Technical Manual for Land Use Allocation model

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NIES

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1. The Land Use Allocation Model

1.1 Fundamental Approach

- In the model, the land owner determines the allocation of land use based on economic rationality to maximize profit (minimize costs) obtained from the production in each grid cell. Here, profit is defined as revenue minus expenses.
- Optimization problems are solved for a single country or region. Cross-regional exchanges are not considered within this model.
- The demand for land use related to human production activity is set exogenously. That is, the demand for land needed for production of agricultural and forest goods is set exogenously and the model searches for land use allocations that meet that demand. Other land is land that is not required for human production activity.
- The model is sequential; the results for land use distribution for each period are passed to the next period.
- The units for geographic information are 0.5° × 0.5° grid cells.
- The potential production per unit area of each grid cell (hereinafter productivity) is calculated considering biophysical conditions.

1.2 Formularization

Unless otherwise specified, the formulas are for a certain country or region in a certain year.
Gross profit is maximized.

$$\Phi = \sum_{l,g} Z_{l,g} \rightarrow \text{Max.} \qquad \text{(EQOBJ)}$$

Profit is defined as revenue minus costs (including land use conversion costs). Land use conversion cost a_{lg} is applied to the conversion of land use from the previous time period. Land use conversion costs are derived from the fractional increase in area for a given land use.

$$Z_{l,g} = Y_{l,g} \cdot \overline{S_{l,g}} - \overline{a_{l,g}} \cdot \Delta YP_{l,g}, \qquad g \in G,\ l \in L \qquad \text{(EQPRF}(l,g))$$

a_{lgI}: land conversion cost per area (US$)

In order to calculate land use conversion costs based on increase in fractional area, land use change is divided into factional increases and fractional decreases.

$$Y_{l,g} - \overline{Ypre_{l,g}} = \Delta YP_{l,g} - \Delta YN_{l,g} \qquad \text{(EQYPN}(l,g))$$

$\Delta YP_{l,g}(>0)$: Land use area fractional increase

$\Delta YN_{l,g}(>0)$: Land use area fractional decrease

The following conditions are imposed:
The share of each land use within a grid cell cannot be a negative value.

$$Y_{l,g} \geq 0, \quad g \in G, l \in L \qquad \text{(YL}(l,g))$$

The combined area of all land uses within a grid cell cannot exceed the area of the grid cell.

$$\sum_l Y_{l,g} \leq 1, \qquad g \in G, l \in L \qquad \text{(EQTOTY }(g))$$

The sum of demand (exogenous) for all land uses must be equal to the area $LDM_{t,l}$ or the area ratio.

$$\sum_g \overline{GA_g} \cdot Y_{l,g} = \overline{LDM_l}, \qquad l \in L \cap l \neq prmfrs \cap l \neq havfrs \cap l \neq afr \qquad \text{(EQLDM}(l))$$

$$\sum_{l' ifmapl(l',l)} \sum_g \overline{GA_g} \cdot Y_{l',g} = \overline{LDM_l}, \qquad l \in L \cap l \neq prmfrs \cap l \neq havfrs \cap l \neq afr \qquad \text{(EQLDM2}(l))$$

The amount of carbon stock harvested from wood production forests must be equal to the carbon equivalent of timber demand (exogenous).

$$\sum_g \overline{CS_{l,g}} \cdot Y_{l,g} \cdot \overline{GA_g} = \overline{\mathrm{CDM}_l}, \qquad l = havfrs \qquad \text{(EQCDM}(l))$$

$CS_{l,g}$: Carbon stock density [MgC/ha] for land use category l in grid cell g

The carbon flow absorbed by afforestation must be equal to the carbon absorbed by afforestation (exogenous).

$$\sum_{g} \overline{CF_{l,g}} \cdot Y_{l,g} \cdot \overline{GA_g} = \overline{\mathrm{CDM}_l}, \qquad l = afr \qquad \text{(EQCDM}(l)\text{)}$$

$CF_{l,g}$: Carbon flow (net absorption, negative absorption) [MgC/ha] for land use category l in grid cell g

Land that is not related to human production activity is the land remaining after the land used for human production activity is excluded from total land. That is, forest and grassland is equal to total land minus all land uses other than forest and grassland.

$$Y_{'prm\sec',g} = 1 - \sum_{l \neq prm\sec} Y_{l,g} \qquad \text{(EQYPRMSEC)}$$

In order to prevent protected areas from being converted to other land uses, the condition is imposed that the fraction of forest and grassland area must not be lower than the fraction of protected area.

$$Y_{'prm\sec',g} \geq \overline{Yprotect_g} \qquad \text{(EQYPROTECT(G))}$$

$Yprotect_g$: Fraction of protected area

$$Y_{l,g} - \overline{Ypre_{l,g}} \geq 0 \qquad \perp \quad RSAFR_{l,g} > 0 \quad , \qquad l = afr \qquad \text{(EQYAFR)}$$

Below $Y_{'prm\sec',g}$ is categorized as pasture, forest, and grassland.

