint matrix, directly impacting numerical stability and, in some cases, solution efficiency. Here's a breakdown of each value and its potential effects:

- Default (-1): Automatically scales rows and columns for stability, then reverts to unscaled form, usually speeding up solutions but sometimes increasing constraint violations.
- Disable Scaling (0): Avoids scaling, which may reduce constraint violations but could slow down solution time.
- Specific Scaling Method (1): Applies a set scaling method; performance impact varies, so testing is recommended.
- Geometric Mean Scaling (2): Ideal for models with a wide range of coefficients, improving stability and performance.
- Alternative Scaling Method (3): A different scaling approach with variable results; testing is suggested for optimal use.

In LUTO 2.0, the ScaleFlag parameter is set to -1, favoring automatic scaling with a focus on stability and reduced solution time.

24.2.9. Numeric Focus

In LUTO 2.0, the 'NumericFocus' parameter is configured with a default setting of 0. This parameter provides a balance between computational speed and numerical accuracy. With the default setting at 0, the employed model prioritizes speed while performing essential numerical checks.

- Setting 1 introduces a moderate increase in accuracy checks without significantly impacting solve time.
- Setting 2 considerably enhances numerical robustness, though it substantially increases computation time (by about 4 times).
- Setting `3 further maximizes stability and accuracy, which is especially useful in complex calculations where precision is essential but may lead to a notable performance reduction.

24.2.10. Threads

With the 'Threads' parameter sets the number of threads used by the solver:

- **In LUTO 2.0:** Set to **50** threads.

Using 50 threads leverages high parallel computing capabilities, significantly improving performance for large, complex models—provided sufficient memory and CPU resources are available.

24.2.11. Barrier homogeneous algorithm

The 'BarHomogeneous' parameter in LUTO 2.0, set to 1, actively enables the homogeneous barrier algorithm for all applicable models. This enhances the solver's ability to detect infeasibility or unboundedness. The available settings are:

- **Default (-1):** Uses the homogeneous algorithm only for node relaxations in MIP (Mixed-Integer Programming) models.
- **0:** Disables the homogeneous barrier algorithm entirely.
- **1:** Forces the homogeneous algorithm for all model instances, regardless of type.

The homogeneous barrier algorithm improves the model's robustness in identifying problematic cases but typically slows down the solution process by up to three times compared to the standard barrier method.

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In LUTO 2.0, by setting BarHomogeneous = 1, the configuration prioritizes the accurate detection of infeasibility and unboundedness over solve speed, which is particularly valuable in complex optimization scenarios where rigorous evaluation of model feasibility is critical.

24.2.12. Crossover

The `Crossover parameter determines whether the solver converts the interior solution from the barrier method into a basic solution:

- **0:** No crossover performed.
- **-1 (Default):** Crossover automatically based on the solver's judgment.

LUTO 2.0 disables crossover by setting Crossover = 0, preserving the interior-point solution and avoiding the substantial time increase sometimes associated with crossover, especially critical for future year scenarios like 2050.

24.3. Model Formulation Process

The formulate method in the solver initiates the setup of the model by systematically defining decision variables, applying constraints, and setting up the objective function—essential steps for structuring the optimization problem. The process is organized into four main stages:

1. Decision Variables Initialization
2. Constraints Definition
3. Objective Function Formulation
4. Summary of Formulation Process

Each of these components is detailed in the following sections.

24.3.1. Decision Variables Initialization

This section introduces the decision variables, which represent land use and management choices within the model. These include core land use allocations (both agricultural and non-agricultural), management-specific practices, and demand-related decision variables.

24.3.2. Land Use Allocation Variables for Agricultural and Non-Agricultural Cells

The land use allocation variables are critical for representing the distribution and usage of land cells across both agricultural and non-agricultural purposes. This section (_setup_x_vars) is responsible for defining these variables, setting their bounds, and ensuring that each cell is assigned a specific land use designation. It introduces the initialization of variables that govern how each cell is allocated to dryland agriculture, irrigated agriculture, or non-agricultural land uses. The following subsections provide a detailed breakdown of how each type of land use variable is set up.

24.3.2.1. Agricultural Land Use Variables

LUTO 2.0 distinguishes between dryland and irrigated agricultural land use by creating separate variables for each:

24.3.2.1.1. Dryland Agriculture

The variable $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}$ represents the allocation of cells for dryland agricultural use:

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$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	
$\mathbf{DAAC}^{\mathrm{AG}} = \left[\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}\right] \in \mathbb{R}^{N_{lu} \times N_c}$	Equation 548

where,

- N_c represents the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$,
- N_{lu} represents the number of agricultural land-use classes ($\mathcal{L}$),
- $\mathbb{R}^{N_{lu} \times N_c}$ denotes the space of matrix with N_{lu} rows and N_c columns where each entry is a real number ($\mathbb{R}$),
- $\mathcal{L}$ is the set of Agricultural land use classes (Equation 1)

In Equation 548, the brackets indicate that $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}$ is an indexed element of the matrix $\mathbf{DAAC}^{\mathrm{AG}}$. The subscripts ℓ and r specify that $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}$ refers to the element corresponding to land use type ℓ and cell r. Thus, the brackets emphasize that we are referencing an individual position or allocation within a structured 2D matrix.

Initially each element in $\mathbf{DAAC}^{\mathrm{AG}}$ is set to zero, as follows:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	
$\mathbf{DAAC}_{\ell r}^{\mathrm{AG}} = 0_{(N_{lu} \times N_c)}$	Equation 549

The allocation of cells for dryland agricultural use is determined by the Boolean Exclusion Matrix $\mathbf{XCM}_{mr\ell}$, (Equation 244), which updates annually to reflect changes in allowable land use:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \ell \in \mathcal{L}$	
$\mathbf{DAAC}_{\ell r}^{\mathrm{AG}} = \begin{cases} \mathrm{GurobiVar}_{r\ell}^{AG}\left(\mathbf{UBA}_{\ell}^{\mathrm{AG}}, VarName\right), & \text{if} \quad \mathbf{XCM}_{mr\ell} = 1 \\ 0, & \text{if} \quad \mathbf{XCM}_{mr\ell} = 0 \end{cases}$	Equation 550

where,

- $\mathrm{GurobiVar}_{r\ell}^{AG}$ is the Gurobi decision variable created with an upper bound $\mathbf{UBA}_{\ell}^{\mathrm{AG}} = 1$, representing that the allocation for dryland use in cell r under agricultural land use ℓ is possible,
- $\mathbf{XCM}_{mr\ell}$ is the Boolean Exclusion Matrix, where a value of 1 indicates that cell r is allowed for a specific change in land use or management practices across the landscape,
- $VarName$ is the generated variable name, constructed using the variable's name, the land use ℓ, and the cell ID r.

24.3.2.1.2. Irrigation land Agriculture

Define the variable $\mathbf{IAAC}_{r\ell}^{\mathrm{AG}}$ that represents the allocation of cells specifically for irrigation agricultural use (corresponding to X_ag_irr_vars_jr), as follow:

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$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	
$\mathbf{IAAC}^{\mathrm{AG}} = \left[\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}\right] \in \mathbb{R}^{N_{lu} \times N_c}$	Equation 551

where,

- N_c represents the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$,
- N_{lu} represents the number of agricultural land-use classes ($\mathcal{L}$),
- $\mathbb{R}^{N_{lu} \times N_c}$ is the space of matrices with N_{lu} rows and N_c columns where each entry is a real number,
- $\mathcal{L}$ is the set of the agricultural land use classes (Equation 1).

In Equation 551, the brackets indicate that $\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}$ is an indexed element of the matrix $\mathbf{IAAC}^{\mathrm{AG}}$. The subscripts ℓ and r specify that $\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}$ refers to the element corresponding to land use type ℓ and cell r. Thus, the brackets emphasize that we are referencing an individual position or allocation within a structured 2D matrix.

Initially each element in $\mathbf{IAAC}^{\mathrm{AG}}$ is set to zero, as follows:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}$	
$\mathbf{IAAC}_{\ell r}^{\mathrm{AG}} = 0_{(N_{lu} \times N_c)}$	Equation 552

The allocation of cell for irrigation agricultural use is determined by the Boolean Exclusion Matrix $\mathbf{XCM}_{mr\ell}$, (Equation 244), which updates annually to reflect changes in allowable land use:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \mathcal{L}$	
$\mathbf{IAAC}_{\ell r}^{\mathrm{AG}} = \begin{cases} \mathrm{GurobiVar}_{r\ell}^{AG}\left(\mathbf{UBA}_{\ell}^{\mathrm{AG}}, VarName\right), & \text{if} \quad \mathbf{XCM}_{mr\ell} = 1 \\ 0, & \text{if} \quad \mathbf{XCM}_{mr\ell} = 0 \end{cases}$	Equation 553

where,

- $\mathrm{GurobiVar}_{r\ell}^{AG}$ is a Gurobi variable created with an upper bound $\mathbf{UBA}_{\ell}^{\mathrm{AG}} = \mathbf{1}$, representing the eligible allocation for irrigation land use in cell r under agricultural land use ℓ
- $\mathbf{XCM}_{mr\ell}$ is the Boolean Exclusion Matrix, where a value of 1 indicates that cell r is allowed for a specific change in land use or management practices across the landscape
- $VarName$ is the generated variable name, which consists of the variable's name, the land use ℓ, and the cell ID r.

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24.3.2.2. Non- Agricultural Land use

24.3.2.2.1. Variable Definition

Define the variable $\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}}$, which represents the allocation of cells specifically for non-agricultural land use, as follow:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	
$\mathbf{NAAC}^{\mathrm{NonAG}} = \left[\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}}\right] \in \mathbb{R}^{N_{lu} \times N_c}$	Equation 554

where,

- N_c represents the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$
- N_{lu} represents the number of non-agricultural land-use classes ($\mathcal{L}_{\mathrm{NonAgrLand}}$).
- $\mathbb{R}^{N_{lu} \times N_c}$ is the space of matrices with N_{lu} rows and N_c columns where each entry is a real number ($\mathbb{R}$)
- $\mathcal{L}_{\mathrm{NonAgrLand}}$ is the set of the non-agricultural land use classes (Equation 13)

In Equation 554, the brackets indicate that $\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}}$ is an indexed element of the matrix $\mathbf{NAAC}^{\mathrm{NonAG}}$. The subscripts ℓ and r specify that $\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}}$ refers to the element corresponding to land use type ℓ and cell r, highlighting that we are referencing individual allocations within a structured 2D matrix.

Initially each element in $\mathbf{NAAC}^{\mathrm{NonAG}}$ is set to zero, as follows:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	
$\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}} = 0_{(N_{lu} \times N_c)}$	Equation 555

24.3.2.2.2. Eligible Cells for Non-Agricultural Land Use

To update $\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}}$, the set of eligible cells for each non-agricultural land use type ℓ is determined by the following condition:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	
$\mathbf{EligibleCells}_{\ell}^{\mathrm{NonAG}} = \left\{r \middle| \mathbf{XCM}_{r\ell}^{\mathrm{NonAgToAg}} = 1\right\}$	Equation 556

- $\mathbf{XCM}_{r\ell}^{\mathrm{NonAgToAg}}$ is the aggregated transition cost matrix from all non-agricultural land use (Equation 545)

24.3.2.2.3. Lower Bound Assignment

The lower bound $\mathbf{LBA}_{\ell}^{\mathrm{NonAG}}$ for the allocation variable is determined based on the reversibility of the land use:

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$\forall \ell \in \mathcal{L}_{\text{NonAgrLand}}, r \in \mathbf{EligibleCells}_{\ell}^{\text{NonAG}}$	
$\mathbf{LBA}_{\ell}^{\text{NonAG}} = \begin{cases} 0 & \text{If } RI_{\ell}^{\text{NonAG}} = 1 \\ \mathbf{LB}_{mr\ell}^{\text{NonAG}} & \text{If } RA_{\ell}^{\text{NonAG}} = 0 \end{cases}$	Equation 557

where,

- $\mathbf{LB}_{mr\ell}^{\text{NonAG}}$ represent the lower bound matrices for non-agricultural land use during the current year's optimization (Equation 287)
- RI_{ℓ}^{NonAG} is the Reversibility Indicator for land use type ℓ , determined as:

$\forall \ell \in \mathcal{L}_{\text{NonAgrLand}}, r \in \mathbf{EligibleCells}_{\ell}^{\text{NonAG}}$	
$RI_{\ell}^{\text{NonAG}} = \begin{cases} 1 & \text{If } \ell \text{ is reversible} \\ 0 & \text{Otherwise} \end{cases}$	Equation 558

Note: In LUTO 2.0, none of the land use classes in $\mathcal{L}_{\text{NonAgrLand}}$ are considered reversible.

24.3.2.2.4. Upper Bound Assignment

The upper bound $\mathbf{UBA}_{\ell}^{\text{NonAG}}$ for the allocation variable is given by:

$\forall \ell \in \mathcal{L}_{\text{NonAgrLand}}, r \in \mathbf{EligibleCells}_{\ell}^{\text{NonAG}}$	
$\mathbf{UBA}_{r\ell}^{\text{NonAG}} = \mathbf{XCM}_{r\ell}^{\text{NonAgToAg}}$	Equation 559

Then, the computed $\mathbf{LBA}_{\ell}^{\text{NonAG}}$ (Equation 557) and $\mathbf{UBA}_{r\ell}^{\text{NonAG}}$ (Equation 559) are used as input parameters for $\text{GurobiVar}_{r\ell}^{AG}$ to update the values of $\mathbf{NAAC}_{\ell r}^{\text{NonAG}}$, as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	
$\mathbf{NAAC}_{\ell r}^{\text{NonAG}} = \begin{cases} \text{GurobiVar}_{r\ell}^{\text{NonAG}}\left(\mathbf{LBA}_{\ell}^{\text{NonAG}}, \mathbf{UBA}_{r\ell}^{\text{NonAG}}, VarName\right), & \text{if } r \in \mathbf{EligibleCells}_{\ell}^{\text{NonAG}} \\ 0, & \text{otherwise} \end{cases}$	Equation 560

where,

- $\text{GurobiVar}_{r\ell}^{\text{NonAG}}$ is a Gurobi variable created with the lower bound $\mathbf{LBA}_{\ell}^{\text{NonAG}}$, and the upper bound $\mathbf{UBA}_{r\ell}^{\text{NonAG}}$, and a unique name generated using ℓ and r
- $\mathbf{LBA}_{\ell}^{\text{NonAG}}$ represents the lower bound assignment (Equation 557)
- $\mathbf{UBA}_{r\ell}^{\text{NonAG}}$ represents the upper bound assignment (Equation 559)
- $\mathbf{EligibleCells}_{\ell}^{\text{NonAG}}$ represents the set of eligible cells for non-agricultural land use (Equation 556)

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- $VarName$ is the generated variable name, consisting of the variable's type, the land use ℓ, and the cell ID r.

24.4. Land Use Allocation Variables for Agricultural Management Practices

This section allocates decision variables to agricultural management practices (Equation 22), which offer specific management options for agricultural land. By including these variables, the model can evaluate and optimize the adoption of agricultural management practices across eligible land-use cells.

24.4.1. Variable Initialization

To initialize the required variables, consider that a dictionary $\mathcal{D}$ maps keys k to values v, as:

$\mathcal{D} = \{k \rightarrowtail v \mid k \in \mathcal{K}, v \in \mathcal{V}\}$	Equation 561

where,

- $\mathcal{K}$ is the set of all keys
- $\mathcal{V}$ is the set of all possible values corresponding to the keys

Regarding the agricultural management practices,

- $\mathcal{K}$ is the set lists agricultural management practices that can be applied to different land use types (Equation 22).
- As mentioned in Equation 23, there is a rule or mapping ϕ that relates elements from the set of agricultural management practices (the domain $\mathcal{K}$) to the set of land uses $\mathcal{L}$ (Equation 1) that are relevant or applicable to that practice.
- The practices related to each agricultural management practices are mentioned in Equation 24-Equation 32.

24.4.2. Dryland Agricultural Management Practices Variables Initialization

Define the variable $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}$, which represents a dictionary of agricultural management practice variables for land designated as dryland agriculture, denoted by $\mathbf{DAMC}_{kr}^{\text{AGMP}}$. It is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}\ \exists k \mid k \in \mathcal{K}$	Equation 562
$\mathcal{X}_{\text{Dry}}^{\text{AGMP}} = \left\{k \rightarrowtail \mathbf{DAMC}_{kr}^{\text{AGMP}} \mid r \in \{1, \dots, N_r\}, k \in \mathcal{K}, \mathbf{DAMC}_{kr}^{\text{AGMP}} \in \mathbb{R}^{N_{lu}^k \times N_c}\right\}$	

where,

- $\mathcal{K}$ is the set of agricultural management practices that can be applied to different land use types (Equation 22)
- $\mathbb{R}^{N_{lu}^k \times N_c}$ is the space of matrix with N_{lu}^k rows and N_c columns, where each entry is a real number ($\mathbb{R}$)
- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$

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- N_{lu}^{k} represents the number of land-use types associated with each agricultural management practice $\mathcal{K}$ (see Equation 24-Equation 32)

24.4.2.1. Lower Bound Assignment

The lower bound $\mathbf{LBA}_k^{\text{AGMP}}$ for the allocation variable is determined based on whether the agricultural management practice k is reversible:

$\forall k \in \mathcal{K}, m \in \{0\}$	
$\mathbf{LBA}_k^{\text{AGMP}} = \begin{cases} 0 & \text{If } RI_k^{\text{AGMP}} = 1 \\ \mathbf{LB}_{mr\ell}^{\text{AGMP}} & \text{If } RA_k^{\text{AGMP}} = 0 \end{cases}$	Equation 563

where

- $\mathbf{LB}_{mr\ell}^{\text{AGMP}}$ represents the lower bound matrices for agricultural land use during the current year's optimization (Equation 287).
- RI_k^{AGMP} is the Reversibility Indicator for the agricultural management practice type k.

The reversibility indicator is defined as:

$\forall k \in \mathcal{K}$	
$RI_k^{\text{AGMP}} = \begin{cases} 1 & \text{If } k \text{ is reversible} \\ 0 & \text{Otherwise} \end{cases}$	Equation 564

At the current version of LUTO 2.0, all the agricultural management practices included in $\mathcal{K}$ are considered reversible.

24.4.2.2. Upper Bound Assignment

The upper bound $\mathbf{UBA}_k^{\text{AGMP}}$ for the allocation variable is defined simply as:

$\forall k \in \mathcal{K}$	
$\mathbf{UBA}_k^{\text{AGMP}} = 1$	Equation 565

24.4.2.3. Updating the values of $\mathcal{X}_{Dry}^{AGMP}$

Then, the computed $\mathbf{LBA}_k^{\text{AGMP}}$ (Equation 563) and $\mathbf{UBA}_k^{\text{AGMP}}$ (Equation 565) are used as the input parameters of $\text{GurobiVar}_{rk}^{AG}$ to update the values of $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}$, as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, k \in \mathcal{K}$	
$\mathcal{X}_{\text{Dry}}^{\text{AGMP}} = \left\{k \rightarrowtail \text{GurobiVar}_{rk}^{AG}\left(\mathbf{LBA}_k^{\text{AGMP}}, \mathbf{UBA}_{rk}^{\text{AGMP}}, VarName\right)\right\}$	Equation 566

where,

- $\text{GurobiVar}_{rk}^{AG}$ is the Gurobi variable created with the lower bound $\mathbf{LBA}_{k}^{\text{AGMP}}$, upper bound $\mathbf{UBA}_{rk}^{\text{AGMP}}$, and a unique name.
- $VarName$ is the generated variable name, which consists of the variable's name, the land use ℓ, and the cell ID r.

24.4.3. Irrigation Agricultural Management Practices Variables Initialization

Define the variable $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}$, which represents a dictionary of agricultural management practice variables for land designated as irrigation $\mathbf{IAMC}_{kr}^{\text{AGMP}}$. It is defined as:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}\ \exists k\ , k \in \mathcal{K}$	Equation 567
$\mathcal{X}_{\text{Irr}}^{\text{AGMP}} = \left\{ k \rightarrowtail \mathbf{IAMC}_{kr}^{\text{AGMP}} \middle\vert r \in \{1, \dots, N_r\}, k \in \mathcal{K}, \mathbf{DAMC}_{kr}^{\text{AGMP}} \in \mathbb{R}^{N_{lu}^{k} \times N_c} \right\}$	

where,

- $\mathcal{K}$ is the set lists agricultural management practices that can be applied to different land use types (Equation 22).
- $\mathbb{R}^{N_{lu}^{k} \times N_c}$ is the space of matrix with N_{lu}^{k} rows and N_c columns, where each entry is a real number ($\mathbb{R}$).
- N_c represents the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_{lu}^{k} represents the number of land-use classes associated with each agricultural management practice $\mathcal{K}$ (as defined in Equation 24-Equation 32)

24.4.3.1. Lower Bound Assignment

The lower bound $\mathbf{LBA}_{k}^{\text{AGMP}}$ for the allocation variable is determined based on whether the land use is reversible:

$\forall k \in \mathcal{K}, m \in \{1\}$	
$\mathbf{LBA}_{k}^{\text{AGMP}} = \begin{cases} 0 & \text{If } RI_{k}^{\text{AGMP}} = 1 \\ \mathbf{LB}_{mr\ell}^{\text{AGMP}} & \text{If } RA_{k}^{\text{AGMP}} = 0 \end{cases}$	Equation 568

where

- $\mathbf{LB}_{mr\ell}^{\text{AGMP}}$ represent the lower bound matrices for agricultural land use during the current year's optimization (Equation 287)
- RI_{k}^{AGMP} represent the Reversibility Indicator for the agricultural management practice type k (see Equation 564)

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24.4.3.2. *Updating the values of $\mathcal{X}_{Irr}^{AGMP}$*

The computed $\mathbf{LBA}_k^{\mathrm{AGMP}}$ (Equation 568) and $\mathbf{UBA}_k^{\mathrm{AGMP}}$ (Equation 565) are used as input parameters of $\mathrm{GurobiVar}_{rk}^{AG}$ to update the values of $\mathcal{X}_{\mathrm{Irr}}^{\mathrm{AGMP}}$, as:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, k \in \mathcal{K}$	
$\mathcal{X}_{\mathrm{Irr}}^{\mathrm{AGMP}} = \{k \rightarrowtail \mathrm{GurobiVar}_{rk}^{AG}(\mathbf{LBA}_k^{\mathrm{AGMP}}, \mathbf{UBA}_{rk}^{\mathrm{AGMP}}, VarName)\}$	Equation 569

where,

- $\mathrm{GurobiVar}_{rk}^{AG}$ is the Gurobi variable created with the lower bound $\mathbf{LBA}_k^{\mathrm{AGMP}}$, upper bound $\mathbf{UBA}_{rk}^{\mathrm{AGMP}}$, and a unique variable name.
- $\mathbf{LBA}_k^{\mathrm{AGMP}}$ represents the lower bound assignment (Equation 568).
- $\mathbf{UBA}_{rk}^{\mathrm{AGMP}}$ represents the upper bound assignment (Equation 565).
- $VarName$ is the generated variable name, composed of the variable's type, the land use ℓ, and the cell ID r.