Pasture

As there is not sufficient information regarding the mechanism for determining the distribution of pasture, the model simply assigns increases and decreases to the reference use distribution for the base year so as to meet demand.

$$sfpas0 = \frac{LDM_{'pas'}}{\sum_{g} Ybase_{'pas',g}}$$

$$Y_{'pas',g} = \begin{cases} Ybase_{'pas',g} \cdot sfpas & ,if\ Y_{'prm\sec',g} \geq Ybase_{'pas',g} \cdot sfpas0 \\ Y_{'prm\sec',g} & ,if\ Y_{'prm\sec',g} < Ybase_{'pas',g} \cdot sfpas0 \end{cases}$$

First, changes are applied uniformly to grid cells that have pastures in the base year. The following 4 equations comprising Loop 1 are repeated until $ADDpas = 0$ or $Ypas\_nfull = 0$. The former condition indicates that all pasture demand area has been allocated while the latter condition indicates that there is no surplus land $Y_{'prm\sec',g}$ in the grid cells where pastures existed in the base year.

Step 1: Change in pasture land in the selected grid cells

$$ADDpas = LDM_{'pas'} - \sum_{g} Y_{'pas',g} \qquad \text{(Loop1-1)}$$

$ADDpas(\geq 0)$: Area of added pasture land

$$Ypas\_nfull = \sum_{g\ if\ 0 < Y_{'pas',g} < Y_{'prm\sec',g}} \left(GA_g \cdot Y_{'pas',g} \right) \qquad \text{(Loop1-2)}$$

$Ypas\_nfull$: Pasture area of grid cells that contain pasture land and that have surplus land

$$sfpas = \frac{ADDpas}{Ypas\_nfull} \qquad \text{(Loop1-3)}$$

$$Y_{'pas',g} = \begin{cases} Y_{'pas',g} \cdot \left(1 + sfpas\right) & ,if\ Y_{'prm\sec',g} - Yprotect_g \geq Y_{'pas',g} \cdot \left(1 + sfpas\right) \\ Y_{'prm\sec',g} - Yprotect_g & ,if\ Y_{'prm\sec',g} - Yprotect_g < Y_{'pas',g} \cdot \left(1 + sfpas\right) \end{cases}$$

(Loop1-4)

If $ADDpas \neq 0$ then move on to Step 2.

Select grid cells as targets for expansion that do not have pasture land in the base year but are adjacent to grid cells that have pasture in the base year and that have carbon stock.

Step 2: Expansion of pasture land to adjacent grid cells

$$ADDpas = LDM_{'pas'} - \sum_{g} Y_{'pas',g} \qquad \text{(Loop2-1)}$$

$$PNBPAS_g = \sum_{g'\ if\ Y_{'pas',g'} > 0} WG_{g,g'}, \qquad if\ Y_{'pas',g} = 0\ and\ CDT_g > 0 \qquad \text{(Loop2-2)}$$

$PNBPAS_g$: Flag for grid cells with carbon stock but no pasture land that are adjacent to grid cells with pasture land.

$$AREA\_npas = \sum_{g\, if\, PNBPAS_g} \left(GA_g \cdot \left(Y_{'prm\sec',g} - Yprotect_g \right) \right) \qquad \text{(Loop2-3)}$$

$AREA\_npas$: Potential land area to be pasture

$$sfpas2 = \frac{ADDpas}{AREA\_npas} \qquad \text{(Loop2-4)}$$

$$Y_{'pas',g} = \begin{cases} Y_{'prm\sec',g} \cdot sfpas2 & ,if\ \ PNBPAS_g > 0,\ 0 < sfpas2 \le 1 and\ \ Y_{'prm\sec',g} - Yprotect_g \ge Y_{'prm\sec',g} \cdot sfpas2 \\ Y_{'prm\sec',g} - Yprotect_g & ,if\ \ PNBPAS_g > 0,\ 0 < sfpas2 \le 1 and\ \ Y_{'prm\sec',g} - Yprotect_g < Y_{'prm\sec',g} \cdot sfpas2 \\ Y_{'prm\sec',g} - Yprotect_g & ,if\ PNBPAS_g > 0,\ sfpas2 > 1 \end{cases}$$

(Loop2-5)

If $ADDpas > 0$ and $sfpas2 \le 1$, Step 1 and Step 2 are repeated until $ADDpas = 0$.

<u>Forest and Grassland</u>

Forests and grassland are classified based on carbon stock. The boundary criterion $\overline{CSB}$ for forests and grassland is set so that forest area matches the base year value from statistical data.

$$Y_{'prmfrs',g} = Y_{'prm\sec',g} \quad if\ \overline{CS_{l,g}} \ge \overline{CSB}$$

$$Y_{'gl',g} = Y_{'prm\sec',g} \quad if\ \overline{CS_{l,g}} < \overline{CSB}$$

However,

$\overline{CSB}$: Carbon stock [MgC/ha] is the boundary criterion between forests and grass lands.