24.5. **Object Function Formulation**

The objective function in the LUTO solver is dynamically formulated based on the specified settings and model objectives. It integrates agricultural and non-agricultural land-use components, along with alternative management options and demand constraints.

24.5.1. Objective Setting

The objective can be configured as either:

- Maximizing Profit
- Minimizing Cost

The Maximizing Profit objective function maximizes the net revenue by subtracting production and transition costs from the generated revenue.
The Minimizing Cost objective function minimizes total production and transition costs, without explicitly considering revenue.

24.5.2. Maximising Profit

As LUTO 2.0 considers agricultural classes, non-agricultural classes, and agricultural management practices, for each, a specific profit calculation objective function is defined.

24.5.2.1. *Net Profit Calculation for Agricultural Land Use*

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	

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$\mathbf{NetProfit}^{AG}(y) = -\dfrac{\mathbf{Revenue}_{mr\ell}(y) - \left(\mathbf{Cost}_{mr\ell}(y) + \mathbf{TotTranMatC}^{AG}_{mr\ell}(y) + \mathbf{TCM}^{\mathrm{NonAgToAg}}_{mr\ell}(y)\right)}{Penalty}$	Equation 570

where,

- $\mathbf{Revenue}_{mr\ell}(y)$ represents the revenue matrix that contains both crops and livestock revenue (Equation 216)
- $\mathbf{Cost}_{mr\ell}(y)$ represents the total cost matrix (Equation 62)
- $\mathbf{TotTranMatC}^{AG}_{mr\ell}(y)$ represents the total transition cost for agricultural land uses (Equation 280)
- $\mathbf{TCM}^{\mathrm{NonAgToAg}}_{mr\ell}(y)$ represents the total transition costs from non-agricultural to agricultural land uses (Equation 524)
- $Penalty$ is a scaling factor used to balance the influence of demand versus cost when the demand constraint type (DCT) is set to "Soft" ($Penalty = 10^5$)

The NaN values of $\mathbf{NetProfit}^{AG}(y)$ must be replaced by 0, as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 571
$\mathbf{NetProfit}^{AG}_{mr\ell}(y) = \begin{cases} 0 & \text{If} \quad \mathbf{NetProfit}^{AG}_{mr\ell}(y) = \mathrm{NaN} \\ \mathbf{NetProfit}^{AG}_{mr\ell}(y) & \text{Otherwise} \end{cases}$	

24.5.2.2. Net Profit Calculation for Non-Agricultural Land Use

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	Equation 572
$\mathbf{NetProfit}^{NonAg}(y) = -\dfrac{\mathbf{Rev}^{NonAg}_{r\ell}(y) - \left(\mathbf{NACM}^{NonAg}_{r\ell}(y) + \mathbf{TotTCM}^{\mathrm{NonAG}}_{r\ell} + \mathbf{TCM}^{\mathrm{AgToNonAg}}_{r\ell}(y)\right)}{Penalty}$	

where,

- $\mathbf{Rev}^{NonAg}_{r\ell}(y)$ represents the revenue matrix for each land uses in $\mathcal{L}_{\mathrm{NonAgrLand}}$ (Equation 391)
- $\mathbf{NACM}^{NonAg}_{r\ell}(y)$ represents the cost matrix of all non-agricultural land uses in $\mathcal{L}_{\mathrm{NonAgrLand}}$ (Equation 310)
- $\mathbf{TotTCM}^{\mathrm{NonAG}}_{r\ell}$ represents the transition cost matrix for non-agricultural land uses in $\mathcal{L}_{\mathrm{NonAgrLand}}$ (Equation 527)
- $\mathbf{TCM}^{\mathrm{AgToNonAg}}_{r\ell}(y)$ represents the total transition costs matrix from agricultural land to non-agricultural land uses (Equation 443)
- $Penalty$ is a scaling factor used to balance the influence of demand versus cost when the demand constraint type (DCT) is set to "Soft" ($Penalty = 10^5$)

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Any NaN values of $\mathbf{NetProfit}^{NonAg}(y)$ must be replaced with 0, as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 573
$\mathbf{NetProfit}_{r\ell}^{NonAg}(y) = \begin{cases} 0 & \text{If} \quad \mathbf{NetProfit}_{r\ell}^{NonAg}(y) = \text{NaN} \\ \mathbf{NetProfit}_{r\ell}^{NonAg}(y) & \text{Otherwise} \end{cases}$	

24.5.2.3. Net Profit Calculation for Agricultural Management Practices

For agricultural management practices:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 574
$\mathbf{Revenue}_k^{\text{AGMP}}(y) \longrightarrow \mathbf{Revenue}_{mr\ell}^{\text{AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathbf{Cost}_k^{\text{AGMP}}(y) \longrightarrow \mathbf{Cost}_{mr\ell}^{\text{AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathbf{TranMatC}_k^{\text{AGMP}}(y) \longrightarrow \mathbf{TranMatC}_{mr\ell}^{\text{AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathbf{NetProfit}_k^{\text{AGMP}}(y) = \left\{ k \rightarrowtail -\frac{\mathbf{Revenue}_{mr\ell}^{\text{AGMP}}(y) - \left(\mathbf{Cost}_{mr\ell}^{\text{AGMP}}(y) + \mathbf{TranMatC}_{mr\ell}^{\text{AGMP}}(y)\right)}{Penalty} \middle\vert k \in \mathcal{K} \right\}$	

where,

- $\mathbf{Revenue}_k^{\text{AGMP}}(y)$ represents a dictionary where each key $k \in \mathcal{K}$ maps to a 3D matrix of the revenue for agricultural management practice variables ($\mathbf{Revenue}_{mr\ell}^{\text{AGMP}}$) (Equation 228)
- $\mathbf{Cost}_k^{\text{AGMP}}(y)$ represents a dictionary where each key $k \in \mathcal{K}$ maps to a 3D matrix of the total cost for agricultural management practice variables ($\mathbf{Cost}_{mr\ell}^{\text{AGMP}}$) (Equation 74)
- $\mathbf{TranMatC}_k^{\text{AGMP}}(y)$ represents a dictionary where each key $k \in \mathcal{K}$ maps to a 3D matrix of the total transition costs of agricultural management practice variables ($\mathbf{TranMatC}_{mr\ell}^{\text{AGMP}}$) (Equation 289)
- $Penalty$ is a scaling factor used to balance the influence of demand versus cost when the demand constraint type (DCT) is "Soft" ($Penalty = 10^5$)

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24.5.2.4. The total contribution of production and transition costs for all agricultural land uses

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \ell \in \mathcal{L}$	Equation 575
$\mathbf{NetProfit}_{r\ell}^{Dry,AG}(y) = \begin{cases} \mathbf{NetProfit}_{mr\ell}^{AG}(y) & \text{If} \quad \mathrm{m} = 0 \wedge \mathbf{BLuLmM}_{0,r,\ell_r} = \text{True} \\ \mathbf{0} & \text{otherwise} \end{cases}$	
$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \mathcal{L}$	Equation 576
$\mathbf{NetProfit}_{r\ell}^{Irr,AG}(y) = \begin{cases} \mathbf{NetProfit}_{mr\ell}^{AG}(y) & \text{If} \quad \mathrm{m} = 1 \wedge \mathbf{BLuLmM}_{1,r,\ell_r} = \text{True} \\ \mathbf{0} & \text{otherwise} \end{cases}$	
$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 577
$\mathbf{ObjContrProfit}_{r\ell}^{AG}(y) = \sum_{\ell \in \mathcal{L}} \left[\left(\mathbf{NetProfit}_{r\ell}^{Dry,AG}(y) \times \mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)^T \right) + \left(\mathbf{NetProfit}_{r\ell}^{Irr,AG}(y) \times \mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)^T \right) \right]$	

where,

- $\mathbf{NetProfit}_{mr\ell}^{AG}(y)$ is the net profit calculation for agricultural land use (Equation 571),
- $\mathbf{BLuLmM}_{0,r,\ell_r}$ is the Boolean tensor representing the land-use under dryland management system (Equation 234),
- $\mathbf{BLuLmM}_{1,r,\ell_r}$ is the Boolean tensor representing the land-use under irrigation land management system (Equation 235),
- $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)$ is the decision variable matrix for dryland agricultural practices (Equation 550),
- $\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)$ is the decision variable matrix for irrigation agricultural practices (Equation 553),
- $\mathbf{ObjContr}_{r\ell}^{AG}(y)$ represents the total contribution of production and transition costs for all agricultural land uses $\mathcal{L}$ in the objective function,
- T denotes the transpose operator.

24.5.2.5. The Total Contribution of Production and Transition Costs for all Agricultural Management Practices

Let $\mathcal{K}$ be the set of keys in the dictionary $\mathbf{NetProfit}_k^{\mathrm{AGMP}}$ (Equation 574). Each $k \in \mathcal{K}$ maps to a 3D matrix, denote as

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 578
$\mathbf{NetProfit}_k^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{NetProfit}_{mr\ell}^{\mathrm{AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathcal{X}_{\mathrm{Dry}}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	

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$\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathbf{NetProfit}_{r\ell}^{Dry,\text{AGMP}}(y) = \begin{cases} \mathbf{NetProfit}_{mr\ell}^{\text{AGMP}}(y) & \text{If} \quad m = 0 \ \wedge \ \mathbf{BLuLmM}_{0,r,\ell_r} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	
$\mathbf{NetProfit}_{r\ell}^{Irr,\text{AGMP}}(y) = \begin{cases} \mathbf{NetProfit}_{mr\ell}^{\text{AGMP}} & \text{If} \quad m = 1 \ \wedge \ \mathbf{BLuLmM}_{1,r,\ell_r} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	
$\mathbf{ObjContrProfit}_{k}^{\text{AGMP}}(y) = \left\{ k \longmapsto \left[\sum_{\ell \in \phi(k)} \left[\left(\mathbf{NetProfit}_{r\ell}^{Dry,AG}(y) \times \mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y)^T \right) + \left(\mathbf{NetProfit}_{r\ell}^{Irr,AG}(y) \times \mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y)^T \right) \right] \right] \middle| k \in \mathcal{K}, \ell \in \phi(k) \right\}$	

where,

- $\mathbf{NetProfit}_{mr\ell}(y)$ the extracted 3D matrix of net profits for agricultural management practice variables associated with each k , $k \in \mathcal{K}$
- $\mathbf{BLuLmM}_{0,r,\ell_r}$ is the Boolean tensor indicating dryland management land use (Equation 234).
- $\mathbf{BLuLmM}_{1,r,\ell_r}$ is the dictionary of dryland agricultural management practice decision variables (Equation 234).
- $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(y)$ is the dictionary of irrigation agricultural management practice decision variables (Equation 569).
- $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(y)$ is a dictionary of the irrigation agricultural management practices variables (Equation 567).
- $\phi(k)$ defines the mapping from management practices to the set of associated land use classes.
- $\mathbf{ObjContrProfit}_{k}^{\text{AGMP}}(y)$ represents the total contribution to the objective function from all agricultural management practices.
- $\mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y)$ represents the extracted matrix of dryland agricultural management practice decision variables associated with key k , $k \in \mathcal{K}$.
- $\mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y)$ represents the extracted matrix of irrigation agricultural management practice decision variables associated with key k , $k \in \mathcal{K}$.
- T denotes the transpose operation.

24.5.2.6. The Total Contribution of Production and Transition Costs for All Non-Agricultural Land Uses

For all cells $r \in \{1, \dots, N_r\}$ and non-agricultural land uses $\ell \in \mathcal{L}_{\text{NonAgrLand}}$:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 579
$\mathbf{ObjContrProfit}_{\ell}^{\text{NonAg}}(y) = \begin{cases} \sum_{\ell \in \mathcal{L}_{\text{NonAgrLand}}} \mathbf{NetProfit}_{r\ell}^{NonAg}(y) \times \mathbf{NAAC}_{r\ell}^{NonAg} & \textit{if} \quad \mathbf{BLuLmM}_{mr\ell}^{NOT} = True \\ \mathbf{0} & \textit{otherwise} \end{cases}$	

where,

- $\mathbf{NetProfit}_{r\ell}^{NonAg}(y)$ is the net profit calculation for non-agricultural land use (Equation 573)
- $\mathbf{NAAC}_{r\ell}^{\text{NonAG}}$ represents the allocation of cells specifically for non-agricultural land use (Equation 560)
- $\mathbf{BLuLmM}_{mr\ell}^{\text{NOT}}$ is the Boolean tensor indicating whether the cell is designated as non-agricultural land use (Equation 235)
- $\mathcal{L}_{\text{NonAgrLand}}$ is the set of the non-agricultural land use classes (Equation 13)

24.5.2.7. Objective Function for the Soft Demand Constraint Type

If the demand constraint type is set to "soft," the objective function is calculated by combining several components, as:

$\mathbf{ObjectiveProfit}^{Soft} = \mathbf{ObjContrProfit}_{r\ell}^{AG}(y) + \mathbf{ObjContrProfit}_{k}^{\text{AGMP}}(y) + \mathbf{ObjContrProfit}_{\ell}^{\text{NonAg}}(y) + \sum_{c=1}^{ncms} \mathbf{V}[c]$	Equation 580

where,

- $\mathbf{ObjContrProfit}_{r\ell}^{AG}(y)$ represents the total contribution of production and transition costs for all agricultural land uses (Equation 575)
- $\mathbf{ObjContrProfit}_{k}^{\text{AGMP}}(y)$ represents the total contribution of production and transition costs for all agricultural management practices (Equation 578)
- $\mathbf{ObjContrProfit}_{\ell}^{\text{NonAg}}(y)$ represents the total contribution of production and transition costs for all non-agricultural land uses (Equation 579)
- $\mathbf{V}$ represents a vector of decision variables related to commodity demand adjustments (Equation 581)

Here, $\mathbf{V}$ is a vector of decision variables, where each element $\mathbf{V}[c]$ corresponds to the decision variable associated with commodity c, with $c \in \{1,2,\cdots,ncms\}$, where $ncms$ denotes the number of commodities considered in the model. Mathematically, the vector $\mathbf{V}$ is expressed as:

$\mathbf{V} = [\boldsymbol{V}[0], \boldsymbol{V}[1], \cdots, \boldsymbol{V}[ncms]]$	Equation 581

Where $\mathbf{V}[c]$ represents the decision variable corresponding to commodity c. These decision variables are used to model the deviation from demand for each commodity under the soft demand constraint.

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24.5.2.8. Objective Function for the Hard Demand Constraint Type

If the demand constraint type is set to "hard," the objective function is calculated by combining several components, as:

$\mathbf{ObjectiveProfit}^{\text{Hard}} = \mathbf{ObjContrProfit}_{r\ell}^{AG}(y) + \mathbf{ObjContrProfit}_{k}^{\text{AGMP}}(y) + \mathbf{ObjContrProfit}_{\ell}^{\text{NonAg}}(y)$	Equation 582

where,

- $\mathbf{ObjContrProfit}_{r\ell}^{AG}(y)$ represents the total contribution of production and transition costs for all agricultural land uses (Equation 575)
- $\mathbf{ObjContrProfit}_{k}^{\text{AGMP}}(y)$ represents the total contribution of production and transition costs for all agricultural management practices (Equation 578)
- $\mathbf{ObjContrProfit}_{\ell}^{\text{NonAg}}(y)$ represents the total contribution of production and transition costs for all non-agricultural land uses (Equation 579)

24.5.2.9. General Form of the Objective Function

The computed $\mathbf{ObjectiveProfit}^{\text{Soft}}$ (Equation 584) and $\mathbf{ObjectiveProfit}^{\text{Hard}}$ (Equation 586) are employed to calculate $\mathbf{ObjectiveFunction}$, as:

$\mathbf{ObjectiveFunction} = \begin{cases} \mathbf{ObjectiveProfit}^{\text{Soft}} & \text{if} \quad \text{Demad Constraint Type is "soft"} \\ \mathbf{ObjectiveProfit}^{\text{Hard}} & \text{if} \quad \text{Demad Constraint Type is "hard"} \end{cases}$	Equation 583

24.5.3. Minimizing Cost

As LUTO 2.0 considers the agricultural classes, non-agricultural classes, and agricultural management practices, a specific cost calculation objective function is defined for each of them, as follows:

24.5.3.1. Net Cost Calculation for Agricultural Land Use

$\mathbf{NetCost}^{AG}(y) = \dfrac{\mathbf{Cost}_{mr\ell}(y) + \mathbf{TotTranMatC}_{mr\ell}^{AG}(y) + \mathbf{TCM}_{mr\ell}^{\text{NonAgToAg}}(y)}{Penalty}$	Equation 584

where,

- $\mathbf{Cost}_{mr\ell}(y)$ represents the total cost matrix (Equation 62)
- $\mathbf{TotTranMatC}_{mr\ell}^{AG}(y)$ represents the total transition cost for agricultural land uses (Equation 280)
- $\mathbf{TCM}_{mr\ell}^{\text{NonAgToAg}}(y)$ represents the total transition costs from non-agricultural to agricultural land uses (Equation 524)
- $Penalty$ is a balancing factor to control the influence of demand versus cost when the Demand Constraint Type (DCT) is Soft; it is set to 10^5 ($Penalty = 10^5$)

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If the calculated net cost $\mathbf{NetCost}^{AG}(y)$ contains NaN values, they must be replaced with zero, as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 585
$\mathbf{NetCost}_{mr\ell}^{AG}(y) = \begin{cases} 0 & \text{If} \quad \mathbf{NetCost}_{mr\ell}^{AG}(y) = \text{NaN} \\ \mathbf{NetCost}_{mr\ell}^{AG}(y) & \text{Otherwise} \end{cases}$	

24.5.3.2. Net Cost Calculation for Non-Agricultural Land Use

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	
$\mathbf{NetCost}^{\text{NonAg}}(y) = \dfrac{\mathbf{NACM}_{r\ell}^{\text{NonAg}}(y) + \mathbf{TotTCM}_{r\ell}^{\text{NonAG}} + \mathbf{TCM}_{r\ell}^{\text{AgToNonAg}}(y)}{Penalty}$	Equation 586

where,

- $\mathbf{NACM}_{r\ell}^{\text{NonAg}}(y)$ represents the cost matrix of all non-agricultural land uses in $\mathcal{L}_{\text{NonAgrLand}}$ (Equation 310)
- $\mathbf{TotTCM}_{r\ell}^{\text{NonAG}}$ represents the transition cost matrix for non-agricultural land uses in $\mathcal{L}_{\text{NonAgrLand}}$ (Equation 527)
- $\mathbf{TCM}_{r\ell}^{\text{AgToNonAg}}(y)$ represents the total transition costs matrix from agricultural land to non-agricultural land uses (Equation 443)
- $Penalty$ is used to balance influence of demand versus cost when the demand constraint type (DCT) is "Soft" ($Penalty = 10^5$)

If the calculated net cost $\mathbf{NetCost}^{\text{NonAg}}(y)$ contains NaN values, they must be replaced with zero:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 587
$\mathbf{NetCost}_{r\ell}^{\text{NonAg}}(y) = \begin{cases} 0 & \text{If} \quad \mathbf{NetCost}_{r\ell}^{NonAg}(y) = \text{NaN} \\ \mathbf{NetCost}_{r\ell}^{\text{NonAg}}(y) & \text{Otherwise} \end{cases}$	

24.5.3.3. Net Cost Calculation for Agricultural Management Practices

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 588
$\mathbf{Cost}_k^{\text{AGMP}}(y) \longrightarrow \mathbf{Cost}_{mr\ell}^{\text{AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathbf{TranMatC}_k^{\text{AGMP}}(y) \longrightarrow \mathbf{TranMatC}_{mr\ell}^{\text{AGMP}}(y), \qquad \forall k \in \mathcal{K}$	

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$$\mathbf{NetCost}_k^{\mathrm{AGMP}}(y) = \left\{ k \rightarrowtail \frac{\mathbf{Cost}_{mr\ell}^{\mathrm{AGMP}}(y) + \mathbf{TranMatC}_{mr\ell}^{\mathrm{AGMP}}(y)}{Penalty} \mid k \in \mathcal{K} \right\}$$	

where,

- $\mathbf{Cost}_k^{\mathrm{AGMP}}(y)$ is a dictionary where each key $k \in \mathcal{K}$ maps to a 3D matrix of the total cost matrix of agricultural management practice ($\mathbf{Cost}_{mr\ell}^{\mathrm{AGMP}}$) variables (Equation 74)
- $\mathbf{TranMatC}_k^{\mathrm{AGMP}}(y)$ is a dictionary where each key $k \in \mathcal{K}$ maps to a 3D matrix of the total transition costs for agricultural management practice ($\mathbf{TranMatC}_{mr\ell}^{\mathrm{AGMP}}$) variables (Equation 289)
- $Penalty$ is again applied to balance the demand and cost emphasis under the soft constraint type "Soft" ($Penalty = 10^5$)

24.5.3.4. The Total Contribution of Production and Transition Costs for All Agricultural Land Uses

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 589
$\mathbf{NetCost}_{r\ell}^{Dry,AG}(y) = \begin{cases} \mathbf{NetCost}_{mr\ell}^{AG}(y) & \text{If} \quad \mathrm{m} = 0 \wedge \mathbf{BLuLmM}_{0,r,\ell_r} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	
$\mathbf{NetCost}_{r\ell}^{Irr,AG}(y) = \begin{cases} \mathbf{NetCost}_{mr\ell}^{AG}(y) & \text{If} \quad \mathrm{m} = 1 \wedge \mathbf{BLuLmM}_{1,r,\ell_r} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	
$\mathbf{ObjContrCost}_{r\ell}^{AG}(y) = \sum_{\ell \in \mathcal{L}} \left[\left(\mathbf{NetCost}_{r\ell}^{Dry,AG}(y) \times \mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)^T \right) + \left(\mathbf{NetCost}_{r\ell}^{Irr,AG}(y) \times \mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)^T \right) \right]$	

where,

- $\mathbf{NetCost}_{mr\ell}^{AG}(y)$ is the net cost calculation for agricultural land use (Equation 585)
- $\mathbf{BLuLmM}_{0,r,\ell_r}$ is the Boolean tensor representing dryland management system allocations (Equation 234)
- $\mathbf{BLuLmM}_{1,r,\ell_r}$ is the Boolean tensor representing irrigation land management system allocations (Equation 235)
- $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)$ is the dryland agricultural allocation variable (Equation 550)
- $\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)$ is the irrigation agricultural allocation variable (Equation 553)
- $\mathbf{ObjContr}_{r\ell}^{AG}(y)$ represents the total contribution of production and transition costs for all agricultural land uses $\mathcal{L}$ in the objective function.
- T denotes the transpose

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24.5.3.5. The Total Contribution of Production and Transition Costs for All Agricultural Management Practices

Let $\mathcal{K}$ be the set of keys in the dictionary $\mathbf{NetCost}_k^{\text{AGMP}}$ (Equation 588). Each $k \in \mathcal{K}$ maps to a 3D matrix, denoted as

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 590
$\mathbf{NetCost}_k^{\text{AGMP}}(y) \longrightarrow \mathbf{NetCost}_{mr\ell}^{\text{AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathbf{NetCost}_{r\ell}^{Dry,\text{AGMP}}(y) = \begin{cases} \mathbf{NetCost}_{mr\ell}^{\text{AGMP}}(y) & \text{If} \quad \text{m} = 0 \ \wedge \ \mathbf{BLuLmM}_{0,r,\ell_r} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	
$\mathbf{NetCost}_{r\ell}^{Irr,\text{AGMP}}(y) = \begin{cases} \mathbf{NetCost}_{mr\ell}^{\text{AGMP}} & \text{If} \quad \text{m} = 1 \ \wedge \ \mathbf{BLuLmM}_{1,r,\ell_r} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	
$\mathbf{ObjContrCost}_k^{\text{AGMP}}(y) = \left\{ k \longmapsto \left[\sum_{\ell \in \phi(k)} \left[\left(\mathbf{NetCost}_{r\ell}^{Dry,AG}(y) \times \mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y)^T \right) + \left(\text{NetCost}_{r\ell}^{Irr,AG}(y) \times \mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y)^T \right) \right] \right] \middle| k \in \mathcal{K}, \ell \in \phi(k) \right\}$	

where,

- $\mathbf{NetCost}_k^{\text{AGMP}}(y)$ is the extracted 3D matrix of net costs for agricultural management practices associated with key k , $k \in \mathcal{K}$.
- $\mathbf{BLuLmM}_{0,r,\ell_r}$ is the Boolean tensor representing dry land management system allocations (Equation 234)
- $\mathbf{BLuLmM}_{1,r,\ell_r}$ is the Boolean tensor representing irrigation land management system allocations (Equation 234)
- $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(y)$ is the dictionary of dryland agricultural management practices (Equation 569)
- $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(y)$ is the dictionary of irrigation agricultural management practices (Equation 567)
- $\phi(k)$ is a rule or mapping that relates elements from the set of agricultural management practices ($\mathcal{K}$) to the power set of land uses ($\mathcal{L}$).

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- $\mathbf{ObjContrCost}_{k}^{\mathrm{AGMP}}(y)$ represents the total contribution of production and transition costs for each agricultural management practice $\mathcal{K}$ in the objective function.
- $\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y)$ is the dryland agricultural management practice decision variable extracted for k , $k \in \mathcal{K}$
- $\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y)$ is the irrigation agricultural management practice decision variable extracted for k , $k \in \mathcal{K}$
- T denotes the matrix transpose

24.5.3.6. The Total Contribution of Production and Transition Costs for all non-Agricultural Land Uses

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	Equation 591
$\mathbf{ObjContrCost}_{\ell}^{\mathrm{NonAg}}(y) = \begin{cases} \sum_{\ell \in \mathcal{L}_{\mathrm{NonAgrLand}}} \mathbf{NetCost}_{r\ell}^{NonAg}(y) \times \mathbf{NAAC}_{r\ell}^{\mathrm{NonAG}} & \text{if} \quad \mathbf{BLuLmM}_{mr\ell}^{NOT} = \mathrm{True} \\ 0 & \text{otherwise} \end{cases}$	

where,

- $\mathbf{NetCost}_{r\ell}^{\mathrm{NonAg}}(y)$ is the net profit calculation for non-agricultural land use (Equation 588)
- $\mathbf{NAAC}_{r\ell}^{\mathrm{NonAG}}$ represents the allocation of cells specifically for non-agricultural land use (Equation 560)
- $\mathbf{BLuLmM}_{mr\ell}^{\mathrm{NOT}}$ is the Boolean tensor representing the non-agricultural land-use (Equation 235)
- $\mathcal{L}_{\mathrm{NonAgrLand}}$ is a set of the non-Agricultural land use classes (Equation 13)

24.5.3.7. Objective Function for the Soft Demand Constraint Type

If the **demand constraint type** is set to "soft," the objective function is calculated by combining several components, as:

$\mathbf{ObjectiveCost}^{\mathrm{Soft}} = \mathbf{ObjContrCost}_{r\ell}^{AG}(y) + \mathbf{ObjContrCost}_{k}^{\mathrm{AGMP}}(y) + \mathbf{ObjContrCost}_{\ell}^{\mathrm{NonAg}}(y) + \sum_{c=1}^{ncms} \mathbf{V}[c]$	Equation 592

where,

- $\mathbf{ObjContrCost}_{r\ell}^{AG}(y)$ represents the total contribution of production and transition costs for all agricultural land uses (Equation 589)
- $\mathbf{ObjContrCost}_{k}^{\mathrm{AGMP}}(y)$ represents the total contribution of production and transition costs for all agricultural management practices (Equation 590)
- $\mathbf{ObjContrCost}_{\ell}^{\mathrm{NonAg}}(y)$ represents the total contribution of production and transition costs for all non-agricultural land uses (Equation 591)

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- $\mathbf{V}$ represents a vector of decision variables associated with commodities (defined in Equation 581)

Here, $\mathbf{V}$ is a vector of decision variables, where each element $\mathbf{V}[c]$ corresponds to a decision variable for commodity c, with $c \in \{1,2,\cdots,ncms\}$, and $ncms$ being the number of commodities. Mathematically, it can be written as:

$\mathbf{V} = [\boldsymbol{V}[0], \boldsymbol{V}[1], \cdots, \boldsymbol{V}[ncms]]$	Equation 593

Where $\mathbf{V}[c]$ represents the decision variable corresponding to commodity c. These decision variables are used to model the deviation from demand for each commodity under the soft demand constraint.

24.5.3.8. Objective Function for the Hard Demand Constraint Type

If the demand constraint type is set to "hard," the objective function is calculated by combining several components, as:

$\mathbf{ObjectiveCost}^{\text{Hard}} = \mathbf{ObjContrCost}_{r\ell}^{AG}(y) + \mathbf{ObjContrCost}_{k}^{\text{AGMP}}(y) + \mathbf{ObjContrCost}_{\ell}^{\text{NonAg}}(y)$	Equation 594

where,

- $\mathbf{ObjContrCost}_{r\ell}^{AG}(y)$ represents the total contribution of production and transition costs for all agricultural land uses (Equation 589)
- $\mathbf{ObjContrCost}_{k}^{\text{AGMP}}(y)$ represents the total contribution of production and transition costs for all agricultural management practices (Equation 590)
- $\mathbf{ObjContrCost}_{\ell}^{\text{NonAg}}(y)$ represents the total contribution of production and transition costs for all non-agricultural land uses (Equation 591)

24.5.3.9. The General Form of the Objective Function

The computed $\mathbf{ObjectiveCost}^{\text{Soft}}$ (Equation 592) and $\mathbf{ObjectiveCost}^{\text{Hard}}$ (Equation 594) are employed to calculate final Objective $\mathbf{Objective}$, as:

$\mathbf{Objective} = \begin{cases} \mathbf{ObjectiveCost}^{\text{Soft}} & \text{if Demad Constraint Type is "soft"} \\ \mathbf{ObjectiveCost}^{\text{Hard}} & \text{if Demad Constraint Type is "hard"} \end{cases}$	Equation 595

24.6. Introduction to Constraints

Constraints are an integral part of any optimization model, as they define the feasible solution space by enforcing conditions that must be satisfied. In the LUTO 2.0 model, constraints are designed to ensure the proper allocation and utilization of resources, adherence to land-use policies, satisfaction of agricultural demand, and compliance with land management practices.

In the context of land management and agricultural optimization, constraints serve to:

- Enforce resource limits: Ensure that land-use cells are utilized effectively without exceeding their capacity.
- Maintain feasibility: Guarantee that solutions respect adoption rates, transition feasibility, and commodity demand requirements.

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- Guide towards realistic solutions: Ensure that model outputs align with environmental, economic, and policy-driven goals.

The LUTO 2.0 model incorporates several types of constraints, each managed through specific functions:

- Cell Usage Constraints: Ensure that all land-use cells are allocated to exactly one land-use type.
- Agricultural Management Constraints: Govern how agricultural management practices are assigned and applied across land-use cells.
- Agricultural Management Adoption Limit Constraints: Restrict the extent to which agricultural management practices can be adopted within the landscape.
- Demand Constraints: Enforce compliance with agricultural commodity demand requirements, depending on whether a soft or hard demand constraint type is selected.
- Transition Constraints: Control the conditions and limitations on transitioning between different land-use types over time.

Each constraint type is formulated carefully to reflect the complex interactions between land management, agricultural productivity, environmental sustainability, and economic objectives.

24.6.1. Cell Usage Constraints

This section defines the Cell Usage Constraints, which ensure that all land-use cells are fully allocated to one or more land-use types—a fundamental requirement for resource allocation in the LUTO model. This constraint guarantees that the total area of each cell is fully utilized, with no land left unassigned.

If a subset of cells is specified through the cells parameter, the constraint applies only to these selected cells, ensuring that their total area is allocated appropriately.

The constraint is formulated as:

$$\sum_{\ell \in \mathcal{L}} \mathcal{X}_{\text{Sum}}^{\text{AG}}(y) = 1, \qquad \forall r \in \mathcal{C}_{selected}$$	Equation 596

where:

- $\mathcal{C}_{selected} \subseteq \mathcal{C}$ is the subset of all cells selected for constraint application, with $\mathcal{C}$ being the complete set of all land-use cells.

The term $\mathcal{X}_{\text{Sum}}^{\text{AG}}(y)$ is computed as:

$$\mathcal{X}_{\text{Sum}}^{\text{AG}}(y) = \mathbf{DAAC}_{\ell r}^{\text{AG},\mathcal{C}_{selected}}(y) + \mathbf{IAAC}_{\ell r}^{\text{AG},\mathcal{C}_{selected}}(y) + \mathbf{NAAC}_{r\ell}^{\text{NonAG},\mathcal{C}_{selected}}(y)$$	Equation 597

where:

- $\mathbf{DAAC}_{\ell r}^{\text{AG},\mathcal{C}_{selected}}$ = subset of dryland agricultural allocation variables for selected cells
- $\mathbf{IAAC}_{\ell r}^{\text{AG},\mathcal{C}_{selected}}$ = subset of irrigation agricultural allocation variables for selected cells
- $\mathbf{NAAC}_{r\ell}^{\text{NonAG},\mathcal{C}_{selected}}$ = subset of non-agricultural land-use allocation variables for selected cells

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Each subset is derived as:

$\mathbf{DAAC}_{\ell r}^{\mathrm{AG},\mathcal{C}_{selected}}(y) = \mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y) \mid r \in \mathcal{C}_{selected}$	Equation 598
$\mathbf{IAAC}_{\ell r}^{\mathrm{AG},\mathcal{C}_{selected}}(y) = \mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y) \mid r \in \mathcal{C}_{selected}$	Equation 599
$\mathbf{NAAC}_{r\ell}^{\mathrm{NonAG},\mathcal{C}_{selected}}(y) = \mathbf{NAAC}_{r\ell}^{\mathrm{NonAG}}(y) \mid r \in \mathcal{C}_{selected}$	Equation 600

where,

- $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)$ are dryland agricultural allocation decision variables (Equation 550)
- $\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)$ are irrigation agricultural allocation decision variables (Equation 553)
- $\mathbf{NAAC}_{r\ell}^{\mathrm{NonAG}}$ are non-agricultural land use allocation variables (Equation 560)

Then, the following constraints are added using the GurobiAddConstrs function to ensure that the total fraction of land allocated in each cell across all land-use types l $\boldsymbol{\ell} \in \boldsymbol{\mathcal{L}}$ must equal 100% (or 1 in normalized terms):

$\mathbf{CellUsageConstr}_r = \mathrm{GurobiAddConstrs}\left(\sum_{\ell \in \mathcal{L}} \mathcal{X}_{\mathrm{Sum}}^{\mathrm{AG}}(y) = 1\right)$	Equation 601

As mentioned in Equation 596, this constraint guarantees that all available land within each selected cell is fully utilized without:

- **Under-allocation** (where the total land-use fraction is less than 1), or
- **Over-allocation** (where the total land-use fraction exceeds 1).

Thus, the model maintains spatial and resource consistency across the landscape for every optimization cycle.

Implications of Constraint Violations

1. **Over-Allocation ($\sum_{\ell \in \mathcal{L}} \mathcal{X}_{\mathrm{Sum}}^{\mathrm{AG}}(y) > 1$):**
    - More land is assigned to various land uses than is physically available within the cell.
    - This is unrealistic and would likely cause the optimization problem to become infeasible or produce invalid results.
2. **Under-Allocation ($\sum_{\ell \in \mathcal{L}} \mathcal{X}_{\mathrm{Sum}}^{\mathrm{AG}}(y) < 1$):**
    - Some portion of the land within the cell remains unutilized or unassigned to any land-use type.
    - Although under-allocation may be acceptable in certain real-world contexts (e.g., land reserved for conservation or natural regeneration), it could conflict with the model's goal of maximizing resource use or meeting specific land allocation targets.

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24.6.2. Agricultural Management Constraints

This section defines constraints related to agricultural management practices. The primary purpose is to ensure that the application of agricultural management practices does not exceed the underlying agricultural capacity of each land-use cell. These constraints help the model respect physical and management limitations across the landscape.

Initially, the Updated Cells Index **(UCI)** is set to None, indicating that no land-use cells require adjustments at the start of the optimization or simulation process.

As the optimization proceeds, particularly across simulation iterations, the **UCI** is dynamically updated to include the indices of cells $r \in \mathbf{UCI}$ that exhibit violations of the skipping criteria (specified in Equation 635–Equation 640).

These violations trigger two key actions:

- Removal of outdated constraints associated with the affected cells.
- Redefinition of constraints to realign them with updated land-use or agricultural management conditions.

This updating process ensures that the constraint set remains consistent with evolving land management states throughout the simulation horizon.

The agricultural management constraints enforce that the agricultural management decision variables cannot exceed the available agricultural allocation in each land-use cell. Specifically:

- For dryland agricultural management, the decision variable $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(y)$ must not exceed the corresponding dryland allocation variable $\mathbf{DAAC}_{\ell r}^{\text{AG}}(y)$.
- For irrigated agricultural management, the decision variable $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(y)$ must not exceed the corresponding irrigated allocation variable $\mathbf{IAAC}_{\ell r}^{\text{AG}}(y)$.

These constraints ensure that agricultural management practices are applied only within the physical and operational capacity of the land, maintaining model feasibility and ensuring alignment with real-world land-use limitations.

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}$	Equation 602
$\mathbf{DCV}^{\text{AGMP}} = \begin{cases} \bigcup_{r \in \text{UCI}} r & \text{If} \quad r \in \mathbf{UCI} \\ \mathbf{BLuLmM}_{0,r,\ell_r} & \text{If} \quad \mathbf{UCI} = \text{None} \end{cases}$	
$\mathbf{ICV}^{\text{AGMP}} = \begin{cases} \bigcup_{r \in \text{UCI}} r & \text{If} \quad r \in \mathbf{UCI} \\ \mathbf{BLuLmM}_{1,r,\ell_r} & \text{If} \quad \mathbf{UCI} = \text{None} \end{cases}$	

where,

- $\mathbf{BLuLmM}_{0,r,\ell_r}$ is the Boolean tensor representing the land-use under the dryland management system (Equation 234)
- $\mathbf{BLuLmM}_{1,r,\ell_r}$ is the Boolean tensor representing the land-use under the irrigation land management system (Equation 235)

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- $\mathbf{DCV}^{\mathrm{AGMP}}$ are the cell values for dryland cells (Dryland Cell Values for Agricultural Management Practices).
- $\mathbf{ICV}^{\mathrm{AGMP}}$ are the cell values for irrigated cells (Irrigated Cell Values for Agricultural Management Practices).

This equation defines two key variables:

- $\mathbf{DCV}^{\mathrm{AGMP}}$ (Dryland Cell Values for Agricultural Management Practices)
- $\mathbf{ICV}^{\mathrm{AGMP}}$ (Irrigated Cell Values for Agricultural Management Practices)

These variables are essential for dynamically representing and updating agricultural management constraints under different optimization and simulation scenarios.
Their behaviour is as follows:

- **Case 1:** If $r \in \mathbf{UCI}$ (Updated Cells Index), it indicates that initial parameters or input data have changed. In this case, $\mathbf{DCV}^{\mathrm{AGMP}}$ and $\mathbf{ICV}^{\mathrm{AGMP}}$ are updated to reflect the union of all cell indices in the $\mathbf{UCI}$.
- **Case 2:** If $\mathbf{UCI} = \mathrm{None}$, it means that the simulation is in its initial stage, or that no updates to the initial land-use conditions have occurred. Then,
  - $\mathbf{DCV}^{\mathrm{AGMP}}$ defaults to $\mathbf{BLuLmM}_{0,r,\ell_r}$ (dryland management tensor).
  - $\mathbf{ICV}^{\mathrm{AGMP}}$ defaults to $\mathbf{BLuLmM}_{1,r,\ell_r}$ (irrigation management tensor).

The list of selected cells is then $\mathcal{C}_{selected} = \mathbf{DCV}^{\mathrm{AGMP}} \cup \mathbf{ICV}^{\mathrm{AGMP}}$.

The computed $\mathbf{DCV}^{\mathrm{AGMP}}$ and $\mathbf{ICV}^{\mathrm{AGMP}}$ are used to define the agricultural management constraints as:

$\forall r \in \mathcal{C}_{selected}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 603
$\mathcal{X}_{\mathrm{Dry}}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathcal{X}_{\mathrm{Irr}}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathbf{AMC}_r^{\mathrm{AGMP}} = \mathrm{GurobiAddConstrs}\left[\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y) \leq \mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)\right], \quad \forall r \in \mathbf{DCV}^{\mathrm{AGMP}}, \ell \in \phi(k), k \in \mathcal{K}$	
$\mathbf{AMC}_r^{\mathrm{AGMP}} = \mathrm{GurobiAddConstrs}\left[\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y) \leq \mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)\right], \quad \forall r \in \mathbf{ICV}^{\mathrm{AGMP}}, \ell \in \phi(k), k \in \mathcal{K}$	
$\mathbf{AMC}^{\mathrm{AGMP}} = \bigcup_{r \in \mathcal{C}_{selected}} \mathbf{AMC}_r^{\mathrm{AGMP}}$	

where,

- $\mathcal{X}_{\mathrm{Dry}}^{\mathrm{AGMP}}(y)$ is the dictionary of dryland agricultural management practice decision variables (Equation 569)
- $\mathcal{X}_{\mathrm{Irr}}^{\mathrm{AGMP}}(y)$ is the dictionary of irrigated agricultural management practice decision variables (Equation 567)
- $\phi(k)$ is the rule or mapping from agricultural management practices (domain $\mathcal{K}$) to land uses $\mathcal{L}$

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- $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)$ are the dryland agricultural allocation variables (Equation 550)
- $\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)$ are the irrigation agricultural allocation variables (Equation 553)

24.6.3. Agricultural Management Practices Adoption Limit Constraints

This section ensures that the adoption of agricultural management practices does not exceed predefined limits $\mathbf{TranMatC}^{\mathrm{AGMP}}(y)$. These constraints are crucial for modeling the practical boundaries on how much a particular agricultural management practice can be implemented, based on:

- Availability of resources,
- Physical and operational feasibility,
- Sustainability considerations.

This constraint ensures that the decision variables representing agricultural management adoption (e.g., $\mathcal{X}_{\mathrm{Dry}}^{\mathrm{AGMP}}(y)$ for dryland uses) adhere to the limits set by the corresponding agricultural allocation variables (e.g., $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)$). Specifically:

- Dryland agricultural management variables must not exceed the dryland agricultural allocations.
- Irrigated agricultural management variables must not exceed the irrigated agricultural allocations.

Without these constraints, the model could attempt to over-allocate land to management practices, leading to infeasibility or unrealistic resource use.

For all cells $r \in \{1, \dots, N_r\}$, modes $m \in \{0,1\}$, land uses $\ell \in \phi(k)$, and agricultural management practices $k \in \mathcal{K}$:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 604
$\mathbf{TranMatC}^{\mathrm{AGMP}}(y) \longrightarrow \mathcal{AL}_{\ell}^{\mathrm{AGMP}}, \qquad \forall k \in \mathcal{K}$	
$\mathcal{X}_{\mathrm{Dry}}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathcal{X}_{\mathrm{Irr}}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\mathcal{X}_{\mathrm{Sum}}^{\mathrm{AGMP}}(y) = \sum_{r} \mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y) + \sum_{r} \mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y), \quad \forall \ell \in \phi(k), k \in \mathcal{K}$	
$\mathcal{X}_{\mathrm{Sum}}^{\mathrm{AG}}(y) = \sum_{r} \mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y) + \sum_{r} \mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y), \quad \forall \ell \in \mathcal{L}, k \in \mathcal{K}$	
$\mathbf{ALC}^{\mathrm{AGMP}} = \mathrm{GurobiAddConstrs}\left[\mathcal{X}_{\mathrm{Sum}}^{\mathrm{AGMP}}(y) \leq \mathcal{AL}_{\ell}^{\mathrm{AGMP}} \times \mathcal{X}_{\mathrm{Sum}}^{\mathrm{AG}}(y)\right], \quad \forall \ell \in \phi(k), k \in \mathcal{K}$	
$\mathbf{ALC}^{\mathrm{AGMP}} = \bigcup_{r \in \mathcal{C}_{selected}} \mathbf{ALC}_{r}^{\mathrm{AGMP}}$	

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where,

- $\mathbf{TranMatC}^{\text{AGMP}}(y)$: A dictionary mapping each agricultural management practice k to its associated transition cost matrix $\mathbf{TranMatC}^{k}_{mr\ell}$, reflecting the cost impacts of adopting the k-th practice (Equation 288).
- $\mathcal{X}^{\text{AGMP}}_{\text{Dry}}(y)$: A dictionary containing the decision variables for dryland agricultural management practices (Equation 569)
- $\mathcal{X}^{\text{AGMP}}_{\text{Irr}}(y)$: A dictionary containing the decision variables for irrigated agricultural management practices (Equation 567)
- $\phi(k)$: A mapping function that associates each agricultural management practice $k \in \mathcal{K}$ to the relevant set of land-use types $\ell \in \mathcal{L}$.
- $\mathbf{DAAC}^{\text{AG}}_{\ell r}(y)$: Decision variable representing the allocation of land cell r to dryland agricultural land use ℓ (Equation 550).
- $\mathbf{IAAC}^{\text{AG}}_{\ell r}(y)$: Decision variable representing the allocation of land cell r to irrigated agricultural land use ℓ (Equation 553).
- $\mathcal{C}_{selected}$: A subset of all land-use cells $\mathcal{C}$, where $\mathcal{C}_{selected} \subseteq \mathcal{C}$, representing the cells included in the constraint evaluation.
- $\mathcal{AL}^{\text{AGMP}}_{\ell}$: The adoption limit value assigned to land-use class $\ell \in \phi(k)$ for agricultural management practice $k \in \mathcal{K}$.
- $\mathcal{X}^{\text{AGMP}}_{\text{Sum}}(y)$: The total sum of agricultural management practice decision variables across all cells $r \in \mathcal{C}_{selected}$ for land uses $\ell \in \phi(k)$.
- $\mathcal{X}^{\text{AG}}_{\text{Sum}}(y)$: The total sum of agricultural allocation decision variables across all cells $r \in \mathcal{C}_{selected}$ for all agricultural land uses $\ell \in \mathcal{L}$.
- $\mathbf{ALC}^{\text{AGMP}}$: The set of adoption limit constraints ensuring that management practice adoption does not exceed allowable limits for each land-use class.