1.3 Parameters Settings

(1) $WG_{g,g'}$

$WG_{g,g'}$ is a matrix that indicates whether grid cells g and g' are adjacent.

$$WG_{g,g'} = \begin{cases} 1 \text{ if the } g\text{th grid cell and the } g'\text{th g grid cell are adjacent} \\ 0 \text{ifthe gth grid cell and the } g'\text{thgrid cell are not adjacent} \end{cases}$$

		1	2			720
	1	g=1	g=2	g=3	· · ·	g=720
	2	g=721	g=722	g=723	· · ·	g=1440
		g=1441	g=1442	g=1443		
i						
				· · ·		
	360					

Grid cells adjacent to red grid cell

Figure 1 Image of grid cell number and adjacent grid cells

This can be calculated as follows:

$$WG_{g,g'} = \sum_{(i,j)\, if\, MGIJ_{g,i,j}} \; \sum_{(i',j')\, if\, MGIJ_{g',i',j'}} MIJ_{i,j,i',j'} \qquad \text{(WG}(g,g'))$$

where, $MIJ_{i,j,i',j'}$ represents the relationship between grid cell (i,j) and grid cell (i',j') and is 1 when the grid cells are adjacent and 0 when the grid cells are not adjacent.

$$MIJ_{i,j,i',j'} = \begin{cases} 1, & if \left\{ abs(i-i') <= 1 \text{ and } abs(j-j') <= 1 \, and \left(not\,(i = i' \, and \; j = j') \right) \right\} = TRUE \\ 0, & FALSE \end{cases}$$

(MIJ(i,ji',j'))

(2) Land conversion cost $a_{l,g}$

The land conversion cost $a_{l,g}$ per unit land area is expressed as follows:

$$a_{l,g} = pldc \cdot glmin_{l,g} + plcc_l + pirr_{l,g} + ctax \cdot CS_{l,g} \quad \text{(A}(l,g))$$

$a_{l,g}$: Land conversion cost (million USD/ha)

$pldc$: Road construction cost per unit distance (million USD/km)

$glmin_{l,g}$: Distance (km) from grid cell g to the nearest grid cell of the same land use category l

$pirr$: Irrigation system construction cost per unit area (million USD/ha)

$plcc_l$: Cost for converting land use to land use category l (excluding road construction costs) (million USD)

$ctax$: Carbon price (million USD/MgC)

$CS_{l,g}$: Carbon stock [MgC/ha] for land use category l in grid cell g

$glmin_{l,g}$ defines the minimum distance from a grid cell to another grid cell of the same land use category as follows.

$$glmin_{l,g} = \min_{g' if Ypre_{l,g'}>0} GL_{g,g'}$$

For cropland, the minimum distance from a grid cell to another cropland grid cell (crop type not considered) is defined as.

$$glmin_{lcrop,g} = \min_{(g',lcrop') if Ypre_{lcrop',g'}>0} GL_{g,g'}$$

where $GL_{g,g'}$ is the distance (km) between grid cell g and g'.

Land use conversion costs (labor etc.) excluding road construction cost $plcc_{l,g}$ is defined by the equation below. as the difference between the maximum value of land rent minus road construction cost and the minimum profit for land selected in the base year. In the future, this will increase in proportion to wages.

$$plcc_l = \max_g \left(S_{l,g} - pldc \cdot glmin_{l,g} \right) - \min_{g\, if\, Ybase_{l,g}>0} S_{l,g}$$

Table. Land Use Category map l (*l,l'*)

Land Use Category (*l*)		Land Use Category (*l*) (irrigated or not irrigated)
PRM_FRS	.	PRM_FRS
HAV_FRS	.	HAV_FRS
AFR	.	AFR
PAS	.	PAS
PDR	.	PDR_FIRR
WHT	.	WHT_FIRR
GRO	.	GRO_FIRR
OSD	.	OSD_FIRR
C_B	.	C_B_FIRR
BIO	.	BIO_FIRR
OTH_A	.	OTH_A_FIRR

PDR	.	PDR_NOIRR
WHT	.	WHT_NOIRR
GRO	.	GRO_NOIRR
OSD	.	OSD_NOIRR
C_B	.	C_B_NOIRR
BIO	.	BIO_NOIRR
OTH_A	.	OTH_A_NOIRR
CROP_FLW	.	CROP_FLW
GL	.	GL
SL	.	SL
OL	.	OL

(3) Net Profit $S_{l,g}^{t}$

Net profit $S_{l,g}^{t}$ is calculated by subtracting the cost per unit area from the revenue per unit area from production activities for land use *l*. Revenue is obtained by multiplying the production per unit area by the producer price. Costs include per-unit-area intermediate inputs, labor, capital, production tax, and subsidies. Producer prices and costs are uniform for grid cells in the target region.

$$S_{l,g} = \mathrm{Revenue}_{l,g} - Cost_{l,g}$$
$$\mathrm{Revenue}_{l,g} = \sum_{r\, if\, MGR(g,r)} \left(\mathrm{ProducerPrice}_{l,r}\right) \cdot Yield_{l,g}$$
$$Cost_{l,g} = \frac{\sum_{r\, if\, MGR(g,r)} \left(IntermediateInput_{l,r} + Capital_{l,r} + Labor_{l,r}\right)}{\sum_{r\, if\, MGR(g,r)} \left(Area_{l,r}\right)}$$

$MGR(g,r)$ is the correspondence table for grid cell *g* and region *r*.