24.6.4. Demand Penalty Constraints

This section introduces constraints on agricultural production to address deviations from pre-specified demand levels. These constraints penalize both underproduction and overproduction, ensuring that production closely aligns with demand requirements. They account for outputs under both dryland and irrigated management practices and introduce a penalty mechanism for deviations.

24.6.4.1. Dry Quantities in Product Representation

This part computes the total dry agricultural production for each product $\ell_i \in \mathcal{L}_{\text{Products}}$.
The computation involves summing over the yield matrix $\mathbf{YieldQ}^{\text{AGMP}}(y)$, which provides product-specific yields across land-management types, weighted by the decision variable $\mathbf{Q}^{\text{Dry,AG}}_{r\ell}(y)$.

This highlights the contribution of dry production at the product level, offering insights into how individual products contribute to overall agricultural outputs.

$\forall r \in \{1, \dots, N_r\}\ \exists \ell_i, \ell_j \mid \ell_i \in \mathcal{L}_{\text{Products}}, \ell_j \in \mathcal{L}$	Equation 605
$\mathbf{Q}^{\text{Dry,AG}}_{r\ell_j}(y) = \begin{cases} \mathbf{DAAC}^{\text{AG}}_{\ell_j r}(y) & \text{if} \quad \mathbf{LU2ProdM}_{\ell_i,\ell_j} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	

where,

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- $\mathbf{DAAC}_{\ell}^{\mathrm{AG}}(y)$ is the dryland agricultural land-use allocation variable (Equation 550)
- $\mathbf{LU2ProdM}_{\ell_i,\ell_j}$ is the Land Use to Products mapping matrix (see Figure 534)

Then, using $\mathbf{Q}_{r\ell}^{\mathrm{Dry,AG}}(y)$ and $\mathbf{YieldQ}^{\mathrm{AGMP}}(y)$, we compute the dryland quantities $\mathbf{DQPR}_{\ell}^{\mathrm{AG}}(y)$ specific to product ℓ, as:

$\forall r \in \{1,\dots,N_r\}, m \in \{0,1\}, \ell_i \in \mathcal{L}_{\mathrm{Products}}, \ell_j \in \phi(k), k \in \mathcal{K}$	Equation 606
$\mathbf{YieldQ}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{YieldQ}_{mr\ell}^{\mathrm{AGMP}}, \qquad \forall k \in \mathcal{K}$	
$\mathbf{YieldQ}_{mr\ell}^{\mathrm{AGMP}} \longrightarrow \mathbf{YieldQ}_{r\ell}^{\mathrm{Dry,AGMP}}, \qquad m \in \{1\}$	
$\mathbf{DQPR}_{\ell}^{\mathrm{AG}}(y) = \sum_{r\in\{1,\dots,N_r\}} \mathbf{Q}_{r\ell}^{\mathrm{Dry,AG}}(y) \times \mathbf{YieldQ}_{r\ell}^{\mathrm{Dry,AGMP}}(y)$	

where,

- $\mathbf{YieldQ}^{\mathrm{AGMP}}$ is a dictionary mapping management practices to yield quantities for crops and livestock products (Equation 135)

24.6.4.2. Irrigation Quantities in Product Representation

This section computes the total irrigation agricultural production for each product $\ell_i \in \mathcal{L}_{\mathrm{Products}}$. The computation involves summing over the yield quantity matrix of agricultural classes $\mathbf{YieldQ}^{\mathrm{AGMP}}(y)$, which provides product-specific yields across land-management types, weighted by the decision variable $\mathbf{Q}_{r\ell}^{\mathrm{Irr,AG}}(y)$.

This formulation highlights the contribution of irrigated production at the product level, offering insights into how individual products contribute to irrigation-based agricultural outputs.

$\forall r \in \{1,\dots,N_r\}\ \exists \ell_i, \ell_j \mid \ell_i \in \mathcal{L}_{\mathrm{Products}}, \ell_j \in \mathcal{L}$	Equation 607
$\mathbf{Q}_{r\ell_j}^{\mathrm{Irr,AG}}(y) = \begin{cases} \mathbf{IAAC}_{\ell_j r}^{\mathrm{AG}}(y) & \text{if} \quad \mathbf{LU2ProdM}_{\ell_i,\ell_j} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	

where,

- $\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)$ is the irrigated agricultural land-use allocation variable (Equation 553).
- $\mathbf{LU2ProdM}_{\ell_i,\ell_j}$ is the Land use to Products mapping matrix (see Figure 534).

Then, using $\mathbf{Q}_{r\ell}^{\mathrm{Irr,AG}}(y)$ and $\mathbf{YieldQ}^{\mathrm{AGMP}}(y)$, we compute the irrigated quantities $\mathbf{IQPR}_{\ell}^{\mathrm{AG}}(y)$ specific to product ℓ, as:

$\forall r \in \{1,\dots,N_r\}, m \in \{0,1\}, \ell_i \in \mathcal{L}_{\mathrm{Products}}, \ell_j \in \phi(k), k \in \mathcal{K}$	Equation 608
$\mathbf{YieldQ}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{YieldQ}_{mr\ell}^{\mathrm{AGMP}}, \qquad \forall k \in \mathcal{K}$	
$\mathbf{YieldQ}_{mr\ell}^{\mathrm{AGMP}} \longrightarrow \mathbf{YieldQ}_{r\ell}^{\mathrm{Irr,AGMP}}, \qquad m \in \{1\}$	

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$$\mathbf{IQPR}_{\ell}^{\mathrm{AG}}(y) = \sum_{r \in \{1,\ldots,N_r\}} \mathbf{Q}_{r\ell}^{\mathrm{Irr,AG}}(y) \times \mathbf{YieldQ}_{r\ell}^{\mathrm{Irr,AGMP}}(y)$$	

where,

- $\mathbf{YieldQ}^{\mathrm{AGMP}}$ is a dictionary representing the yield quantities for both crop and livestock products (Equation 135)

24.6.4.3. Dry Quantities in Commodity Representation

This section computes the total dryland agricultural production aggregated at the commodity level. It is calculated by summing the dryland quantities $\mathbf{DQPR}_{\ell}^{\mathrm{AG}}$ mapped to a specific commodity $\ell_j \in \mathcal{L}_{\mathrm{Commodities}}$, using the Product-to-Commodity Mapping Matrix $\mathbf{Prod2ComM}$.

This transformation enables the evaluation of dryland production contributions at the commodity level, providing a broader perspective on the dryland agricultural system.

$\forall \ell_i \in \mathcal{L}_{\mathrm{Products}}, \ell_j \in \mathcal{L}_{\mathrm{Commodities}}$	Equation 609
$$\mathbf{DQCR}_{\ell}^{\mathrm{AG}}(y) = \sum_{\ell_i \in \mathcal{L}_{\mathrm{Products}}} \mathbf{DQPR}_{\ell}^{\mathrm{AG}}(y) \times \delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right)$$	

where,

- $\mathbf{DQCR}_{r}^{\mathrm{AG}}(y)$ is the dryland quantities in commodity representation.
- $\mathbf{DQPR}_{\ell}^{\mathrm{AG}}(y)$ is the dryland quantities in product representation (Equation 606).
- $\delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right)$ is the products-to-commodities delta function (Equation 610)

The delta function $\delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right)$ is defined as:

$\forall \ell_i \in \mathcal{L}_{\mathrm{Products}}, \ell_j \in \mathcal{L}_{\mathrm{Commodities}}$	Equation 610
$$\delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right) = \begin{cases} 1, & \text{if} \quad \mathbf{Prod2ComM}_{\ell_i,\ell_j} = 0 \\ 0, & \text{if} \quad \mathbf{Prod2ComM}_{\ell_i,\ell_j} = 1 \end{cases}$$	

where,

- $\mathbf{Prod2ComM}_{\ell_i,\ell_j}$ is the Products-to-Commodities Mapping Matrix (see Figure 690).

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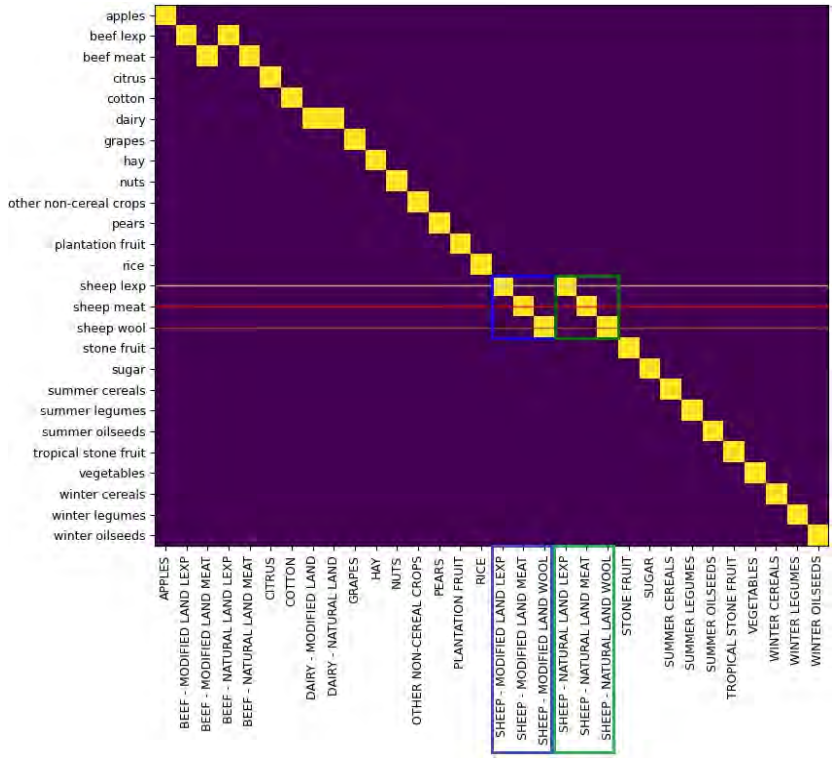

Figure 690 Products to Commodities matrix (**Prod2ComM**)

24.6.4.4. Irrigation Quantities in Commodity Representation

This section computes the total irrigation agricultural production aggregated at the commodity level. It is calculated by summing the irrigation quantities $\mathbf{IQPR}_{\ell}^{\mathrm{AG}}$ mapped to a specific commodity $\ell_j \in \mathcal{L}_{\mathrm{Commodities}}$, using the product-to-commodity mapping matrix **Prod2ComM**. This transformation enables evaluation of irrigation production at the commodity level, providing a broader understanding of contributions to irrigation agricultural systems.

$\forall \ell_i \in \mathcal{L}_{\mathrm{Products}}, \ell_j \in \mathcal{L}_{\mathrm{Commodities}}$	Equation 611
$\mathbf{IQCR}_{\ell}^{\mathrm{AG}}(y) = \sum_{\ell_i \in \mathcal{L}_{\mathrm{Products}}} \mathbf{IQPR}_{\ell}^{\mathrm{AG}}(y) \times \delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right)$	

where,

- $\mathbf{IQCR}_{r}^{\mathrm{AG}}(y)$ is the irrigation quantities in commodity representation.
- $\mathbf{IQPR}_{\ell}^{\mathrm{AG}}(y)$ is the irrigation quantities in product representation (Equation 608).
- $\delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right)$ is the same products-to-commodities delta function defined in Equation 612.

As previously defined, the delta function $\delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right)$ is:

$\forall \ell_i \in \mathcal{L}_{\mathrm{Products}}, \ell_j \in \mathcal{L}_{\mathrm{Commodities}}$	Equation 612
$\delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right) = \begin{cases} 1, & \text{if} \quad \mathbf{Prod2ComM}_{\ell_i,\ell_j} = 1 \\ 0, & \text{if} \quad \mathbf{Prod2ComM}_{\ell_i,\ell_j} = 0 \end{cases}$	

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where,

- $\mathbf{Prod2ComM}_{\ell_i,\ell_j}$ is the Products-to-Commodities Mapping Matrix (see Figure 690).

24.6.4.5. Variables in Product Representation (Dry/Irrigated)

To represent the contributions of agricultural management practices in terms of quantities in commodity representation, two variables are initialized:

- $\mathbf{DVPL}_{\ell r}^{\text{Dry,AGMP}}(y)$: Dry agricultural management decision variables at the product level.
- $\mathbf{DVPL}_{\ell r}^{\text{Irr,AGMP}}(y)$: Irrigated agricultural management decision variables at the product level.

Initialization:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{Products}}$	Equation 613
$\mathbf{DVPL}_{\ell r}^{\text{Dry,AGMP}} = 0_{(N_p \times N_c)}$	
$\mathbf{DVPL}_{\ell r}^{\text{Irr,AGMP}} = 0_{(N_p \times N_c)}$	Equation 614

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- N_p is the number of agricultural products in $\mathcal{L}_{\text{Products}}$ (hence, $N_p = 32$).

To update $\mathbf{DVPL}_{\ell r}^{\text{Dry,AGMP}}(y)$ and $\mathbf{DVPL}_{\ell r}^{\text{Irr,AGMP}}(y)$, the variable $\mathbf{L2P}$ is required. $\mathbf{L2P}$ represents the mapping between land-use classes and their associated agricultural products. This mapping facilitates the decision-making process by linking land-use types to the specific products they produce, thereby supporting resource allocation and optimization across the landscape.

$\forall r \in \{1, \dots, N_r\} \ \exists \ell_i, \ell_j \mid \ell_i \in \mathcal{L}_{\text{Products}}, \ell_j \in \mathcal{L}, k \in \mathcal{K}$	Equation 615
$\mathbf{L2P} = \begin{Bmatrix} \ell_j \rightarrowtail \ell_i & \text{if} & \mathbf{LU2ProdM}_{\ell_i,\ell_j} = \text{True} \\ \ell_j \rightarrowtail [\ \ ] & & \text{otherwise} \end{Bmatrix}$	

Here, if the matrix $\mathbf{LU2ProdM}_{\ell_i,\ell_j}$ evaluates to **True**, it indicates that a mapping exists from ℓ_j (land use) to ℓ_i (product). Otherwise, ℓ_j maps to an empty list, meaning no direct association exists. In the resulting dictionary $\mathbf{L2P}$, ℓ_j is treated as the key, and ℓ_i is assigned as the corresponding value linked to that key.

The dryland agricultural management decision variable $\mathbf{DVPL}_{\ell r}^{\text{Dry,AGMP}}$ is then updated as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 616

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$\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\forall \ell_i \in \mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y) \; \exists \; \mathbf{L2P}_{\ell_i} \longrightarrow \mathbf{SL2P}$	
$\forall \ell_{\text{L2P}} \in \mathbf{SL2P}$, $\mathbf{DVPL}_{\ell r}^{\text{Dry,AGMP}} = \begin{cases} \mathbf{AMPDV}_{\ell_{\text{L2P}},r}^{\text{Dry,AGMP}}(y) & \text{if} \quad \mathbf{LU2ProdM}_{\ell_{\text{L2P}},\ell_i} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	

where,

- $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(y)$ is the dictionary of dryland agricultural management practice decision variables (Equation 569)
- $\mathbf{L2P}$ is the dictionary mapping between land-use types and their associated products (Equation 615)
- $\mathbf{LU2ProdM}$ is the Land-Use-to-Products mapping matrix (Figure 534)

Similarly, the irrigated agricultural management decision variable $\mathbf{DVPL}_{\ell r}^{\text{Irr,AGMP}}$ is updated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 617
$\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	
$\forall \ell_i \in \mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y) \exists \mathbf{L2P}_{\ell_i} \longrightarrow \mathbf{SL2P}$	
$\forall \ell_{\text{L2P}} \in \mathbf{SL2P}$, $\mathbf{DVPL}_{\ell r}^{\text{Irr,AGMP}} = \begin{cases} \mathbf{AMPDV}_{\ell_{\text{L2P}},r}^{\text{Irr,AGMP}}(y) & \text{if} \quad \mathbf{LU2ProdM}_{\ell_{\text{L2P}},\ell_i} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	

where,

- $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(y)$ is the dictionary of irrigated agricultural management practice decision variables (Equation 567)
- $\mathbf{L2P}$ represents the dictionary mapping land-use types to their associated products (Equation 615)
- $\mathbf{LU2ProdM}$ is the Land-Use-to-Products mapping matrix (Figure 534)

24.6.4.6. Dryland Agricultural Management Quantity in Product Representation

This section computes the total dryland agricultural management quantity aggregated at the commodity level $\mathbf{DQCR}_{\ell}^{\text{AGMP}}$.

It is calculated by summing the contributions of agricultural management practices in terms of quantities in product representation $\mathbf{DVPL}_{\ell r}^{\text{Dry,AGMP}}$ (Equation 616) mapped to a specific commodity $\ell_j \in \mathcal{L}_{\text{Commodities}}$, using the product-to-commodity mapping matrix $\mathbf{Prod2ComM}$.

This transformation enables the evaluation of dryland production at the commodity level, providing a broader understanding of contributions to dryland agricultural management systems.

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$\forall \ell_i \in \mathcal{L}_{\text{Products}}, \ell_j \in \mathcal{L}_{\text{Commodities}}$	Equation 618
$\mathbf{DQCR}_{\ell}^{\text{AGMP}}(y) = \sum_{\ell_i \in \mathcal{L}_{\text{Products}}} \mathbf{DVPL}_{\ell_i r}^{\text{Dry,AGMP}}(y) \times \delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right), \quad \forall k \in \mathcal{K}$	

where,

- $\mathbf{DVPL}_{\ell r}^{\text{Dry,AGMP}}(y)$ is the contribution of agricultural management practices in terms of quantities under dryland management (Equation 616)
- $\delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right)$ is the products-to-commodities delta function (Equation 612)

24.6.4.7. Irrigation Agricultural Management Quantity in Product Representation

This section computes the total irrigation agricultural management quantity aggregated at the commodity level $\mathbf{IQCR}_{\ell}^{\text{AGMP}}$.

It is calculated by summing the contributions of agricultural management practices in terms of quantities in product representation$\mathbf{DVPL}_{r\ell}^{\text{Irr,AGMP}}$ (Equation 617) mapped to a specific commodity $\ell_j \in \mathcal{L}_{\text{Commodities}}$, , using the product-to-commodity mapping matrix $\mathbf{Prod2ComM}$.

This transformation enables the evaluation of irrigation production at the commodity level, providing a broader understanding of contributions to irrigation agricultural management systems.

$\forall \ell_i \in \mathcal{L}_{\text{Products}}, \ell_j \in \mathcal{L}_{\text{Commodities}}$	Equation 619
$\mathbf{IQCR}_{\ell}^{\text{AGMP}}(y) = \sum_{\ell_i \in \mathcal{L}_{\text{Products}}} \mathbf{DVPL}_{\ell_i r}^{\text{Irr,AGMP}}(y) \times \delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right), \quad \forall k \in \mathcal{K}$	

where,

- $\mathbf{DVPL}_{\ell r}^{\text{Irr,AGMP}}(y)$ is the contributions of agricultural management practices in terms of quantities in product representation under irrigation land management (Equation 617)
- $\delta\left(\mathbf{Prod2ComM}_{\ell_i,\ell_j}\right)$ is the products-to-commodities delta function (Equation 612)

24.6.4.8. Updated Variables in Product Representation (Dry/Irrigated)

After computing $\mathbf{DQCR}_{\ell}^{\text{AGMP}}$and $\mathbf{IQCR}_{\ell}^{\text{AGMP}}$ (from Equation 618 and Equation 619), the calculated quantities for dryland $\mathbf{DQCR}_{\ell}^{\text{AG}}$ (Equation 609) and irrigated $\mathbf{DVPL}_{\ell r}^{\text{Irr,AGMP}}$ (Equation 617) agricultural management practices are updated by adding the contributions from agricultural management practices:

$\mathbf{DQCR}_{r}^{\text{AG}}(y) = \mathbf{DQCR}_{r}^{\text{AG}}(y) + \mathbf{DQCR}_{\ell}^{\text{AGMP}}(y)$	Equation 620
$\mathbf{IQCR}_{r}^{\text{AG}}(y) = \mathbf{IQCR}_{r}^{\text{AG}}(y) + \mathbf{IQCR}_{\ell}^{\text{AGMP}}(y)$	Equation 621

where,

- $\mathbf{DQCR}_{r}^{\text{AG}}(y)$ is the dryland quantities in commodity representation (Equation 609)
- $\mathbf{IQCR}_{r}^{\text{AG}}(y)$ is the irrigation quantities in commodity representation (Equation 611)

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- $\mathbf{DQCR}_{\ell}^{\mathrm{AGMP}}(y)$ is the dry agricultural management quantity at the commodity level (Equation 618)
- $\mathbf{IQCR}_{\ell}^{\mathrm{AGMP}}(y)$ is the irrigation agricultural management quantity at the commodity level (Equation 619)

24.6.4.9. Calculation of Non-Agricultural Commodity Contributions

This section computes the total non-agricultural commodity contributions $\mathbf{QCR}_{r}^{NonAg}$ by aggregating the production from all non-agricultural land uses across resources.
The contributions are weighted by a non-agricultural quantity matrix $\mathbf{CPM}_{\ell_{Com},r,\ell_i}^{NonAg}$ (Equation 348) and the corresponding non-agricultural land allocation decision variables $\mathbf{NAAC}_{r\ell}^{\mathrm{NonAG}}$.

Specifically, the total non-agricultural production for each cell is obtained by summing the contributions across:

- All non-agricultural land uses $\mathcal{L}_{\mathrm{NonAgrLand}}$, and
- All commodities $\mathcal{L}_{\mathrm{Commodities}}$.