(4) Grid cell and country correspondence table

$$mapNIJ_{n,i,j} = \begin{cases} 1, & if\ mapNIJ0_{i,j} = ordN_n \\ 0, & if\ not \end{cases}$$

ここで、

$$ordN_n = order_n$$

$$mapRIJ_{r,i,j} = \sum_{n\,if\ mapNR_{n,r}} mapNIJ_{n,i,j}$$

MAPGIJ(g,i,j) is the matrix showing the relationship between grid cell number *g* and the grid cell's coordinates (*i*,*j*) and is expressed as follows:

$$mapgij_{g,i,j} = \begin{cases} 1, & if \quad \left\{ g = \dfrac{360}{GS} \cdot (i-1) + j \right\} = TRUE \\ 0, & if \qquad\qquad FALSE \end{cases} \qquad \text{(MGIJ(g},i,j\text{))}$$

$$mapRG_{r,g} = \sum_{(i,j)\,if\ mapgij(g,i,j)} mapRIJ_{r,i,j}$$

$$GA_g = \sum_{(i,j)\,if\ mapgij(g,i,j)} GAIJ_{i,j}$$

$$AREA0_{l,r} = \sum_{g\,if\ mapRG(r,g)} \left(Y0_{l,g} \cdot GA_g \right)$$

$$GL_{i,j,i',j'} = \left(\left| i - i' \right|^2 + \left| j - j' \right|^2 \right)^{0.5} \cdot \frac{40,000km}{360 / GS}$$

$$GL_{g,g'} = \sum_{map\_gij(g,i,j)} \sum_{map\_gij(g',i',j')} GL_{i,j,i',j'}$$

where

N: Country number (1–357)

$ordN_n$: Serial number (1–357) for country number *n*

$mapNIJ0_{i,j}$: Country number table for grid cell (*i*,*j*)

$mapNIJ_{n,i,j}$: Correspondence table for country number *N* and grid cell (*i*,*j*)

$mapRIJ_{r,i,j}$: Correspondence table for country code *r* and grid cell (*i*,*j*)

$mapNR_{n,r}$: Correspondence table for country number *N* and country code *r*

$mapSrG_{Sr,g}$: Correspondence table for country code *Sr* and grid cell *g*

$Y0_{l,g}$: Fraction of land use category *l* in grid cell *g* (base year)

GA_g : Area of grid cell *g* [kha]

$AREA0_{l,r}$: Land use category *l* area (base year) [kha] for country code *r*

$LDMR_{l,r,t}$: Land use category l area for year t and country code r

$WG_{g,g'}$: Matrix representing whether grid cells g, g' are adjacent

$GL_{g,g'}$: Distance [km] between grid cells g, g'

(5) Forest carbon amount ($CS_{l,g,t}$, $CF_{l,g,t}$)

For future development, we describe methods considering and not considering tree age. At this stage, the method not considering tree age is used for the following reasons.

When the tree age for each grid cell is unknown for the base year data, tree age is not considered for the base year carbon stock and flow. Even if tree age is considered from the next year and added, inconsistency will occur. Depending on the purpose of the model, not considering tree age may change the results slightly; however, tree age cannot be considered unless there is a map with tree age. The model can be updated to consider tree age when such data becomes available or when such consideration becomes necessary.

If tree age is not considered, the stock amount from VISIT for the 2000s is used for $CS_{1,g}$ and the flow amount from VISIT for the 2000s is used for $CF_{1,g}$.

If tree age is considered, carbon amount is calculated as follows.

a) Wood biomass yield function ($WCS_{1,g,t,t'}$, $WFT_{g,t,t'}$)

The timber yield function ($WCS_{1,g,t,t'}$) (following equation) proposed by Sohngen et al. (2009) is used to determine change in forest carbon with time. Here parameter δ_g is calculated assuming that the carbon stock of VISIT would be reached at tree age 60 years.

$$WCS_{g,t,t'} = \delta_g \cdot \exp\left[5.2 - \frac{30}{t-t'}\right]$$

δ_g : parameter

$WCS_{g,t,t'}$: Amount of carbon stock [MgC/ha] for grid cell g in year t for a forest converted in year t' from other land use

The flow is the slope of the Yield function—i.e., the change in stock from the previous period.

$WCF_{g,t,t'} = WCS_{g,t+1,t'} - WCS_{g,t,t'}$

$WCF_{g,t,t'}$: Carbon flow [MgC/ha/year] for grid cell g in year t for a forest converted in year t' from land use l

Figure 2. Biomass and Merchantable timber yield functions for upland hardwoods in the U.S. south.