Mathematically, this is expressed as:

$\forall r \in \{1, \dots, N_r\}, \ell_i \in \mathcal{L}_{\mathrm{NonAgrLand}}, \ell_{Com} \in \mathcal{L}_{\mathrm{Commodities}}$	Equation 622
$\mathbf{QCR}_{r}^{NonAg}(y) = \sum_{\ell_i \in \mathcal{L}_{\mathrm{NonAgrLand}}} \sum_{\ell_{Com} \in \mathcal{L}_{\mathrm{Commodities}}} \mathbf{CPM}_{\ell_{Com},r,\ell_i}^{NonAg}(y) \times \mathbf{NAAC}_{r\ell_i}^{\mathrm{NonAG}}$	

where,

- $\mathbf{NAAC}_{r\ell}^{\mathrm{NonAG}}$ is the allocation variable for non-agricultural land use (Equation 560)
- $\mathbf{CPM}_{\ell_j,r,\ell_i}^{NonAg}(y)$ is the non-agricultural commodity production matrix (Equation 348)
- $\mathcal{L}_{\mathrm{NonAgrLand}}$ is a set of the non-Agricultural land use classes (Equation 13)
- $\mathcal{L}_{\mathrm{Commodities}}$ is the set of all available commodities, which contains 26 members (Equation 36)

Thus, $\mathbf{QCR}_{r}^{NonAg}(y)$ provides an aggregated measure of non-agricultural commodity production per land-use cell, supporting later calculations of total resource supply and demand matching.

24.6.4.10. Calculation of Total Land-Use Commodity Contributions at the Cell Level

This section computes the total commodity contributions across agricultural and non-agricultural land uses by aggregating three components:

$\forall r \in \{1, \dots, N_r\}$	Equation 623
$\mathbf{TQCR}_{\ell}^{AG,NonAg}(y) = \mathbf{DQCR}_{\ell}^{\mathrm{AG}}(y) + \mathbf{IQCR}_{\ell}^{\mathrm{AG}}(y) + \mathbf{QCR}_{r}^{NonAg}(y)$	

where,

- $\mathbf{DQCR}_{r}^{\mathrm{AG}}(y)$ is the dryland quantities (Equation 609),
- $\mathbf{IQCR}_{r}^{\mathrm{AG}}(y)$ is the irrigation quantities (Equation 611),
- $\mathbf{QCR}_{r}^{NonAg}(y)$ is the non-agricultural commodity production (Equation 622).

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24.6.4.11. Soft Demand Constraints with Slack Variables

To allow flexibility in meeting commodity demands, soft demand constraints are imposed using slack variables.

$\forall r \in \{1, \dots, N_r\}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 624
$\mathbf{UBA}_{\ell_{Com}}^{Soft} = \text{GurobiAddConstrs}\left[\left(\mathbf{DC}_{\ell_{Com}}(y) - \mathbf{TQCR}_{\ell_{Com}}^{AG,NonAg}(y)\right) \leq \mathbf{V}[\ell_{Com}]\right]$	
$\mathbf{LBA}_{\ell_{Com}}^{Soft} = \text{GurobiAddConstrs}\left[\left(\mathbf{TQCR}_{\ell_{Com}}^{AG,NonAg}(y) - \mathbf{DC}_{\ell_{Com}}(y)\right) \leq \mathbf{V}[\ell_{Com}]\right]$	
$\mathbf{DPC}^{AG,NonAg} = \mathbf{DPC}^{AG,NonAg} \cup \mathbf{UBA}_{\ell_{Com}}^{Soft} \cup \mathbf{LBA}_{\ell_{Com}}^{Soft}$	

where,

- $\mathbf{DC}_{\ell_{Com}}$ represents the demand constraint for commodity ℓ_{Com},
- $\mathbf{V}[\ell_{Com}]$ represents the decision variable corresponding to commodity ℓ_{Com} (Equation 593),
- $\mathbf{TQCR}_{\ell_{Com}}^{AG,NonAg}(y)$ is the total commodity production across all land uses (Equation 623)

24.6.4.12. Strict Demand Constraints with No Deviations Allowed

In the case of strict (hard) demand constraints, the model enforces that the total quantity of commodity contributions across all land use types must meet or exceed the specified demand levels, with no deviations allowed.

Mathematically, this is represented as:

$\forall r \in \{1, \dots, N_r\}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 625
$\mathbf{UBA}_{\ell_{Com}}^{Hard} = \text{GurobiAddConstrs}\left[\mathbf{TQCR}_{\ell_{Com}}^{AG,NonAg}(y) \geq \mathbf{DC}_{\ell_{Com}}(y)\right]$	
$\mathbf{DPC}^{AG,NonAg} = \mathbf{DPC}^{AG,NonAg} \cup \mathbf{UBA}_{\ell_{Com}}^{Hard}$	

where,

- $\mathbf{DC}_{\ell_{Com}}$ represents the demand constraint introduced by the LUTO 2.0 model.
- $\mathbf{TQCR}_{\ell_{Com}}^{AG,NonAg}(y)$ is the total quantity of commodity contributions across all land use types (Equation 623)
- $\mathbf{DPC}^{AG,NonAg}$ represents the set of demand penalty constraints across all land use types.

24.6.5. Water Usage limits Constraints

This section introduces constraints to ensure that regional water usage stays within predefined limits. It calculates the net water yield for each Drainage Division $\boldsymbol{R}$, accounting for contributions from:

- Dryland agriculture

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- Irrigated agriculture
- Alternative agricultural management practices (both dryland and irrigated)
- Non-agricultural land uses
- Contributions from outside the study area
- Climate change impacts

The net water yield for drainage division $\boldsymbol{R}$ in year y is computed as:

$\forall R \in \{1, \cdots, N_{DD}\}$	Equation 626
$\mathbf{WYield}_R^{Net}(y) = \mathbf{WContr}_R^{OutSide} + \mathbf{WContr}_R^{AG}(y) + \mathbf{WContr}_R^{\mathrm{AGMP}}(y) + \mathbf{WContr}_R^{NonAg}(y) + \mathbf{WContr}_R^{CCI}(y)$	

where,

- $\mathbf{WContr}_R^{OutSide}$ is the contribution to water net yield from cells outside the LUTO study area.
- $\mathbf{WContr}_R^{AG}(y)$ is the contribution from agricultural land uses (Equation 630)
- $\mathbf{WContr}_R^{\mathrm{AGMP}}(y)$ is the contribution from agricultural management practices (Equation 634)
- $\mathbf{WContr}_R^{NonAg}(y)$ is the contribution from non-agricultural land uses (Equation 635)
- $\mathbf{WContr}_R^{CCI}(y)$ represents the impact of climate change on the net water yield (Equation 627)

24.6.5.1. Climate Change Impacts of the Base Year (2010)

This section defines how climate change impacts on water yield are incorporated into the model for the base year (2010).

The climate change contribution to the net water yield for each Drainage Division R in year 2010 is defined as:

$\forall y \in \{2010, \cdots, 2100\} \exists\ Ind_R \mid Ind_R \subseteq \{1, \cdots, N_r\}$	Equation 627
$\mathbf{WYield}_{DD}^{\mathrm{CCI}}(y) \longrightarrow \mathbf{WContr}_R^{CCI}(y), \qquad \forall y \in \{2010\}$	

where,

- $\mathbf{WYield}_{DD}^{\mathrm{CCI}}(y)$ is the climate change impact on water yield across drainage divisions (defined in Equation 146)
- $\mathbf{WContr}_R^{CCI}(y)$ is the climate change contribution to the net water yield for each Drainage Division R during the base year 2010.
- Ind_R is the set of indices corresponding to the cells associated with Drainage Division R.

This mapping ensures that the model correctly accounts for baseline climate change effects in the water balance calculations from the very beginning of the simulation horizon.

24.6.5.2. Water Usage Limits by Agricultural Contribution

This section calculates the contribution of agricultural land uses (both dryland and irrigated) to the total water yield within each Drainage Division R.

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For dryland agricultural land uses, the contribution to the water yield is computed as:

$\forall m \in \{0\}, \ell \in \mathcal{L}, R \in \{1, \cdots, N_{DD}\} \exists\ Ind_R \mid Ind_R \subseteq \{1, \cdots, N_r\}$	Equation 628
$\mathbf{AgWContr}_R^{\mathrm{Dry}}(y) = \sum_{\ell \in \mathcal{L}} \sum_{r \in Ind_R} \mathbf{WYield}_{mr\ell}^{Net}(y) \times \left(\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)\right)^T$	
$\forall m \in \{1\}, \ell \in \mathcal{L}, R \in \{1, \cdots, N_{DD}\} \exists\ Ind_R \mid Ind_R \subseteq \{1, \cdots, N_r\}$	Equation 629
$\mathbf{AgWContr}_R^{\mathrm{Irr}}(y) = \sum_{\ell \in \mathcal{L}} \sum_{r \in Ind_R} \mathbf{WYield}_{mr\ell}^{Net}(y) \times \left(\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)\right)^T$	
$\mathbf{WContr}_R^{AG}(y) = \mathbf{AgWContr}_R^{\mathrm{Dry}}(y) + \mathbf{AgWContr}_R^{\mathrm{Irr}}(y)$	Equation 630

where,

- $\mathbf{WYield}_{mr\ell}^{Net}(y)$ is the water net yield matrices (defined in Equation 145).
- $\mathbf{DAAC}_{\ell r}^{\mathrm{AG}}(y)$ is the allocation of cells specifically for dryland agricultural use (Equation 550).
- $\mathbf{IAAC}_{\ell r}^{\mathrm{AG}}(y)$ is the allocation of cells specifically for irrigated agricultural use (Equation 553).
- Ind_R is the set of indices of cells located in Drainage Division R.
- N_{DD} is the number of Drainage Division.

24.6.5.3. Water Usage Limits by Agricultural Management Practice Contribution

This section calculates the contribution of agricultural management practices (dryland and irrigated) to the total water yield within each Drainage Division R.

First, agricultural management water requirement matrices are extracted:

$\forall r \in \{1, \ldots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 631
$\mathbf{WReqM}_k^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{WReqM}_{r\ell}^{\mathrm{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}, m = 0$	
$\mathbf{WReqM}_k^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{WReqM}_{r\ell}^{\mathrm{Irr,AGMP}}(y), \qquad \forall k \in \mathcal{K}, m = 1$	
$\mathcal{X}_{\mathrm{Dry}}^{\mathrm{AGMP}} \longrightarrow \mathbf{DAMC}_{r\ell}^{\mathrm{AGMP}}$	
$\mathcal{X}_{\mathrm{Irr}}^{\mathrm{AGMP}} \longrightarrow \mathbf{IAMC}_{r\ell}^{\mathrm{AGMP}}$	
$\forall m \in \{0\}, \ell \in \phi(k), R \in \{1, \cdots, N_{DD}\} \exists\ Ind_R \mid Ind_R \subseteq \{1, \cdots, N_r\}$	Equation 632

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$$\mathbf{AGMPWContr}_R^{\text{Dry}}(y) = \sum_{\boldsymbol{\ell}\in\boldsymbol{\phi}(\boldsymbol{k})} \sum_{r\in Ind_R} \mathbf{WReqM}_{r\ell}^{\text{Dry,AGMP}}(y) \times \left(\mathbf{DAMC}_{r\ell}^{\text{AGMP}}(y)\right)^T$$	
$\forall m \in \{1\}, \ell \in \phi(k), R \in \{1,\cdots,N_{DD}\} \exists\ Ind_R \mid Ind_R \subseteq \{1,\cdots,N_r\}$	Equation 633
$$\mathbf{AGMPWContr}_R^{\text{Irr}}(y) = \sum_{\ell\in\phi(k)} \sum_{r\in Ind_R} \mathbf{WReqM}_{r\ell}^{\text{Irr,AGMP}}(y) \times \left(\mathbf{IAMC}_{r\ell}^{\text{AGMP}}(y)\right)^T$$	
$\mathbf{WContr}_R^{\text{AGMP}}(y) = \mathbf{AGMPWContr}_R^{\text{Dry}}(y) + \mathbf{AGMPWContr}_R^{\text{Irr}}(y)$	Equation 634

where,

- $\mathbf{WReqM}_k^{\text{AGMP}}$ is the dictionary of water requirement matrices for agricultural management practices, mapping each key k to its corresponding value $\mathbf{WReqM}_{mr\ell}^k$ (Equation 158)
- $\mathbf{DAMC}_{r\ell}^{\text{AGMP}}$ represents the adoption under dryland agricultural management (Equation 566).
- $\mathbf{IAMC}_{r\ell}^{\text{AGMP}}$ represents the adoption under irrigation agricultural management (Equation 569).
- Ind_R is the set of indices of cells that are located within Drainage Division R.
- N_{DD} is the total number of Drainage Divisions considered in the model.
- $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}$ is the dictionary of agricultural management practice decision variables for dryland areas (corresponding to $\mathbf{DAMC}_{\ell r}^{\text{AGMP}}$, Equation 566)
- $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}$ is the dictionary of agricultural management practice decision variables for irrigated areas (corresponding to $\mathbf{IAMC}_{\ell r}^{\text{AGMP}}$, Equation 569)

24.6.5.4. Water Usage Limits by Non-Agricultural Contribution

The contribution of non-agricultural land uses to water usage in each drainage division R is computed as:

$\forall \ell \in \mathcal{L}_{\text{NonAgrLand}}, R \in \{1,\cdots,N_{DD}\} \exists\ Ind_R \mid Ind_R \subseteq \{1,\cdots,N_r\}$	Equation 635
$$\mathbf{WContr}_R^{NonAg}(y) = \sum_{\boldsymbol{\ell}\in\mathcal{L}_{\text{NonAgrLand}}} \sum_{r\in Ind_R} \mathbf{WRM}_{r\ell}^{NonAg}(y) \times \left(\mathbf{NAAC}_{\ell r}^{\text{NonAG}}(y)\right)^T$$	

where,

- $\mathbf{NAAC}_{\ell r}^{\text{NonAG}}$ represents the allocation of cells specifically for non- agricultural land use (Equation 560)
- $\mathbf{WRM}_{r\ell}^{NonAg}$ is the overall water requirements matrix for all non-agricultural land uses (Equation 364)
- Ind_{RR} is the list of indices of cells that are located in Drainage Division R
- N_{DD} is the number of Drainage Division considered in the model.

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24.6.5.5. Strict Demand Constraints with No Deviations Allowed

The strict demand constraints enforce that water yield in each drainage division must meet or exceed the historical limit, without allowing any deviation.

$\forall r \in \{1, \dots, N_r\}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 636
$WYC_R = \text{GurobiAddConstrs}[\mathbf{WYield}_R^{Net}(y) \geq \mathbf{WYield}_R^{HL}]$	
$\mathbf{WLC}^{AG,NonAg} = \bigcup_{R \in \{1,\cdots,N_{\mathbf{DD}}\}} WYC_R$	

where,

- $\mathbf{WLC}^{AG,NonAg}$ is the set of Water Limit Constraints applied across all drainage divisions.
- $\mathbf{WYield}_R^{Net}(y)$ is the total net water yield for region R (Equation 626).
- $\mathbf{WYield}_R^{HL}(y)$ is the historical limit for water yield in region R.

The contribution of climate change on water yield for drainage division R year y is represented as $\mathbf{WContr}_R^{CCI}(y)$ in Equation 627.

The **delta change** in the climate change impact between two years (FinalTargetYear and TargetYear) is calculated as:

$\triangle \mathbf{WContr}_R^{CCI} = \mathbf{WContr}_R^{CCI}(\text{FinalTargetYear}) - \mathbf{WContr}_R^{CCI}(\text{TargetYear})$	Equation 637

where,

- $\mathbf{WContr}_R^{CCI}(\text{FinalTargetYear})$ is the climate change on water yield contribution in the final target year
- $\mathbf{WContr}_R^{CCI}(\text{TargetYear})$ is the climate change on water yield contribution in the target year

The initial constraint on the net water yield is calculated by adjusting the historical limit with the delta climate change effect:

$\mathbf{WNetYield}_R^{Constraint} = \mathbf{WNetYield}_R^{Limit} + \triangle \mathbf{WContr}_R^{CCI}$	Equation 638

where,

- $\mathbf{WNetYield}_R^{Limit}$ is the predefined historical water yield limit.

If the value of relaxed water limits for infeasibility ($\mathbf{RWLI} = \text{"on"}$) on the base year solution

In case of Drainage Division:

If $\mathbf{RWLI} = \text{"on"}$ and a base year solution exists ($\mathbf{AGSol}_{mr\ell}^{BYear} \neq None$), then:

- **For Drainage Divisions**:

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$\mathbf{WYield}_{mr\ell}^{BYear} = \mathbf{WNetY}_{mr\ell}^{DD}, \quad \text{If} \quad \left(\mathbf{AGSol}_{mr\ell}^{BYear} \neq \text{None}\right) \wedge (\mathbf{RWLI} = \text{on}) = \text{True}$	Equation 639

- **For River Region:**

$\mathbf{WYield}_{mr\ell}^{BYear} = \mathbf{WNetY}_{mr\ell}^{RR}, \quad \text{If} \quad \left(\mathbf{AGSol}_{mr\ell}^{BYear} \neq None\right) \wedge (\mathbf{RWLI} = \text{on}) = \text{True}$	Equation 640

If the base year water yield ($\mathbf{WYield}_{mr\ell}^{BYear}$) is less than the predefined limit ($\mathbf{WNetYield}_{R}^{Limit}$), then the constraint is corrected:

$\mathbf{WNetYield}_{R}^{Constraint} = \mathbf{WYield}_{mr\ell}^{BYear} \quad \text{if} \quad \mathbf{WYield}_{mr\ell}^{BYear} < \mathbf{WNetYield}_{R}^{Limit}$	Equation 641

where,

- $\mathbf{WYield}_{mr\ell}^{BYear}$ is the water yield calculated for the base year.
- $\mathbf{WNetY}_{mr\ell}^{DD}$ is the water net yield for drainage division
- $\mathbf{WNetY}_{mr\ell}^{RR}$ is the water net yield for river region

Before applying constraints, it is confirmed that the net water contribution is non-zero:

$\text{if} \quad \mathbf{WYield}_{R}^{Net}(y) \neq 0$	Equation 642

The final water yield constraint using Gurobi is formulated as:

$\forall r \in \{1, \dots, N_r\}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 643
$WYC_R = \text{GurobiAddConstrs}\left[\mathbf{WYield}_{R}^{Net}(y) \geq \mathbf{WNetYield}_{R}^{Constraint}\right]$	
$\mathbf{WLC}^{AG,NonAg} = \bigcup_{R \in \{1,\cdots,N_{\mathbf{DD}}\}} WYC_R$	

This ensure meaningful constraints are applied only when the water yield contributions are non-trivial and properly validated.

24.6.6. Green House Gas Emissions Constraints

This section defines constraints to ensure that GHG emissions in each region stay within predefined limits. The total GHG emissions are calculated by summing contributions from five sources:

- Dryland agriculture

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- Irrigated agriculture
- Agricultural management practices (both dryland and irrigated)
- Non-agricultural uses
- Non-Study Area impact (areas outside the modeled study region)

Additionally, the GHG emission limit may be adjusted if necessary to avoid infeasibility during optimization.

The total net GHG emissions are given by:

$\mathbf{GHG}^{Net}(y) = \mathbf{GHGContr}^{OutSide}(y) + \mathbf{GHGContr}^{AG}(y) + \mathbf{GHGContr}^{\mathrm{AGMP}}(y) + \mathbf{GHGContr}^{NonAg}(y)$	Equation 644

where,

- $\mathbf{GHGContr}^{OutSide}(y)$ is the contribution to GHG emissions from cells outside the study area.
- $\mathbf{GHGContr}^{AG}(y)$ is the agricultural land-use contribution to GHG emissions (**Error! Reference source not found.**).
- $\mathbf{GHGContr}^{\mathrm{AGMP}}(y)$ is the agricultural management practice contribution to GHG emissions (**Error! Reference source not found.**).
- $\mathbf{GHGContr}^{NonAg}(y)$ is the non-agricultural land-use contribution to GHG emissions (Equation 651).

24.6.6.1. Green House Gas Emissions Contribution by Agricultural Contribution

This section computes the total greenhouse gas (GHG) emissions contributed by agricultural land uses, split between dryland and irrigated systems, and then aggregates these contributions.

- For irrigation management ($m = 1$), the GHG coefficient is similarly calculated:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \ell \in \mathcal{L}$	Equation 645
$\mathbf{GHGCoef}_{\ell r}^{\mathrm{Dry}}(y) = \mathbf{GHGE}_{mr\ell}^{AG,LS}(y) + \mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}(y)$	
$\mathbf{GHGContr}_{\ell}^{\mathrm{Dry,AG}}(y) = \sum_{r \in \{1,\dots,N_r\}} \mathbf{GHGCoef}_{\ell r}^{\mathrm{Dry}}(y) \times \left(\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y)\right)^T$	

- The irrigated agricultural GHG contribution is:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \mathcal{L}$	Equation 646
$\mathbf{GHGCoef}_{\ell r}^{Irr}(y) = \mathbf{GHGE}_{mr\ell}^{AG,LS}(y) + \mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}(y)$	
$\mathbf{GHGContr}_{\ell}^{\mathrm{Irr,AG}}(y) = \sum_{r \in \{1,\dots,N_r\}} \mathbf{GHGCoef}_{\ell r}^{\mathrm{Irr}}(y) \times \left(\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y)\right)^T$	

- Total Agricultural GHG Contribution:
  Finally, the total GHG contribution from all agricultural land uses (both dryland and irrigated) is:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 647
$\mathbf{GHGContr}^{AG}(y) = \sum_{\ell \in \mathcal{L}} \mathbf{GHGContr}_{\ell}^{\mathrm{Dry,AG}}(y) + \mathbf{GHGContr}_{\ell}^{\mathrm{Irr,AG}}(y)$	

where,

- $\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y)$ is the adoption level of agricultural management practices under dryland management (Equation 604)
- $\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y)$ is the adoption level of agricultural management practices under irrigation management (Equation 604)
- $\mathbf{CEP}_{mr\ell}^{\mathrm{NLtoML}}(y)$ represents the carbon emission penalty for transitions from natural land uses ℓ_i to modified land uses ℓ_j (Equation 93)
- $\mathbf{GHGE}_{mr\ell}^{AG,LS}(y)$ represents greenhouse gas emissions for crops and livestock under both dryland and irrigation management systems (Equation 89)

24.6.6.2. Green House Gas Emissions Contribution by Agricultural Management Practice Contribution

This section computes the total GHG emissions contributed specifically by agricultural management practices, separated into dryland and irrigated practices, and then aggregates them.