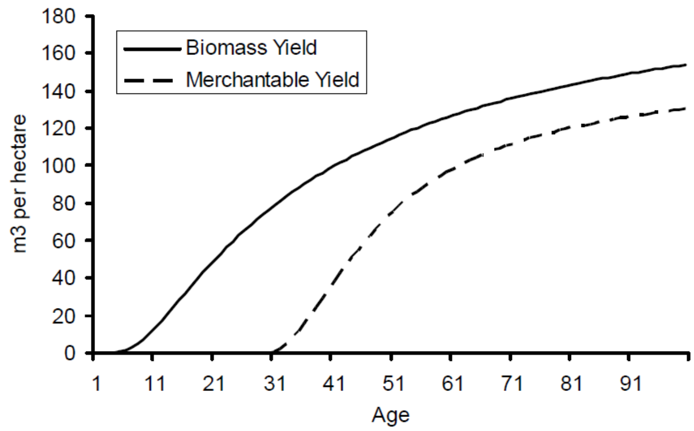


Figure Yield function (Sohngen *et al.* 2009)

Parameter δ is determined so that carbon stock in the 2000s is reached when the trees are 60 years (t-t'=60), and the yield function ($WCS_{1,g,t,t'}$) using that parameter is fitted to that grid cell.

b) Carbon stock ($CST_{1,g,t,t'}$) and flow ($CFT_{1,g,t,t'}$) for period t

The carbon stock $CST_{l,g,t,t'}$ [MgC/ha] in year t for land use category l converted from other land use in year t' for grid cell g can be expressed as follows:

1) The carbon stock in the base year comprises forests planted more than 60 years before the base year.
2) The carbon stock for a forest planted less than 60 years before the base year is the carbon stock in the base year plus the cumulative flow in years following the base year.
3) The carbon stock for a forest planted after the base year is the carbon accumulated in the years after planting.
4) The carbon stock for cropland, pastures, and grasslands is considered to be constant, regardless of the history of land use changes. The stock amount is the carbon stock for cropland and pastures specified by the IPCC guidelines.

$$CST_{l,g,t,t'} = \begin{cases} CSbase_{l,g}, & t = t', l = prmfrs, havfrs \\ CSbase_{l,g}, & t'+60 \le tbase \le t, \quad l = afr \\ CSbase_{l,g} + \sum_{tbase \le t'' < t} WCF_{g,t'',t'}, & tbase - 60 \le t' \le tbase \le t, \quad l = afr \\ \qquad WCS_{g,t,t'}, & tbase \le t' \le t, \quad l = afr \\ 10 & t = t', l = lcrop \\ 2.5 & t = t', l = pas, gl \\ 0 & t = t', l = sl, oth \end{cases} \quad , t' \le t,$$

where,

$CST_{l,g,t,t'}$: Carbon stock [MgC/ha] for land use category *l* converted from other land use in year *t'* for grid cell *g*.

$CSbase_{l,g}$: Base year carbon stock [MgC/ha] for land use category *l* in grid cell *g*

pro_frs : Afforestation for wood production

afr : Afforestation

$lcrop$: Cropland

pas : Pasture

gl : Grassland

On the other hand, flow can be expressed as the change in stock from the previous period.

$$CFT_{l,g,t,t'} = CST_{l,g,t+1,t'} - CST_{l,g,t,t'}$$

$CFT_{l,g,t,t'}$: Carbon flow in year *t* (net absorption, negative absorption) [MgC/ha/year] for land use category *l* converted from other land use in year t' in grid cell *g*.

c) Carbon stock ($CS_{l,g,t}$) and flow ($CF_{l,g,t}$) in grid cell *g* for year *t*

At this time, the change in fractional area for land uses in each grid cell is expressed as follows,

$$\Delta Y_{l,g,t} = Y_{l,g,t+1} - Y_{l,g,t}, \qquad tbase \le t, l = profrs, afr$$

$\Delta Y_{l,g,t}$: In year *t*, the change in fractional area for land use category *l* in grid cell *g* [year–1]

The average carbon stock ($CS_{l,g,t}$) and flow ($CF_{l,g,t}$) for grid cell *g* in year *t* is the average weighted by the change history $\Delta Y_{l,g,t'}$ for the land area ratio in the grid cell.

$$CS_{l,g,t} = \frac{\sum_{tbase \le t' \le t} \left(CST_{l,g,t,t'} \cdot \Delta Y_{l,g,t'} \right)}{\sum_{t'} \left(\Delta Y_{l,g,t'} \right)}, \qquad l = afr$$

$$CF_{l,g,t} = \frac{\sum_{tbase \le t' \le t} \left(CFT_{l,g,t,t'} \cdot \Delta Y_{l,g,t'} \right)}{\sum_{t'} \left(\Delta Y_{l,g,t'} \right)}, \qquad l = profrs$$

1.4 Data Used

d) Productivity map ($Yield_{l,g}$)

- Output from vegetation model VISIT for pasture, bioenergy crops, and fallow land (Ito and Inatomi 2011; Ito and Inatomi 2012)
- The average value for the 10 years of the 2000s is used
- VISIT data was converted from carbon weight to crop weight using conversion coefficients from carbon weight to crop weight for each crop from FAO (2013). For pasture, the conversion factor 0.1 [dry weight/harvest weight] from GAEZ ver. 3.0 was used. The conversion factor from carbon weight to biomass dry weight of 0.47 [ton carbon/biomass dry weight] (IPCC 2006) was used.
- For crops, we used the output from the crop model GAEZ (Masutomi et al. 2009) calculated for average climate for 1981–2000 (crop yield [kg/ha]) was used. The table below shows 13 crops corresponding to Computable General Equilibrium (CGE) goods categories. The fractional area of irrigated land is weighted by the current situation (MICRA2000) and the fractional area of cropland is not considered.
- For the base year, if there is discrepancy between CGE output for production volume and the production volume calculated from the agricultural land map and productivity, an adjustment coefficient is calculated from these two values; the coefficient is multiplied by productivity in the future to eliminate the discrepancy.

Table Correspondence table for vegetation model VISIT and this model

Land Use Category	Code	Vegetation Model VISIT Category
Natural Forest	PRM_FRS	-
Wood Production Forest	HAV_FRS	Carbon Stock
Afforestation	AFR	Carbon Absorption
Pasture	PAS	C4 herbaceous plants（natural vegetation）
Bioenergy Crops	BIO	C4 herbaceous plants（cultivated land）
Fallow Land	CROP_FLW	C4 herbaceous plants (cultivated land)
Grassland	GL	-
Settlement	SL	-
Tundra, Water, etc.	OL	-

Table Correspondence table for crop model GAEZ crop types and this model

Land Use Category	Code	Crop Model GAEZ crop types
Rice	PDR	Wetland_Rice
Wheat	WHT	Wheat
Maize	GRO	Barley, Maize, Millet, Sorghum
Oilseed crops	OAD	Groundnut, Soybean
Sugar Crops	C_B	Sugar beet, Sugar cane
Other Crops	OTH_A	Cassava, Sweet_Potato, White_Potato

e) Land Use Map ($Y_{l,g}$)

- Cropland by Crop: Monfreda et al. (2008) 175 crop types. Correspondences between crop classifications is provided in the appended table.
- Forest, Pasture, Settlement, Tundra, Rocky, Water: RCP (Hurtt et al. 2011)
- Fallow Land: Fallow is RCP cropland minus the covered area (Monfreda et al. 2008)
- Protected Area: UNEP-WCMC (2015). Protected areas are fixed into the future.
- Tundra and Water are obtained from RCP data and fixed into the future.

f) Land Demand (LDM_l^t)

- Estimated values from the AIMCGE model
- Amount of wood harvested: ForeSTAT(FAO) wood volume for base year is converted into carbon weight, and made proportional to future CGE output. For conversion, 0.5 ton carbon/ton wood dry weight (IPCC,

2006, Table 12.4) and wood volume ratio 0.24–1.0 [ton wood/m^3] were used (Yamaji et al. 2000).

Table Land demand calculation method

Land Use Category	Code	Calculation Method
Natural Forest*)	PRM_FRS	AIMCGE model estimated value (area)
Wood Production Forest	HAV_FRS	AIMCGE model estimated value (carbon weight)
Afforestation	AFR	AIMCGE model estimated value (carbon weight)
Pasture	PAS	AIMCGE model estimated value (area)
Rice	PDR	AIMCGE model estimated value (area)
Wheat	WHT	AIMCGE model estimated value (area)
Maize	GRO	AIMCGE model estimated value (area)
Oilseed Crops	OSD	AIMCGE model estimated value (area)
Sugar Crops	C_B	AIMCGE model estimated value (area)
Bioenergy Crops	BIO	AIMCGE model estimated value (area)
Other Crops	OTH_A	AIMCGE model estimated value (area)
Grassland	GL	AIMCGE model estimated value (area)
Settlement	SL	RCP land use data fixed into the future
Tundra, Water, etc.	OL	RCP land use data fixed into the future

*) Natural forest that is fixed into the future in the protected forest map (UNEP-WCMC, 2015)

Table Correspondence table for land use categories used in the AIMCGE model and this model

Category Used in This Model	Code	AIMCGE Model	Code
Natural Forest	PRM_FRS	Base year natural forest	PRM_FRS
Wood production forest	HAV_FRS	Forestry land use area	MNG_FRS
Afforestation	AFR	Increased forest	PRM_FRS
Pasture	PAS	Pasture land	GRAZING
Cropland		Land input by crop. See appended table for corresponding crops.	
Bioenergy crops	BIO	Bioenergy crops	BIOCROP
Fallow Land	CROP_FLW	Fallow Land	CROP_FLW
Grassland	GL	Grassland	GRASS

g) Cost and price ($\mathrm{Cost}_{l,g}$, $\mathrm{ProducerPrice}_{l,r}$) per unit land area