- Dryland Agricultural Management Practices Contribution:
  For dryland agricultural management ($m = 0$), the GHG contribution is:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 648
$\mathbf{GEG}_{k}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{GEG}_{r\ell}^{\mathrm{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}, m = 0$	
$\mathbf{GHGContr}_{\ell}^{\mathrm{Dry,AGMP}}(y) = \sum_{r \in \{1,\dots,N_r\}} \mathbf{GEG}_{r\ell}^{\mathrm{Dry,AGMP}}(y) \times \left(\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y)\right)^T$	

- Irrigated Agricultural Management Practices Contribution:
  For irrigated agricultural management ($m = 1$), the GHG contribution is:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 649
$\mathbf{GEG}_{k}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{GEG}_{r\ell}^{\mathrm{Irr,AGMP}}(y), \qquad \forall k \in \mathcal{K}, m = 1$	
$\mathbf{GHGContr}_{\ell}^{\mathrm{Irr,AGMP}}(y) = \sum_{r \in \{1,\dots,N_r\}} \mathbf{GEG}_{r\ell}^{\mathrm{Irr,AGMP}}(y) \times \left(\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y)\right)^T$	

- Total Agricultural Management Practices GHG Contribution:
  Finally, the total GHG emissions from all agricultural management practices are:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 650
$\mathbf{GHGContr}^{\text{AGMP}}(y) = \sum_{\ell \in \phi(k)} \mathbf{GHGContr}_{\ell}^{\text{Dry,AGMP}}(y) + \mathbf{GHGContr}_{\ell}^{\text{Irr,AGMP}}(y)$	

where,

- $\mathbf{GEG}_k^{\text{AGMP}}$ is the dictionary of greenhouse gas emission coefficients for agricultural management practices, mapping each key k to its corresponding 3D matrix $\mathbf{GEG}_{mr\ell}^{k}$ (Equation 111),
- $\mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y)$ is the adoption level of agricultural management practices under dryland management (Equation 604),
- $\mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y)$ is the adoption level of agricultural management practices under irrigation management (Equation 604),
- Ind_{RR} is the list of index of cells that are located in Drainage Division i ,
- N_{DD} is the number of Drainage Divisions (for water or GHG aggregation when needed).

24.6.6.3. Gas Emissions Contribution by Non-Agricultural Land Uses

This section calculates the total GHG emissions contributed by non-agricultural land uses across all land-use cells and commodities.

The GHG emissions from non-agricultural land uses are computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 651
$\mathbf{GHGContr}^{NonAg}(y) = \sum_{\ell \in \mathcal{L}_{\text{NonAgrLand}}} \sum_{r \in \{1,\dots,N_r\}} \mathbf{GHGE}_{r\ell}^{NonAg}(y) \times \left(\mathbf{NAAC}_{\ell r}^{\text{NonAG}}(y)\right)^T$	

where,

- $\mathbf{GHGContr}^{NonAg}(y)$ is the total GHG emissions from all non-agricultural land uses in year y,
- $\mathbf{NAAC}_{\ell r}^{\text{NonAG}}$ represents the allocation of land-use cells specifically for non-agricultural land uses (Equation 560),
- $\mathbf{GHGE}_{r\ell}^{NonAg}$ represents the greenhouse gas emissions factors for all non-agricultural land uses (Equation 364),
- $\mathcal{L}_{\text{NonAgrLand}}$ is the set of all non-agricultural land use classes considered (Equation 13),
- Ind_{RR} is the list of index of cells that are located in Drainage Division i ,
- N_{DD} is the number of Drainage Divisions (for water or GHG aggregation when needed).

24.6.6.4. Strict GHG emission Constraints with No Deviations Allowed

The strict GHG emission constraints ensure that total greenhouse gas (GHG) emissions in each region stay within predefined limits, with no allowance for deviations.

The constraint is formulated as:

$\forall r \in \{1, \dots, N_r\}, \ell_{Com} \in \mathcal{L}_{\text{Commodities}}$	Equation 652

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$\mathbf{GHGLC}^{AG,NonAg} = \text{GurobiAddConstrs}[\mathbf{GHG}_R^{Net}(y) \leq \mathbf{GHG}_R^{HL}]$	

where,

- $\mathbf{GHGLC}^{AG,NonAg}$ represents the set of GHG emission limit constraints across all drainage divisions or regions.
- $\mathbf{GHG}_R^{Net}(y)$ is the total GHG emission for region R in year y, aggregating contributions from agriculture, agricultural management practices, non-agricultural land uses, and external (outside study area) sources (Equation 644)
- $\mathbf{GHG}_R^{HL}(y)$ represents the historical limit or target limit for GHG emissions in region R for year y.

24.6.7. Biodiversity limit Constraints

This section adds constraints to ensure that biodiversity in each region stays within predefined limits. It calculates the biodiversity contribution for each region by summing contributions from:

- Dryland agriculture,
- Irrigated agriculture,
- Alternative agricultural management practices (both dryland and irrigated),
- Non-agricultural uses,
- Non-study area impacts on biodiversity.

Additionally, it allows for adjustments to the biodiversity limit if necessary to avoid infeasibility during optimization. The overall net biodiversity score is computed as:

$\mathbf{BSM}^{Net}(y) = \mathbf{BSMContr}^{OutSide}(y) + \mathbf{BSMContr}^{AG}(y) + \mathbf{BSMContr}^{\text{AGMP}}(y) + \mathbf{BSMContr}^{NonAg}(y)$	Equation 653

where,

- $\mathbf{BSMContr}^{OutSide}(y)$ is the contribution of cells outside the study area to the Biodiversity Score Matrix.
- $\mathbf{BSMContr}^{AG}(y)$ is the agricultural contribution to the Biodiversity Score Matrix (**Error! Reference source not found.**).
- $\mathbf{BSMContr}^{\text{AGMP}}(y)$ is the agricultural management practice contribution to the Biodiversity Score Matrix (detailed in **Error! Reference source not found.**).
- $\mathbf{BSMContr}^{NonAg}(y)$ is the non-agricultural contribution to the Biodiversity Score Matrix (detailed in Equation 660).

24.6.7.1. Biodiversity Contribution by Agricultural land use

The contribution of agricultural land use to the Biodiversity Score Matrix (BSM) is calculated separately for dryland and irrigated land management systems. The results are then aggregated to compute the total agricultural biodiversity contribution.

- The dryland agricultural contribution is computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \ell \in \mathcal{L}$	

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$$\mathbf{BSMContr}_{\ell}^{\mathrm{Dry,AG}}(y) = \sum_{\ell \in \mathcal{L}} \sum_{r \in \{1,\dots,N_r\}} \mathbf{BSM}_{mr\ell}(y) \times \left(\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y)\right)^T$$	Equation 654

- The irrigated agricultural contribution is computed as:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \mathcal{L}$	Equation 655
$$\mathbf{BSMContr}_{\ell}^{\mathrm{Irr,AG}}(y) = \sum_{\ell \in \mathcal{L}} \sum_{r \in \{1,\dots,N_r\}} \mathbf{BSM}_{mr\ell}(y) \times \left(\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y)\right)^T$$	

- The total agricultural contribution to biodiversity is the sum of the two:

$$\mathbf{BSMContr}^{AG}(y) = \mathbf{BSMContr}_{\ell}^{\mathrm{Dry,AG}}(y) + \mathbf{BSMContr}_{\ell}^{\mathrm{Irr,AG}}(y)$$	Equation 656

where,

- $\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y)$ represents the adoption variables for agricultural management practices under dryland systems (Equation 604)
- $\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y)$ represents the adoption variables for agricultural management practices under irrigation systems (Equation 604)
- $\mathbf{BSM}_{mr\ell}$ is the Biodiversity Score Matrix by Land management (Equation 178)

24.6.7.2. Biodiversity Contribution by Agricultural Management Practice Contribution

This section calculates the contribution of agricultural management practices to biodiversity scores, separately for dryland and irrigated systems. The results are then summed to derive the total agricultural management biodiversity contribution.

- The dryland agricultural management contribution is calculated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 657
$\mathbf{BSM}_{k}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{BSM}_{r\ell}^{\mathrm{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}, m = 0$	
$$\mathbf{BSMContr}_{\ell}^{\mathrm{Dry,AGMP}}(y) = \sum_{r \in \{1,\dots,N_r\}} \mathbf{BSM}_{r\ell}^{\mathrm{Dry,AGMP}}(y) \times \left(\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y)\right)^T$$	

- The irrigated agricultural management contribution is calculated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 658
$\mathbf{BSM}_{k}^{\mathrm{AGMP}}(y) \longrightarrow \mathbf{BSM}_{r\ell}^{\mathrm{Irr,AGMP}}(y), \qquad \forall k \in \mathcal{K}, m = 1$	
$$\mathbf{BSMContr}_{\ell}^{\mathrm{Irr,AGMP}}(y) = \sum_{r \in \{1,\dots,N_r\}} \mathbf{BSM}_{r\ell}^{\mathrm{Irr,AGMP}}(y) \times \left(\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y)\right)^T$$	

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- The total agricultural management practice contribution to biodiversity is:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 659
$\mathbf{BSMContr}^{\mathrm{AGMP}}(y) = \sum_{\ell \in \phi(k)} \mathbf{BSMContr}_{\ell}^{\mathrm{Dry,AGMP}}(y) + \mathbf{BSMContr}_{\ell}^{\mathrm{Irr,AGMP}}(y)$	

where,

- $\mathbf{BSM}_{k}^{\mathrm{AGMP}}$ represents a dictionary that maps agricultural management practices ($k \in \mathcal{K}$) to biodiversity score matrices $\mathbf{BSM}_{mr\ell}^{\boldsymbol{k}}$ (Equation 193)
- $\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(y)$ is the adoption variable for dryland agricultural management practices (Equation 604)
- $\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(y)$ is the adoption variable for irrigated agricultural management practices (Equation 604)
- Ind_{RR} is the list of cell indices located in Drainage Division i
- N_{DD} is the number of drainage divisions considered in the model.

24.6.7.3. Biodiversity Contribution by Non-Agricultural Land Uses

This section calculates the contribution of non-agricultural land uses to biodiversity across the modelled regions. It aggregates biodiversity scores based on the assigned non-agricultural land uses for each cell.

- The non-agricultural biodiversity contribution is calculated as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	Equation 660
$\mathbf{BSMContr}^{NonAg}(y) = \sum_{\ell \in \mathcal{L}_{\mathrm{NonAgrLand}}} \sum_{r \in \{1,\dots,N_r\}} \mathbf{BSM}_{r\ell}^{NonAg}(y) \times \left(\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}}(y)\right)^{T}$	

where,

- $\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}}(y)$ represents the decision variable matrix for the allocation of cells specifically for non-agricultural land uses (Equation 560).
- $\mathbf{BSM}_{r\ell}^{NonAg}(y)$ represents the biodiversity score contribution matrix for non-agricultural land uses (Equation 378).
- Ind_{RR} is the set of indices of cells located within Drainage Division R.
- N_{DD} is the number of Drainage Division in the model.

24.6.7.4. Strict *Biodiversity Contribution* Constraints with No Deviations Allowed

This section enforces that the total biodiversity contribution in each region must meet or exceed a predefined historical limit, without allowing any deviation.

The strict biodiversity constraint is formulated as:

$\forall r \in \{1, \dots, N_r\}, \ell_{Com} \in \mathcal{L}_{\mathrm{Commodities}}$	Equation 661

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$\mathbf{BSMLC}^{AG,NonAg} = \text{GurobiAddConstrs}[\mathbf{BSM}_R^{Net}(y) \geq \mathbf{BSM}_R^{HL}]$	

where,

- $\mathbf{BSMLC}^{AG,NonAg}$ represents set of biodiversity contribution limit constraints applied across all regions.
- $\mathbf{BSM}_R^{Net}(y)$ is the total net biodiversity contribution for each region R (Equation 646).
- $\mathbf{BSM}_R^{HL}(y)$ is the historical limit for biodiversity contribution in region R.

24.6.8. Update Variables Land Use and Management Update Logic

To optimize computational efficiency, the model evaluates whether each cell requires updates to its land use and management variables. Cells that remain unchanged across key attributes between the previous and current periods are excluded from the update process.

The criteria for skipping a cell update are outlined below:

24.6.8.1. Skipping Criteria

A cell r is skipped if all the following conditions are satisfied (Equation 662-Equation 667):

24.6.8.1.1. Land Use Consistency

The land use designation for the cell $\boldsymbol{r}$ remains unchanged:

$\mathbf{LUM}_r^{\text{Old}} = \mathbf{LUM}_r^{\text{Current}}$	Equation 662

24.6.8.1.2. Land Management Consistency

The land management designation for the cell r remains unchanged:

$\mathbf{LMM}_r^{\text{Old}} = \mathbf{LMM}_r^{\text{Current}}$	Equation 663

24.6.8.1.3. Agricultural Variable Consistency

All agricultural decision variables for cell r are identical between the two periods:

$\mathbf{XCM}_{mr\ell}^{\text{Old}} = \mathbf{XCM}_{mr\ell}^{\text{Current}}, \quad \forall\, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 664

where,

- $\mathbf{XCM}_{mr\ell}$ is the Boolean Exclusion Matrix (Equation 244), updated annually to reflect allowable land-use changes.

All agricultural decision variables for the cell r are identical between the two time periods.

24.6.8.1.4. Non-Agricultural Variable Consistency

All non-agricultural decision variables for the cell r are identical:

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$\mathbf{XCM}_{r\ell}^{\text{NonAgToAg,Old}} = \mathbf{XCM}_{r\ell}^{\text{NonAgToAg,Current}}, \quad \forall\, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 665

where,

- $\mathbf{XCM}_{r\ell}^{\text{NonAgToAg}}$ is the aggregated transition cost matrix from non-agricultural to agricultural land in cell r

All non-agricultural decision variables for the cell r are identical.

24.6.8.1.5. Non-Agricultural Lower Bounds Consistency

Lower bounds for non-agricultural decision variables remain consistent for irreversible land uses:

$\mathbf{LBA}_{\ell}^{\text{NonAG,Old}} = \mathbf{LBA}_{\ell}^{\text{NonAG,Current}}, \quad \forall\, \ell \in \mathcal{L}_{\text{NonAgrLand}}, \text{if } RI_{\ell}^{\text{NonAG}} = \text{False}$	Equation 666

where,

- $\mathbf{LBA}_{\ell}^{\text{NonAG}}$ is the lower bound Assignment for non-agricultural land (Equation 557)
- RI_{ℓ}^{NonAG} is the Reversibility Indicator for land use type ℓ (Equation 558)

Lower bounds for non-agricultural decision variables remain consistent for irreversible land uses.

24.6.8.1.6. Agricultural Management Lower Bounds Consistency

Lower bounds for agricultural management decision variables remain consistent for irreversible management options:

$\mathbf{LB}_{mr\ell}^{\text{AGMP,Old}} = \mathbf{LB}_{mr\ell}^{\text{AGMP,Current}}, \forall \ell \in \mathcal{L}, \text{if } RI_{\ell}^{\text{AGMP}} = \text{False}$	Equation 667

where,

- $\mathbf{LB}_{mr\ell}^{AG,\text{Old}}$ is the lower bound matrix for agricultural land-use decision variables (Equation 287)
- RI_{k}^{AGMP} is the Reversibility Indicator for agricultural management practice type k (Equation 564)

Lower bounds for agricultural management decision variables remain consistent for irreversible management options.

24.6.8.2. Skipping Logic

If all the conditions in Equation 662 to Equation 667 are satisfied for a given cell r, the model skips updating the variables for that cell.

The skip condition is formally defined as:

$\mathbf{Skip}_r = \begin{cases} \text{True}, & \text{if} \quad C1_r \wedge C2_r \wedge C3_r \wedge C4_r \wedge C5_r \wedge C6_r \\ \text{False}, & \text{Otherwise} \end{cases}$	Equation 668

where,

- $C1_r$ represents the land use consistency condition (Equation 662)
- $C2_r$ represents the land management consistency condition (Equation 663)
- $C3_r$ represents the agricultural variable consistency condition (Equation 664)

- $C4_r$ represents the non-agricultural variable consistency condition (Equation 665)
- $C5_r$ represents the non-agricultural lower bounds consistency condition (Equation 666)
- $C6_r$ represents the agricultural management lower bounds consistency condition (Equation 667)

The number of skipped cells (NSC), is initially set as $\text{NSC} = 0$, is updated as:

$\text{NSC} = \begin{cases} \text{NSC} + 1 & \text{if} \quad \mathbf{Skip}_r = \text{True} \\ \text{o} & \text{otherwise} \end{cases}$	Equation 669

If any of the conditions (Equation 662-Equation 667) for cell r is violated ($\mathbf{Skip}_r = \text{False}$),

then:

- The cell r is updated.
- The index r is added to the Updated Cells Index **UCI**.

Formally:

$r \in \mathbf{UCI}, \quad \text{if } \mathbf{Skip}_r = \text{False}$	Equation 670

24.6.9. Updating Variables

If $\mathbf{Skip}_r = \text{False}$ (Equation 668), then the variables for cell r are updated as follows:

24.6.9.1. Agricultural Land Use Update

This step handles the removal and redefinition of agricultural land use variables for each cell r. The update process is applied only to cells that violated the skipping conditions (Equation 670).

24.6.9.1.1. Remove Existing Variable's Data

First, the model removes all existing decision variables related to agricultural land use for cells in **UCI**:

$\mathbf{DAAC}_{\ell r}^{\text{AG}} \longleftarrow 0, \quad \forall \ell \in \mathcal{L}, r \in \mathbf{UCI}$	Equation 671
$\mathbf{IAAC}_{\ell r}^{\text{AG}} \longleftarrow 0, \quad \forall \ell \in \mathcal{L}, r \in \mathbf{UCI}$	Equation 672

where,

- $\mathbf{DAAC}_{r\ell}^{\text{AG}}$ is the allocation of dryland agricultural land (Equation 550)
- $\mathbf{IAAC}_{r\ell}^{\text{AG}}$ is the allocation of irrigation agricultural land (Equation 553)
- **UCI** is the Updated Cells Index (Equation 670)

24.6.9.1.2. Redefinition of Variables

Next, the allocation of cells to dryland or irrigated agricultural use is redefined based on the updated Boolean Exclusion Matrix $\mathbf{XCM}_r^{\text{Current}}$ (Equation 244). The redefinition is performed as:

$\forall r \in \mathbf{UCI}, m \in \{0,1\}, \ell \in \mathcal{L}$

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$\mathbf{DAAC}_{\ell r}^{\mathrm{AG}} = \begin{cases} \mathrm{GurobiVar}_{r\ell}^{AG}(\mathbf{UBA}_{\ell}^{\mathrm{AG}}, VarName), & \text{if} \quad \mathbf{XCM}_{r}^{\mathrm{Current}} = 1, m = 0 \\ 0, & \text{otherwise} \end{cases}$	Equation 673
$\mathbf{IAAC}_{\ell r}^{\mathrm{AG}} = \begin{cases} \mathrm{GurobiVar}_{r\ell}^{AG}(\mathbf{UBA}_{\ell}^{\mathrm{AG}}, VarName), & \text{if} \quad \mathbf{XCM}_{r}^{\mathrm{Current}} = 1, m = 1 \\ 0, & \text{otherwise} \end{cases}$	Equation 674

where,

- $\mathrm{GurobiVar}_{r\ell}^{AG}$ is a Gurobi variable created for land use allocation, with an upper bound $\mathbf{UBA}_{\ell}^{\mathrm{AG}} = 1$ (maximum possible allocation).
- $\mathbf{XCM}_{r}^{\mathrm{Current}}$ is the current Boolean Exclusion Matrix, where a value of 1 indicates that cell r is eligible for a specific land use or management action.
- $VarName$ is the automatically generated name for the Gurobi decision variable.

24.6.9.2. Non-Agricultural Land Use Update

This section explains the removal and redefinition of non-agricultural land use variables for each cell r. The process ensures that variables reflect the updated land use designations. Like the agricultural land use update, this step is only applied to cells that violated the skipping conditions (Equation 670).

24.6.9.2.1. Remove Existing Variable

Initially, the model removes all existing decision variables for non-agricultural land use in each updated cell r, as:

$\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}} \longleftarrow 0, \quad \forall \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}, r \in \mathbf{UCI}$	Equation 675

where,

- $\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}}$ is the allocation for non-agricultural land uses (Equation 560)
- $\boldsymbol{\mathcal{L}}_{\mathbf{NonAgrLand}}$ is the set of all non-agricultural land use classes.
- **UCI** is the Updated Cells Index (Equation 670).

24.6.9.2.2. Redefinition of Variables

The redefinition of non-agricultural allocations is determined by the updated Boolean Exclusion Matrix $\mathrm{XCM}_{r}^{\mathrm{Current}}$ (Equation 244) to reflect changes in allowable land use.

The redefinition is performed as:

$\forall r \in \mathbf{UCI}, m \in \{0,1\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	
$\mathbf{NAAC}_{\ell r}^{\mathrm{NonAG}} = \begin{cases} \mathrm{GurobiVar}_{r\ell}^{\mathrm{NonAG}}(\mathbf{LBA}_{\ell}^{\mathrm{NonAG,Current}}, \mathbf{UBA}_{r\ell}^{\mathrm{NonAG}}, VarName), & \text{if} \quad \mathbf{XCM}_{r\ell}^{\mathrm{NonAgToAg,Current}} \\ 0, & \text{otherwise} \end{cases}$	Equation 676

where,

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- $\text{GurobiVar}_{r\ell}^{\text{NonAG}}$ is a Gurobi decision variable created for non-agricultural land use ℓ and r.
- $\mathbf{LBA}_{\ell}^{\text{NonAG,Current}}$ is the lower bound for non-agricultural allocation (Equation 557).
- $\mathbf{UBA}_{r\ell}^{\text{NonAG}}$ is the upper bound for non-agricultural allocation (Equation 559).
- $\mathbf{XCM}_{r\ell}^{\text{NonAgToAg,Current}}$ is the updated Boolean Exclusion Matrix entry, indicating whether cell r is eligible for allocation.
- $VarName$ is the automatically generated variable name for Gurobi.

24.6.9.3. Agricultural Management Update

This section outlines the removal and redefinition of agricultural management variables for each cell r. It ensures that the decision variables align with updated management practices and land use designations. Like the land use updates, this step is only applied to cells r that violated the skipping conditions (Equation 670).