- Cost per unit area is prepared from the AIMCGE model estimated social accounting table
- AIMCGE model estimated value for price is used
- Biofuel was converted from million USD/ktoe to million USD/kton using 0.38 ktoe/kton * 0.5 (fuel conversion efficiency)
- Natural forest, grassland, settlement, tundra, water, etc. are not subject to land use conversion. It is assumed that there will be no change from the present to the future. Therefore profit is zero.
- World Bank (2014) global average road construction cost was converted based on per capita income (IIASA 2012)

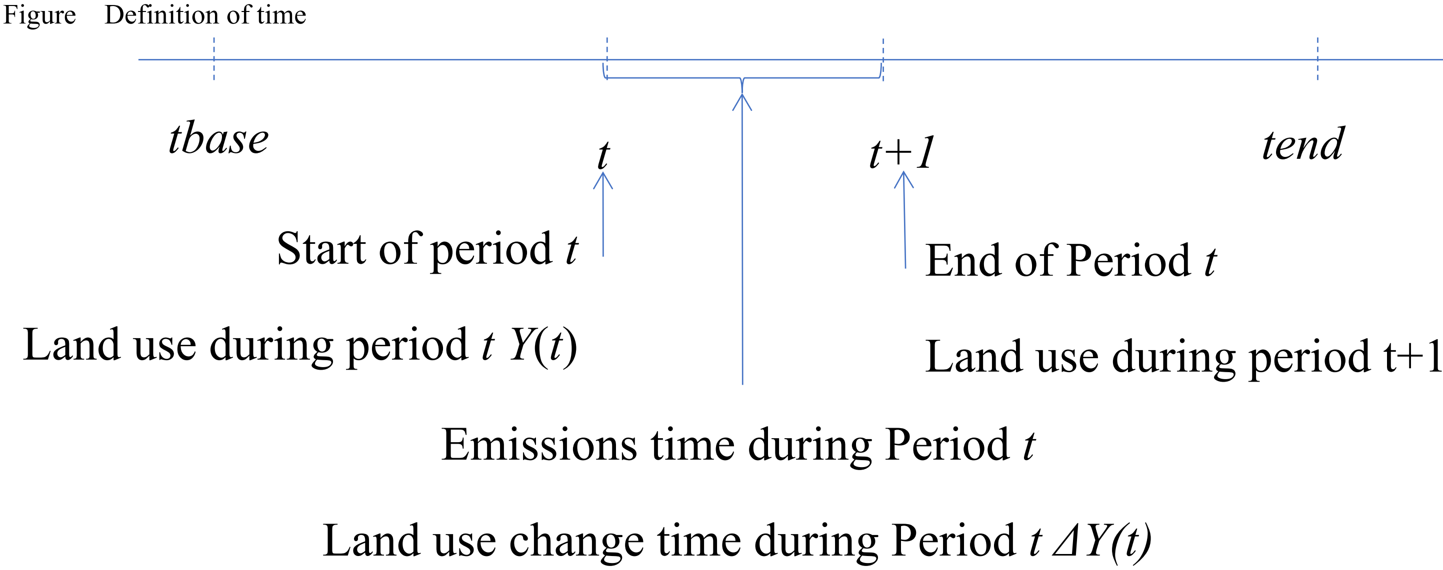
Table　Correspondence table for industrial categories used in the AIMCGE model and this model

Category Used in This Model	Code	AIMCGE model industrial category	Code
Natural Forest	PRM_FRS	-	
Wood production forest	HAV_FRS	Forestry	FRS
Afforestation	AFR	-	
Pasture	PAS	Beef cattle	CTL
		Dairy cows	RMK
		Other livestock products	OTH_L
Rice	PDR	Rice	PDR
Wheat	WHT	Wheat	WHT
Maize	GRO	Maize	GRO
Oilseed crops	OSD	Oilseeds	OSD
Sugar crops	C_B	Sugar crops	C_B
Other crops	OTH_A	Other crops	OTH_A
Bioenergy crops	BIO	Second Generation bioenergy (derived from crop residuals)	BTR3
Fallow land	CROP_FLW	Average for 7 crops (PDR, WHT, GRO, OSD, C_B, OTH_A, BTR3)	
Grassland	GL	-	
Settlement	SL	-	
Tundra, water, etc.	OL	-	

1.5 Estimation of Greenhouse Gas Emissions (option)

Greenhouse gas emissions associated with land use changes are estimated using the land use distribution estimate results obtained above.

Figure　Definition of time



$\Delta Y_{l,g,t} = Y_{l,g,t+1} - Y_{l,g,t}, \qquad tbase \le t \le tend$

$\Delta Y_{l,g,t}$: Change in fractional area for land use category l [1/year] in grid cell g in year t

Emissions $GHGLG_{l,g,t}$ are calculated using the following equation. For wood production forests, the amount of carbon harvested is treated as emissions.

$$GHGLG_{l,g,t} = \begin{cases} \sum_{tbase \le t' \le t} CDT_{l,g,t,t'} \cdot \Delta Y_{l,g,t'} \cdot GA_g \cdot \frac{44}{12} \cdot \frac{1}{1000} \cdot (-1), & l \in L, l \ne havfrs \\ CDT_{l,g,t,t} \cdot Y_{l,g,t} \cdot GA_g \cdot \frac{44}{12} \cdot \frac{1}{1000} & l = havfrs \end{cases}$$

where,

$GHGLG_{l,g,t}$: GHG emissions (CO_2 equivalent) in year t for land use category l in grid cell g (emissions are expressed as positive values) [$MtCO_2$/grid cell/year]

GA_g : Area of grid cell g [kha]

$CDT_{l,g,t,t'}$: The change in carbon per unit area in year t (absorption is expressed as a positive value for flow) [MgC /ha/year] brought about by land use in year t' for land use category l in grid cell g.