24.6.9.3.1. Remove Existing Variable

Initially, the model **removes** all existing decision variables for agricultural management practices in each updated cell:

For dryland management:

$\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(y) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y), \qquad \forall k \in \mathcal{K}$	Equation 677
$\mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y) \longleftarrow 0, \quad \forall \ell \in \phi(k), r \in \mathbf{UCI}$	
$\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(y) = \{k \rightarrowtail \mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y)\}, \quad \forall k \in \mathcal{K}, r \in \{1, \dots, N_r\}$	

For irrigated management:

$\boldsymbol{\mathcal{X}}_{\textbf{Irr}}^{\textbf{AGMP}}(\boldsymbol{y}) \longrightarrow \mathbf{AMPDV}_{\ell r}^{\textbf{Irr,AGMP}}(\boldsymbol{y}), \qquad \forall \boldsymbol{k} \in \boldsymbol{\mathcal{K}}$	Equation 678
$\mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y) \longleftarrow 0, \quad \forall \ell \in \phi(k), r \in \mathbf{UCI}$	
$\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(y) = \{k \rightarrowtail \mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y)\}, \quad \forall k \in \mathcal{K}, r \in \{1, \dots, N_r\}$	

where,

- $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}$ represents a dictionary of agricultural management practice variables for land designated as dry, corresponding to $\mathbf{DAMC}_{kr}^{\text{AGMP}}$ (Equation 562)
- $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}$ represents a dictionary of agricultural management practice variables for land designated as irrigated, corresponding to $\mathbf{DAMC}_{kr}^{\text{AGMP}}$ (Equation 567)
- $\mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(y)$ and $\mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(y)$ represent dryland and irrigated management decision variables.
- $\mathbf{UCI}$ is the Updated Cells Index (Equation 670).
- $\phi(k)$ is the mapping between agricultural management practices k and associated land uses.

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24.6.9.3.2. Redefinition of Variables

The redefinition of agricultural management allocations is based on the updated Boolean Exclusion Matrix to reflect changes in allowable management practices.

The redefinition is done as:

- For dryland management:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}$	
$\mathcal{X}_{\text{Dry}}^{\text{AGMP}} = \{k \rightarrowtail \text{GurobiVar}_{rk}^{AG}(\mathbf{LBA}_k^{\text{AGMP,Current}}, \mathbf{UBA}_{rk}^{\text{AGMP}}, VarName)\}, \quad \forall m = 0, r \in \mathbf{UCI}$	Equation 679

- For irrigated management:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, k \in \mathcal{K}$	
$\mathcal{X}_{\text{Irr}}^{\text{AGMP}} = \{k \rightarrowtail \text{GurobiVar}_{rk}^{AG}(\mathbf{LBA}_k^{\text{AGMP,Current}}, \mathbf{UBA}_{rk}^{\text{AGMP}}, VarName)\}, \quad \forall m = 1, r \in \mathbf{UCI}$	Equation 680

where,

- $\text{GurobiVar}_{rk}^{\text{NonAG}}$ is a Gurobi decision variable for agricultural management practice ℓ at cell r.
- $\mathbf{LBA}_k^{\text{AGMP,Current}}$ is the lower bound for agricultural management practices (Equation 568).
- $\mathbf{UBA}_{rk}^{\text{AGMP}}$ is the upper bound , typically set to 1, $\mathbf{UBA}_{rk}^{\text{AGMP}} = 1$ (Equation 565).
- $VarName$ is the generated name for the decision variable.

24.6.10. Updating the Constraints

This section manages the removal and redefinition of constraints for the updated cells $r \in \mathbf{UCI}$, where **UCI** (Updated Cells Index) represents the set of cells requiring updates due to violations of the skipping criteria (Equation 662-Equation 667).
Constraints are first removed and then redefined to align with the updated land use and management conditions.

The following removals occur for each updated cell:

$\forall r \in \mathbf{UCI}$	
$\mathbf{CellUsageConstrr}_r^{\text{AGMP}} = \text{GurobiRemove}(\mathbf{CellUsageConstrr}_r^{\text{AGMP}})$	Equation 681
$\mathbf{AMC}_r^{\text{AGMP}} = \text{GurobiRemove}(\mathbf{AMC}_r^{\text{AGMP}})$	Equation 682
$\mathbf{ALC}^{\text{AGMP}} = \text{GurobiRemove}(\mathbf{ALC}^{\text{AGMP}})$	Equation 683

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$\mathbf{DPC}^{AG,NonAg} = \text{GurobiRemove}(\mathbf{DPC}^{AG,NonAg})$	Equation 684

Conditional removals if the constraints exist:

$\mathbf{BSMLC}^{AG,NonAg} = \begin{cases} \text{GurobiRemove}(\mathbf{BSMLC}^{AG,NonAg}) & \text{if } \mathbf{BSMLC}^{AG,NonAg} \neq \text{None} \\ \mathbf{BSMLC}^{AG,NonAg} & \text{otherwise} \end{cases}$	Equation 685
$\mathbf{WLC}^{AG,NonAg} = \begin{cases} \text{GurobiRemove}(\mathbf{WLC}^{AG,NonAg}) & \text{if } \mathbf{WLC}^{AG,NonAg} \text{ Exist} \\ \mathbf{BSMLC}^{AG,NonAg} & \text{otherwise} \end{cases}$	Equation 686
$\mathbf{GHGLC}^{AG,NonAg} = \begin{cases} \text{GurobiRemove}(\mathbf{GHGLC}^{AG,NonAg}) & \text{if } \mathbf{GHGLC}^{AG,NonAg} \neq \text{None} \\ \mathbf{BSMLC}^{AG,NonAg} & \text{otherwise} \end{cases}$	Equation 687

where,

- **UCI** represents the updated cells index (Equation **670**)
- $\mathbf{CellUsageConstrr_r}$ represents the Cell Usage Constraints (Equation 601)
- $\mathbf{AMC}_r^{\mathrm{AGMP}}$ represents the agricultural management Constraints (Equation 602)
- $\mathbf{ALC}^{\mathrm{AGMP}}$ represents the Adoption Limit Constraints for Agricultural Management Practices (Equation 604)
- $\mathbf{DPC}^{AG,NonAg}$ represents the Demand Penalty Constraints across all land use types (Equation 624)
- $\mathbf{BSMLC}^{AG,NonAg}$ represents the Biodiversity Contribution limit constraints (Equation 661)
- $\mathbf{WLC}^{AG,NonAg}$ represents the Water Yield Limit Constraints (Equation 636)
- $\mathbf{GHGLC}^{AG,NonAg}$ represents the GHG Emission Limit Constraints (Equation 652)

After removal, new constraints are regenerated based on the updated current conditions using the corresponding formulas from:

- **UCI** (Equation 670),
- $\mathbf{CellUsageConstrr_r}$ (Equation 601),
- $\mathbf{AMC}_r^{\mathrm{AGMP}}$(Equation 602),
- $\mathbf{ALC}^{\mathrm{AGMP}}$(Equation 604),
- $\mathbf{DPC}^{AG,NonAg}$ (Equation 624),
- $\mathbf{BSMLC}^{AG,NonAg}$ (Equation 661),
- $\mathbf{WLC}^{AG,NonAg}$ (Equation 636),
- $\mathbf{GHGLC}^{AG,NonAg}$(Equation 652).

24.7. Mathematical Formulation of Solver Outputs and Land-Use Decision Variables in the LUTO Model

24.7.1. Optimization Process:

The Gurobi solver solves the optimization problem:

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Optimize: **min** ObjectiveFunction	Equation 688

24.7.2. Decision Variables

24.7.2.1. Agricultural Land-Use Decision Variables

To allocate cells in the optimized solution to agricultural land-use classes under both dryland and irrigation management systems, the following variables are defined:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 689
$\mathbf{DAAC}_{r\ell}^{\mathrm{AG,Sol}} = 0_{(N_c \times N_{lu})}$	
$\mathbf{IAAC}_{r\ell}^{\mathrm{AG,Sol}} = 0_{(N_c \times N_{lu})}$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- $N_{lu} = 28$, is 28, corresponding to the set $\mathcal{L}$ containing all agricultural land-use classes (Equation 1).

The agricultural allocation matrices are updated according to the land management type.

- **For Dryland Management:**

$\forall r \in \{1, \dots, N_r\}, m \in \{0\}, \ell \in \mathcal{L}$	Equation 690
$\mathbf{DAAC}_{r\ell}^{\mathrm{AG,Sol}} = \begin{cases} \mathbf{DAAC}_{r\ell}^{\mathrm{AG}} & \text{if} \quad \mathbf{BLuLmM}_{mr\ell} = \text{True} \\ 0 & \text{otherwise} \end{cases}$	

where,

- $\mathbf{DAAC}_{r\ell}^{\mathrm{AG,Sol}}$ represents the allocated cells in the optimized solution for agricultural land-use classes under dryland management.
- $\mathbf{DAAC}_{r\ell}^{\mathrm{AG}}$ represents the allocation of cells specifically for dryland agricultural use in the model before optimization (Equation 673)
- $\mathbf{BLuLmM}_{mr\ell}$ is the Boolean land-use and land management matrix, which is updated based on the land-use class and the management type (dryland or irrigation) (Equation 234)

- **For Irrigation Management:**

$\forall r \in \{1, \dots, N_r\}, m \in \{1\}, \ell \in \mathcal{L}$	

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$$\mathbf{IAAC}_{r\ell}^{\mathrm{AG,Sol}} = \begin{cases} \mathbf{IAAC}_{r\ell}^{\mathrm{AG}} & \text{if} \quad \mathbf{BLuLmM}_{mr\ell} = \mathrm{True} \\ 0 & \text{otherwise} \end{cases}$$	Equation 691

where,

- $\mathbf{IAAC}_{r\ell}^{\mathrm{AG,Sol}}$ represents the allocated cells in the optimized solution for agricultural land-use classes under irrigation management.
- $\mathbf{IAAC}_{r\ell}^{\mathrm{AG}}$ represents the allocation of cells specifically for irrigation agricultural use in the model before optimization (see Equation 674)
- $\mathbf{BLuLmM}_{mr\ell}$ is the Boolean land-use and land management matrix, which is updated based on the land-use class and the management type (dryland or irrigation) (see Equation 234)

Once $\mathbf{DAAC}_{r\ell}^{\mathrm{AG,Sol}}$ and $\mathbf{IAAC}_{r\ell}^{\mathrm{AG,Sol}}$ are obtained, they are combined to create the updated agricultural Boolean exclusion matrix:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 692
$$\mathbf{XCM}_{mr\ell}^{\mathrm{AG,Sol}} = \begin{cases} \mathbf{DAAC}_{r\ell}^{\mathrm{AG,Sol}} & \text{if} \quad m = 0 \\ \mathbf{IAAC}_{r\ell}^{\mathrm{AG,Sol}} & \text{if} \quad m = 1 \end{cases}$$	

where:

- $\mathbf{XCM}_{mr\ell}^{\mathrm{AG,Sol}}$ is the updated Boolean exclusion matrix reflecting the allocation decisions across dryland and irrigation agricultural systems.

24.7.2.2. Non-Agricultural Land-Use Decision Variables

To allocate cells in the optimized solution to non-agricultural land use classes, we define:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	Equation 693
$$\mathbf{NAAC}_{r\ell}^{\mathrm{NonAG,Sol}} = 0_{(N_c \times N_{lu})}$$	

where,

- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\mathrm{BYear}}$.
- N_{lu} is 8, as the set $\mathcal{L}_{\mathrm{NonAgrLand}}$ includes 8 non-agricultural land-use classes (Equation 13).

This matrix is updated as:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\mathrm{NonAgrLand}}$	Equation 694

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$$\mathbf{NAAC}_{r\ell}^{\text{NonAG,Sol}} = \begin{cases} \mathbf{NAAC}_{r\ell}^{\text{NonAG}} & \text{if} \quad \mathbf{NonAgCells}_r = \text{True} \\ 0 & \text{otherwise} \end{cases}$$	

where,

- $\mathbf{NAAC}_{r\ell}^{\text{NonAG,Sol}}$ represents the allocated cells in the optimised solution to non-agricultural land uses.
- $\mathbf{NAAC}_{r\ell}^{\text{NonAG}}$ represents the allocation to non-agricultural land use (Equation 676)
- $\mathbf{NonAgCells}_r$ is a Boolean tensor indicating non-agricultural cells (Equation 239)

To produce the updated Boolean exclusion matrix identifying the dominant non-agricultural class per cell:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 695
$$\mathbf{XCM}_{r\ell}^{\text{NonAG,Sol}} = \begin{cases} \text{True} & \text{if} \quad \ell = \underset{\ell \in \mathcal{L}_{\text{NonAgrLand}}}{\text{Argmax}} \ \mathbf{NAAC}_{r\ell}^{\text{NonAG,Sol}} \\ \text{False} & \text{otherwise} \end{cases}$$	

The computed $\mathbf{XCM}_{r\ell}^{\text{NonAG,Sol}}$ simplifies analysis by clearly indicating the dominant non-agricultural land-use class for each cell.

24.7.2.3. Resolving Conflicts Between Agricultural and Non-Agricultural Land-Use Decision Variables

To resolve the conflict between agricultural ($\mathbf{XCM}_{mr\ell}^{\text{AG,Sol}}$) and non-agricultural variables ($\mathbf{XCM}_{r\ell}^{\text{NonAG,Sol}}$) decisions:

$\forall r \in \{1, \dots, N_r\}, m \in \{1,2\}, \ell_i \in \mathcal{L}_{\text{NonAgrLand}}, \ell_j \in \mathcal{L}$	Equation 696
$$\mathbf{RCBM}_r^{\text{AG,NonAG}} = \begin{cases} \text{True} & \text{if} \quad \underset{\ell_i \in \mathcal{L}_{\text{NonAgrLand}}}{\text{Argmax}} \ \mathbf{XCM}_{r\ell_i}^{\text{NonAG,Sol}} > \underset{\ell_j \in \mathcal{L}, m \in \{1,2\}}{\text{Argmax}} \ \mathbf{XCM}_{mr\ell_j}^{\text{AG,Sol}} \\ \text{False} & \text{otherwise} \end{cases}$$	

where,

- $\mathbf{XCM}_{mr\ell}^{\text{AG,Sol}}$ represents the updated Boolean exclusion matrix for agricultural land use lll under both dry and irrigation land management systems (Equation 692)
- $\mathbf{XCM}_{r\ell}^{\text{NonAG,Sol}}$ represents the allocated cells in the optimized solution to non-agricultural land-use classes (Equation 695)
- $\mathbf{RCBM}_r^{\text{AG,NonAG}}$ represents the resolving conflict binary matrix

This step creates a binary vector that classifies each cell r as::

- **True**, if the cell is dominated by non-agricultural land use.
- **False**, if the cell is dominated by agricultural land use.

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Then, to resolve the conflicts,

For cells dominant by non-agricultural land use, LUTO sets all agricultural allocation to zero:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	Equation 697
$\mathbf{XCM}_{mr\ell}^{\text{AG,Sol}} = \begin{cases} 0 & \text{if} \quad \mathbf{RCBM}_r^{\text{AG,NonAG}} = \text{True} \\ \mathbf{XCM}_{mr\ell}^{\text{AG,Sol}} & \text{otherwise} \end{cases}$	

For cells dominant by agricultural land use, LUTO sets all non-agricultural allocation to zero:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 698
$\mathbf{XCM}_{r\ell}^{\text{NonAG,Sol}} = \begin{cases} 0 & \text{if} \quad \mathbf{RCBM}_r^{\text{AG,NonAG}} = \text{False} \\ \mathbf{XCM}_{r\ell}^{\text{NonAG,Sol}} & \text{otherwise} \end{cases}$	

24.7.2.4. Agricultural Management Practices Decision Variables

To allocated cells in the optimised solution to agricultural land management practices under both dry ($\mathbf{DAAC}_{\text{Dry}}^{\text{AGMP,Sol}}$) and irrigation ($\mathbf{IAAC}_{\text{Irr}}^{\text{AGMP,Sol}}$) management systems, the following are defined:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}, k \in \mathcal{K}$	Equation 699
$\mathbf{DAAC}_{\text{Dry}}^{\text{AGMP,Sol}} = \{k \rightarrowtail \mathbf{DAAC}_{r\ell}^{\text{AGMP}} \mid r \in \{1, \dots, N_r\}, k \in \mathcal{K}, \mathbf{DAMC}_{r\ell}^{\text{AGMP}} \in \mathbb{R}^{N_c \times N_{lu}}\}$	
$\mathbf{IAAC}_{\text{Irr}}^{\text{AGMP,Sol}} = \{k \rightarrowtail \mathbf{IAAC}_{r\ell}^{\text{AGMP}} \mid r \in \{1, \dots, N_r\}, k \in \mathcal{K}, \mathbf{IAMC}_{r\ell}^{\text{AGMP}} \in \mathbb{R}^{N_c \times N_{lu}}\}$	Equation 700
$\mathbf{DTEMP}_{r\ell}^{\text{AGMP}} = \mathbf{ITEMP}_{r\ell}^{\text{AGMP}} = 0_{(N_c \times N_{lu})}$	Equation 701
$\mathbf{TEMP}_{mr\ell}^{\text{AGMP}} = 0_{(N_k \times N_c \times N_{lu})}$	

where,

- $\mathcal{K}$ is the set of agricultural management practices applicable to different land uses (Equation 22).
- $\mathbb{R}^{N_c \times N_{lu}}$ is the real-valued matrix space for cells and land uses.
- N_c is the number of land-use cells (from $\mathbf{LUM}^{\text{BYear}}$)
- N_c is the number of cells in the land-use map $\mathbf{LUM}^{\text{BYear}}$.
- $N_{lu} = 28$ is the number of agricultural land-use types (Equation 1).
- $N_k = 2$ is the number of management practices $m \in \mathcal{M}$ (Equation 21).

The matrices are updated based on the optimization outputs:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 702
• From dry management:	
$\mathcal{X}_{\text{Dry}}^{\text{AGMP}} \longrightarrow \mathbf{AMPDV}_{r\ell}^{\text{Dry,AGMP}}, \qquad \forall k \in \mathcal{K}$	
• From irrigation management:	
$\mathcal{X}_{\text{Irr}}^{\text{AGMP}} \longrightarrow \mathbf{AMPDV}_{r\ell}^{\text{Irr,AGMP}}, \qquad \forall k \in \mathcal{K}$	
• For dryland agricultural management practice decision variables:	
$\mathbf{DTEMP}_{r\ell}^{\text{AGMP}} = \begin{cases} \mathbf{AMPDV}_{r\ell}^{\text{Dry,AGMP}} & \forall \ell \in \phi(k) \\ 0 & \text{otherwise} \end{cases}$	
• For irrigation agricultural management practice decision variables:	
$\mathbf{ITEMP}_{r\ell}^{\text{AGMP}} = \begin{cases} \mathbf{AMPDV}_{r\ell}^{\text{Irr,AGMP}} & \forall \ell \in \phi(k) \\ 0 & \text{otherwise} \end{cases}$	
• Then, combining them into one tensor:	
$\mathbf{TEMP}_{mr\ell}^{\text{AGMP}} = \begin{cases} \mathbf{DTEMP}_{r\ell}^{\text{AGMP}} & \text{if} \quad \text{m} = 0 \\ \mathbf{ITEMP}_{r\ell}^{\text{AGMP}} & \text{if} \quad \text{m} = 1 \end{cases}$	
• Finally, the agricultural management practice solution dictionary is:	
$\mathcal{X}_{k,mr\ell}^{\text{AGMP,Sol}} = \{k \rightarrowtail \mathbf{TEMP}_{mr\ell}^{\text{AGMP}} \mid k \in \mathcal{K}\}$	

where,

- $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}$ is the irrigation agricultural management decision variable dictionary (Equation 566)
- $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}$ is the dryland agricultural management decision variable dictionary (Equation 566)
- $\phi(k)$ is the mapping from management practice k to its applicable land use types.
- $\mathcal{K}$ is the set of agricultural management practices applicable to different land uses (Equation 22).
- $\mathbf{AMPDV}_{r\ell}^{\text{Dry,AGMP}}$ and $\mathbf{AMPDV}_{r\ell}^{\text{Irr,AGMP}}$ are decision variables for dry and irrigation management practices, respectively.

24.7.2.5. Updating Land Use and Land Management Maps

The updated land use and land management maps are computed as follows:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \mathcal{L}$	

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$$\mathbf{LUM}_r^{\text{Current}} = \underset{\ell \in \mathcal{L}}{\text{Argmax}}\, \mathbf{XCM}_{mr\ell}^{\text{AG,Sol}}$$	Equation 703
$$\mathbf{LMM}_r^{\text{Current}} = \underset{m \in \{\mathbf{0},\mathbf{1}\}}{\text{Argmax}}\, \mathbf{XCM}_{mr\ell}^{\text{AG,Sol}}$$	Equation 704

where,

- $\mathbf{XCM}_{mr\ell}^{\text{AG,Sol}}$ is the updated Boolean exclusion matrix for agricultural land use classes under dry and irrigated systems (Equation 697)
- Argmax finds the index ℓ (or m) corresponding to the maximum value.

Since the labels for non-agricultural land use classes start from 100, the class label in $\mathbf{LUM}_r^{\text{Current}}$ must be adjusted as follows:

$\forall r \in \{1, \dots, N_r\}, \ell \in \mathcal{L}_{\text{NonAgrLand}}$	Equation 705
$$\mathbf{LUM}_r^{\text{NonAG,Sol}} = \underset{\ell \in \mathcal{L}}{\text{Argmax}}\, \mathbf{NAAC}_{r\ell}^{\text{NonAG,Sol}}$$	
$\forall r \in \{1, \dots, N_r\}$	Equation 706
$$\mathbf{LUM}_r^{\text{Current}} = \begin{cases} \mathbf{LUM}_r^{\text{NonAG,Sol}} + 100 & \text{if} \quad r \in \{\mathbf{LUM}_r^{\text{NonAG,Sol}} > 0\} \\ \mathbf{LUM}_r^{\text{Current}} & \text{otherwise} \end{cases}$$	

where,

- $\mathbf{NAAC}_{r\ell}^{\text{NonAG,Sol}}$ represents the allocated cells in the optimised solution to non-agricultural land use classes (Equation 694)
- $\mathbf{LUM}_r^{\text{NonAG,Sol}}$ represents the updated land use map for non-agricultural land use classes, based on the optimized solution
- $\mathbf{LUM}_r^{\text{Current}}$ is the final updated land use map, combining agricultural and non-agricultural land use classes after optimization (Equation 703)

As the irrigation land use management type is not considered for non-agricultural land use classes; hence, the values of $\mathbf{LMM}_r^{\text{Current}}$ for those cells must be updated, as:

$\forall r \in \{1, \dots, N_r\}$	Equation 707
$$\mathbf{LMM}_r^{\text{Current}} = \begin{cases} 0 & \text{if} \quad r \in \{\mathbf{LUM}_r^{\text{NonAG,Sol}} > 0\} \\ \mathbf{LMM}_r^{\text{Current}} & \text{otherwise} \end{cases}$$	

where,

$\mathbf{LMM}_r^{\text{Current}}$ is the updated management map (Equation 704)

The updated land use map for agricultural management practices ($\mathbf{LUM}_{k,r}^{\text{AGMP,Sol}}$) is calculated as:

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$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\}, \ell \in \phi(k), k \in \mathcal{K}$	Equation 708
Step 1: Extract dryland and irrigated management decision variables	
$\mathcal{X}_{\text{Dry}}^{\text{AGMP}} \longrightarrow \mathbf{AMPDV}_{r\ell}^{\text{Dry,AGMP}}, \qquad \forall k \in \mathcal{K}$	
$\mathcal{X}_{\text{Irr}}^{\text{AGMP}} \longrightarrow \mathbf{AMPDV}_{r\ell}^{\text{Irr,AGMP}}, \qquad \forall k \in \mathcal{K}$	
Step 2: Temporary allocation	
$\mathbf{TEMP}_{r}^{\text{AGMP}} = \begin{cases} \mathbf{AMPDV}_{r\ell}^{\text{Dry,AGMP}} & \text{if} \quad \text{m} = 0 \\ \mathbf{AMPDV}_{r\ell}^{\text{Irr,AGMP}} & \text{if} \quad \text{m} = 1 \end{cases}$	
Step 3: Generate the agricultural management presence layer	
$\mathbf{LUMT}_{r}^{\text{AGMP}} = \begin{cases} 1 & \text{if} \quad \mathbf{TEMP}_{r}^{\text{AGMP}} \geq 0.1 \\ 0 & \text{otherwise} \end{cases}$	
Step 4: Final agricultural management practice map	
$\mathbf{LUM}_{k,r}^{\text{AGMP,Sol}} = \{k \rightarrowtail \mathbf{LUMT}_{r}^{\text{AGMP}} \mid k \in \mathcal{K}\}$	

where,

- $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}$ represents a dictionary of agricultural management practice decision variables for irrigation management (Equation 566)
- $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}$ represents a dictionary of agricultural management practice decision variables for dryland management (Equation 566)
- $\mathcal{K}$ is the set listing agricultural management practices that can be applied to different land use types (Equation 22)

24.8. Total Commodity Contributions in Production

The total production for each commodity $\ell_{Com} \in \mathcal{L}_{\text{Commodities}}$ is represents as:

$\forall r \in \{1, \dots, N_r\}, m \in \{0,1\} \; \exists k, k \in \mathcal{K}$	Equation 709
$\mathbf{TotProd}^{AG,NonAg} = \left\{ \begin{matrix} k \rightarrowtail \mathbf{TQCR}_{\ell_{Com}}^{AG,NonAg} & \text{if} & k \in (\text{"Production"}) \\ k \rightarrowtail \mathbf{GHG}^{Net} & \text{if} & k \in (\text{"GHG Emission"}) \\ k \rightarrowtail \mathbf{BSM}^{Net} & \text{if} & k \in (\text{"Biodiversity"}) \end{matrix} \right\}$	

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where,

- $\mathbf{TQCR}_{\ell_{Com}}^{AG,NonAg}(y)$ represents the total quantity of commodity contributions across all land-use types (Equation 623)
- $\mathbf{GHG}^{Net}$ represents the total GHG emissions across all agricultural and non-agricultural land use types (Equation 644)
- $\mathbf{BSM}^{Net}$ represents the total biodiversity contribution across all agricultural and non-agricultural land-use types (Equation 653)

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25. Model Simulation

The simulation method typically performs the following operations:

25.1. Define Simulation Period:

The simulation period is defined as:

$\text{SimPeriod} = [\text{BaseYear}, \text{TargetYear}]$	Equation 710

defines the range of years over which the simulation will run. It can be explained as:

25.1.1. Defines the Start and End Points:

- **Base Year (**BaseYear**)**: The starting point of the simulation, representing initial system conditions.
- **Target Year (**TargetYear**)**: The endpoint of the simulation, marking the full scope and duration.

25.1.2. Establishes a Timeline:

This range determines the number of time steps (T) included in the simulation. For examples:

- If $\text{BaseYear} = 2010$ and $\text{TargetYear} = 2100$, the simulation covers all years from 2010 to 2100, inclusive.

25.1.3. Provides a Framework for Iteration:

For each $t \in [\text{BaseYear}, \text{TargetYear}]$, sequential operations (e.g., solving equations, updating decision variables) are performed year by year.

- Solving optimization problems
- Updating decision variables
- Recording system outputs

25.1.4. Organizes Data Storage:

Simulation outputs are grouped and stored by year, improving organization, traceability, and post-analysis.

25.2. Practical Implications

25.2.1. Simulation Steps:

The number of steps is calculated as:

$\text{Steps} = \text{TargetYear} - \text{BaseYear}$	Equation 711

For each simulation step $s \in \{0,1,\cdots,\text{Steps} - 1\}$, the corresponding year is computed as:

$t = \text{BaseYear} + s + 1$	Equation 712

In all previous formulations, y corresponds to t, linking the simulation step to the actual temporal year.

25.2.2. Yearly Updates:

For each t in the simulation period , the following updates occur:

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- **Inputs**: Demands, boundary conditions, and other required inputs for the year are loaded and processed.
- **Decision Variables:** Updated to reflect changes relevant to that specific year t.
- **Results**: For each year y (where $y = t$), results are stored, including:
    - Updated land-use maps.
    - Production outputs (e.g., commodities, GHG emissions, biodiversity scores).
    - Objective function values.

25.2.3. Boundary Conditions:

- The **Base Year** (BaseYear)

  Represents the initial conditions of the system (e.g., starting land-use and management configuration).

- The **Target Year** (TargetYear)

  Defines the final modeled state, guiding the optimization toward the simulation objectives.

25.2.4. Set Paths for Outputs Storage:

To systematically organize simulation outputs, the following directory structure is established:

The directory structure is defined as:

$\text{OutputDirectory} = f(\text{BaseYear}, \text{TargetYear})$	Equation 713

Where f is a formatting function that dynamically generates unique output paths for each simulation run.

Outputs stored in these directories include:

- Decision variable solutions (e.g., land use allocations, agricultural management adoption levels).
- Updated land-use and land-management maps.
- Objective values and model evaluation metrics.

25.3. Data Organization in the Simulation Process:

During simulation initialization, the model configures file paths and data structures to manage intermediate outputs and final results.
This organization ensures that all outputs are correctly grouped by simulation year, maintaining traceability, consistency, and efficiency throughout the simulation process.

25.3.1. Implications of $f(\text{BaseYear}, \text{TargetYear})$

The function call $f(\text{BaseYear}, \text{TargetYear})$ serves critical roles:

25.3.2. Path Initialization:

- Unique directories and file paths are automatically created.
- This prevents overwriting or misplacing simulation data across different runs.
- Results, decision variables, maps, and objective values are systematically saved under year-specific folders.

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25.3.3. Simulation Preparation:

- The data object is configured to handle all required input and output files across the full simulation period $[\text{BaseYear}, \text{TargetYear}]$.
- This preparation enables all downstream model functions to efficiently locate, read, and save the necessary data.

25.3.4. Ensures Compatibility:

- Consistency is established between the defined simulation period and the available time-series input data (e.g., demands, climate data, land-use states).
- Ensures that each simulation year is correctly matched to its corresponding input dataset, avoiding data misalignment.

25.3.5. Error Prevention:

- Automatically checks for the existence of required directories.
- Missing paths are created dynamically, or appropriate errors are raised if directory creation fails.
- This mechanism prevents runtime crashes caused by absent or improperly structured output folders.

25.3.6. Improved Traceability:

- Outputs are organized by simulation year, facilitating:
    - Easier result tracking
    - More straightforward error diagnosis
    - Better reproducibility of simulation runs
- Users can quickly retrieve year-specific data for reporting, analysis, or visualization.

25.3.7. Supports for Sequential Processing:

- Enables sequential year-by-year updates of variables, land-use maps, management decisions, and simulation outputs.
- No manual interventions are needed to manage yearly data flows

25.3.8. Alignment with Simulation Goals:

- Guarantees that all generated outputs (maps, commodity totals, GHG emissions, biodiversity scores, etc.) reflect the intended temporal horizon from Base Year to Target Year.
- Aligns the simulation framework precisely with the study's analytical and policy objectives.

25.4. Simulation Modes

25.4.1. Timeseries Mode

In Timeseries Mode, the simulation runs sequentially over the entire defined period $\text{SimPeriod} = \text{TargetYear} - \text{BaseYear}$.

25.4.1.1. Validation Conditions:

The Demand Matrix **DCY** must satisfy certain properties:

$\mathbf{DCY} \in \mathbb{R}^{T \times C}, \quad T > 0 \quad , \quad C > 0$	Equation 714

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where,

- T: Number of years available (e.g., $T = 91$ for 2010–2100).
- C: Number of commodities modeled.

DCY provides data across five categories:

- Domestic,
- Exports,
- Imports,
- Feed,
- Production,

for climate scenarios SSP 126, SSP 245, SSP 370, and SSP 585.

The simulation period must satisfy:

$$(\text{TargetYear} - \text{BaseYear}) \leq T$$	Equation 715

where T is the total number of available years in the dataset.

If the condition is violated:

$$(\text{TargetYear} - \text{BaseYear}) > T \implies \text{Simulation Undefined}$$	Equation 716

25.4.1.2. Steps Calculation:

The number of simulation steps is calculated as:

$$\text{Steps} = \text{TargetYear} - \text{BaseYear}$$	Equation 717

25.4.1.3. Solve Timeseries:

The solver iteratively computes the state for each year $t \in [\text{BaseYear} + 1, \text{TargetYear}]$:

$$\text{State}_t = S_{\text{timeseries}}(\text{Data}, t), \forall t \in [\text{BaseYear} + 1, \text{TargetYear}]$$	Equation 718

Here,

- $S_{\text{timeseries}}$ denotes the timeseries solving operation.
- State_t represents the computed outputs for year t (e.g., land use, production results). t (e.g., decision variables, land-use allocations).

Alternatively, it can be expressed for the entire period:

$$\{\text{State}_t\}_{t=\text{BaseYear}+1}^{\text{TargetYear}} = S_{\text{timeseries}}(\text{Data}, \text{Steps}, \text{BaseYear}, \text{TargetYear})$$	Equation 719

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25.4.2. Snapshot Mode

In Snapshot Mode, the simulation evaluates the system state for a single year, specifically the TargetYear.

25.4.2.1. Input Preparation:

Input data for the target year is processed as:

$\text{Input}_{\text{TargetYear}} = \mathcal{P}(\text{Data}, \text{BaseYear}, \text{TargetYear})$	Equation 720

where $\mathcal{P}$ represents the input preparation procedure.

25.4.2.2. State Computation:

snapshot solver then computes the state for TargetYear :

$\text{State}_{\text{TargetYear}} = S_{\text{snapshot}}(\text{Input}_{\text{TargetYear}})$	Equation 721

Alternatively:

$\text{State}_{\text{TargetYear}} = S_{\text{snapshot}}(\mathcal{P}(\text{Data}, \text{BaseYear}, \text{TargetYear}))$	Equation 722

Here,

- S_{snapshot} denotes the snapshot-specific solving operation.
- $\text{State}_{\text{TargetYear}}$ represents the decision variables and outputs for the TargetYear.

25.4.3. Error Handling for Unknown Modes

The simulation mode MODE must belong to the recognized set:

$\text{MODE} \in \{\text{'timeseries'}, \text{'snapshot'}\}$	Equation 723

If violated:

$\text{If} \quad \text{MODE} \notin \{\text{'timeseries'}, \text{'snapshot'}\} \Longrightarrow \textit{S}\text{imulation Invalid}$	Equation 724

Alternatively:

$\text{If} \quad \text{MODE} \notin \{\text{'timeseries'}, \text{'snapshot'}\} \Longrightarrow \text{Simulation Undefined}$	Equation 725

25.4.4. Solver Initialization at the First Step

If $s = 0$ (the first simulation step), the solver is initialized:

$\text{Solver}_t = S_{\text{init}}(\text{InputData}_t, \mathbf{DCY}_{C,t}, \text{TargetYear})$	Equation 726

where,

- S_{init} initializes the solver based on the input data and demand matrix.

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25.4.5. Solver Update for Subsequent Steps

For $s > 0$ (subsequent years), the solver is updated using the previous state:

$S_{\text{update}} = \mathcal{U}(\text{InputData}_t, \mathbf{DCY}_{C,t}, \text{OldState}, \mathbf{LUM}^{BYear}, \mathbf{LMM}^{BYear})$	Equation 727

where:

- OldState includes:
  - $\mathbf{D}_{mr\ell}^{AG}(y)$: Agricultural decision variables for $\ell \in \mathcal{L}$ (Equation 1)
  - $\mathbf{D}_{mr\ell}^{NonAgLU}(y)$: Non-agricultural decision variables for $\ell \in \mathcal{L}_{\text{NonAgrLand}}$ (Equation 13)
  - $\mathbf{D}_{mr\ell}^{AgManag}(y)$: Agricultural management practice decision variables for $\ell \in \mathcal{K}$ (Equation 22)
  - $\mathbf{LUM}^{BYear}$ and $\mathbf{LMM}^{BYear}$: Base year land-use and management maps

25.4.6. Solve the Optimization Problem

The optimization problem is solved for each year t:

$\text{Solution} = S_{\text{solve}}(\text{Solver}_t)$	Equation 728

where:

- S_{solve} represents the optimization solving process.
- Solver_t includes necessary inputs for the base year t, such as
  - $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(t)$: Dryland agricultural management practices variables initialization,
  - $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(t)$: Irrigation agricultural management practices variables initialization,
  - $\mathbf{LB}_{mr\ell}^{\text{AGMP}}$: Lower bound matrices for agricultural management practices,
  - $\mathbf{XCM}_{r\ell}^{\text{NonAgToAg}}$**:** Non-agricultural exclusions matrix,
  - $\mathbf{LB}_{r\ell}^{\text{NonAg}}$: Lower bound matrices for non-agricultural land use,
  - $\mathbf{LUM}^{BYear}$: Land-use map for the base year t,
  - $\mathbf{LMM}^{BYear}$: Land management map for the base year t,
  - $\mathbf{DCY}_{C,t}$**:** The demand Matrix for year t,
- The Solution for the target year $TYear$ includes:
  - $\mathbf{LUM}_{TYear}$: Optimized land-use map for the target year $TYear$.
  - $\mathbf{LMM}_{TYear}$: Optimized land-management map for the target year $TYear$.
  - $\mathbf{D}_{mr\ell}^{AG}(TYear)$: Agricultural decision variables for the target year $TYear$.
  - $\mathbf{D}_{mr\ell}^{NonAgLU}(TYear)$: Non-agricultural decision variables for the target year $TYear$.
  - $\mathbf{LUM}_{TYear}^{\text{AGMP}}$: Agricultural management practices map for the target year $TYear$.

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- $\mathbf{D}_{mr\ell}^{AgManag}(TYear)$: Agricultural management practice decision variables for the target year $TYear$.
- ObjValt_{TYear}: Objective value for the optimization.
- $\mathbf{ObjContr}_{k}^{\text{AGMP}}(TYear)$**:** Contribution of management practices.
- $\mathbf{AMPDV}_{\ell r}^{\text{Dry,AGMP}}(TYear)$**:** Extracted matrix of dryland agricultural management practice decision variables for cell r, land use ℓ, and agricultural management practice key $k \in \mathcal{K}$.
- $\mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(TYear)$**:** Extracted matrix of irrigation agricultural management practice decision variables for the target year, associated with key $k \in \mathcal{K}$.

25.4.7. Update Simulation Data

The simulation outputs for the target year $TYear$ are stored into the data structure:

$\mathbf{LUM}_{TYear} \longrightarrow$ Data $\mathbf{LMM}_{TYear} \longrightarrow$ Data $\mathbf{LUM}_{TYear}^{\text{AGMP}} \longrightarrow$ Data $\mathbf{D}_{mr\ell}^{AG}(TYear) \longrightarrow$ Data $\mathbf{D}_{mr\ell}^{NonAgLU}(TYear) \longrightarrow$ Data $\mathbf{D}_{mr\ell}^{AgManag}(TYear) \longrightarrow$ Data $\mathbf{ObjContr}_{k}^{\text{AGMP}}(TYear) \longrightarrow$ Data $\mathbf{AMPDV}_{\ell r}^{\text{Irr,AGMP}}(TYear) \longrightarrow$ Data	Equation 729

25.4.8. Production Data

For each production data type ℓ, the outputs are stored:

$ProdData_{t,i} \longrightarrow$ Data	Equation 730

Where:

- $t = \text{TargetYear}$ **,**
- i is the index corresponding to each production data category ℓ.

Alternatively, using summation for all production categories:

$\{ProdData_{t,i}\}_{i=1}^{n} \longrightarrow$ Data	Equation 731

25.5. Timeseries Simulation Process

The timeseries simulation evaluates the system state iteratively for each year in the simulation period, from BaseYear to TargetYear, over Steps time steps.

25.5.1. Simulation Setup

For each simulation step $s \in \{0,1,\ldots,\text{Steps}-1\}$, the year is computed as:

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$t = \text{BaseYear} + s + 1$	Equation 732

25.5.2. Input Preparation

For target year t, the input data and demand vector are prepared as:

$\text{InputData}_{\text{t}} = \mathcal{P}(\text{Data}, t-1, t)$	Equation 733
$\mathbf{DCY}_{C,t} = \mathbf{DCY}$	Equation 734

where:

- $\mathcal{P}$ represents the input preparation function (e.g. "get_input_data").
- $\mathbf{DCY}$ is the demand matrix, with each element $\mathbf{DCY}_{C,t}$ specifying the demand for commodities in year t.

25.5.3. Solver Initialization

If $s = 0$ (the first step), the solver is initialized as:

$\text{Solver}_t = S_{\text{init}}(\text{InputData}_t, \mathbf{DCY}_{C,t}, \text{TargetYear})$	Equation 735

where S_{init} initializes the solver and formulates the optimization problem.

25.5.4. Solver Update for Subsequent Steps

For $s > 0$, the solver is updated using the previous state:

$S_{\text{update}} = \mathcal{U}\left(\text{InputData}_t, \mathbf{DCY}_{C,t}, \text{OldState}, \mathbf{LUM}_{t-1}, \mathbf{LMM}_{t-1}\right)$	Equation 736

where:

- OldState includes:
  - $\mathbf{D}_{mr\ell}^{AG}(y)$: Agricultural decision variables for $\ell \in \mathcal{L}$ (Equation 1)
  - $\mathbf{D}_{mr\ell}^{NonAgLU}(y)$: Non-agricultural decision variables for $\ell \in \mathcal{L}_{\text{NonAgrLand}}$ (Equation 13)
  - $\mathbf{D}_{mr\ell}^{AgManag}(y)$: Agricultural management practice decision variables for $\ell \in \mathcal{K}$ (Equation 22)
- $\mathbf{LUM}_{t-1}$ and $\mathbf{LMM}_{t-1}$ are the land-use and management maps for the previous year.

25.5.5. Solve the Optimization Problem

The solver computes the optimized state for year t:

$\text{Solution} = S_{\text{solve}}(\text{Solver}_t)$	Equation 737

where:

- S_{solve} represents the optimization process.
- Solver_t includes the required data for year t and $t-1$, such as
  - $\mathcal{X}_{\text{Dry}}^{\text{AGMP}}(t)$: Dryland agricultural management practices variables initialization,
  - $\mathcal{X}_{\text{Irr}}^{\text{AGMP}}(t)$: Irrigation agricultural management practices variables initialization,

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- $\mathbf{LB}_{mr\ell}^{\mathrm{AGMP}}$: Lower bound matrices for agricultural management practices,
- $\mathbf{XCM}_{r\ell}^{\mathrm{NonAgToAg}}$**:** Non-agricultural exclusions matrix,
- $\mathbf{LB}_{r\ell}^{\mathrm{NonAg}}$: Lower bound matrices for non-agricultural land use,
- $\mathbf{LUM}_{t-1}$: Land-use map for time $t-1$,
- $\mathbf{LUM}_{t}$: Land-use map for time t,
- $\mathbf{LMM}_{t-1}$: Land management map for time $t-1$,
- $\mathbf{LMM}_{t}$: Land management map for time t,
- $\mathbf{DCY}_{C,t}$**:** The demand Matrix.

- Solution outputs include the following parameters for time $t+1$:
  - $\mathbf{LUM}_{t+1}$: Optimized land-use map,
  - $\mathbf{LMM}_{t+1}$: Optimized land-management map,
  - $\mathbf{D}_{mr\ell}^{AG}(t+1)$: Agricultural decision variables for year t,
  - $\mathbf{D}_{mr\ell}^{NonAgLU}(t+1)$: Non-agricultural decision variables for year t,
  - $\mathbf{LUM}_{t+1}^{\mathrm{AGMP}}$: The land use map for agricultural management practices,
  - $\mathbf{D}_{mr\ell}^{AgManag}(t+1)$: Agricultural management practice decision variables for year t,
  - $\mathrm{ObjValt}_{t+1}$: Objective value for the optimization,
  - $\mathbf{ObjContr}_{k}^{\mathrm{AGMP}}(t+1)$**:** Total contribution of production and transition costs for all agricultural management practices $\mathcal{K}$ in the objective function,
  - $\mathbf{AMPDV}_{\ell r}^{\mathrm{Dry,AGMP}}(t+1)$: Extracted matrix of dryland agricultural management practice decision variable matrix associated with key k , $k \in \mathcal{K}$,
  - $\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(t+1)$: Extracted matrix of irrigation agricultural management practice decision variable matrix associated with key k , $k \in \mathcal{K}$,

25.5.6. Update Simulation Data

The computed results for year t are stored in the data object:

$\mathbf{LUM}_{t+1} \longrightarrow$ Data $\mathbf{LMM}_{t+1} \longrightarrow$ Data $\mathbf{LUM}_{t+1}^{\mathrm{AGMP}} \longrightarrow$ Data $\mathbf{D}_{mr\ell}^{AG}(t+1) \longrightarrow$ Data $\mathbf{D}_{mr\ell}^{NonAgLU}(t+1) \longrightarrow$ Data $\mathbf{D}_{mr\ell}^{AgManag}(t+1) \longrightarrow$ Data $\mathbf{ObjContr}_{k}^{\mathrm{AGMP}}(t+1) \longrightarrow$ Data	Equation 738

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$\mathbf{AMPDV}_{\ell r}^{\mathrm{Irr,AGMP}}(t+1) \longrightarrow \mathrm{Data}$	

25.5.7. Production Data

For each production data type ℓ, the outputs are stored:

$ProdData_{t,i} \longrightarrow \mathrm{Data}$	Equation 739

Where:

- $t = \mathrm{TargetYear}$ is the target simulation year.
- i is the index corresponding to the production data type ℓ.

Alternatively, using summation notation for all n production data types:

$\{ProdData_{t,i}\}_{i=1}^{n} \longrightarrow \mathrm{Data}$	Equation 740

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