The final (−1) is needed to make $GHGLG_{l,g,t} < 0$ to reflect absorption ($\Delta Y_{afr',g,t'} > 0$ and $CDT_{l,g,t,t'} > 0$) in the case of afforestation ($l = afr$) or to make $GHGLG_{l,g,t} > 0$ to reflect emissions due to reduced area ($\Delta Y_{l,g,t'} < 0$ and $CDT_{l,g,t,t'} > 0$) in the cases other than afforestation $l \ne afr$.

Here,

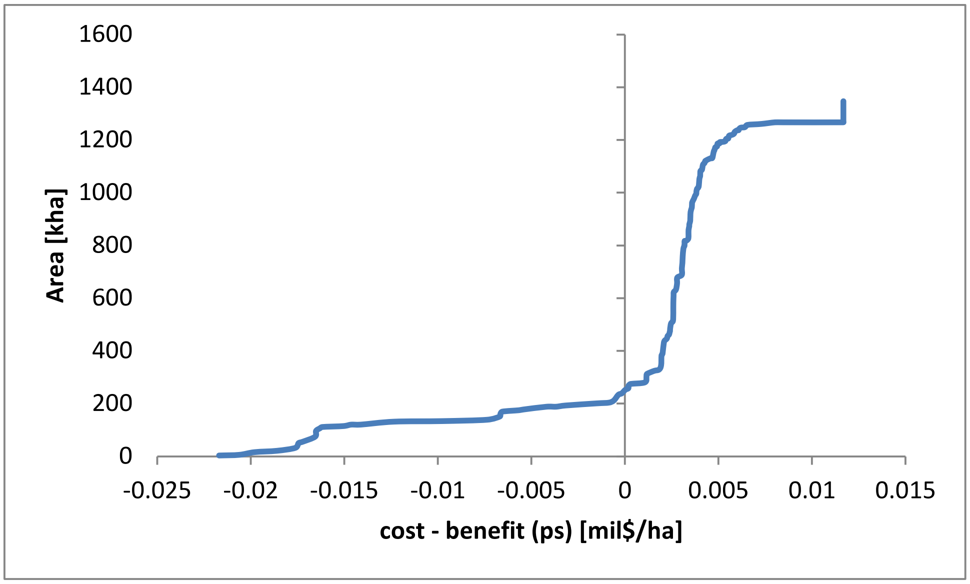
$$CDT_{l,g,t,t'} = \begin{cases} CST_{l,g,t,t}, & l \in prmfrs, havfrs, lcrop, pas, gl \\ CFT_{l,g,t,t'}, & l = afr \end{cases}$$

Table Change in carbon (CDT) due to land use change

Land Use Category	Code	Biomass Change (conceptual)
Natural Forest	PRM_FRS	<Logged Land ($\Delta Y<0$)>
		Amount of biomass stock change is directly emitted
Wood Production Forest	HAV_FRS	Amount of biomass stock change is directly emitted
Afforestation	AFR	Biomass flow is absorbed
Pasture	PAS	Amount of biomass stock change is directly emitted
Rice	PDR	Amount of biomass stock change is directly emitted
Wheat	WHT	Amount of biomass stock change is directly emitted
Maize	GRO	Amount of biomass stock change is directly emitted
Oilseed Crop	OSD	Amount of biomass stock change is directly emitted
Sugar Crop	C_B	Amount of biomass stock change is directly emitted
Bioenergy Crop	BIO	Amount of biomass stock change is directly emitted
Other Crops	OTH_A	Amount of biomass stock change is directly emitted
Fallow Land	CROP_FLW	Amount of biomass stock change is directly emitted
Grassland	GL	Amount of biomass stock change is directly emitted
Urban	SL	No change
Tundra, water, etc.	OL	No change

1.6 Method for creating a biomass supply function

- Comparison of yield function (yield [ton/ha] horizontal axis, land area [ha] vertical axis) with the base year (Monfreda et al. 2008)
- Comparison of the supply function (production cost [USD/ton] horizontal axis, cost [ton])
- GRO from CGE is assumed



1.7 Frequently Asked Questions (FAQ)

Q: Reference map for biomass crops

A: There is no base year map for biomass crops. While there is no map to refer to, in order to meet a given land demand, crops will be introduced to grid cells starting with the most profitable grid cells while taking competition with other land uses into account.

1.8 Future Issues

- Method for analyzing results
- Calculation of biomass and emissions
- Balance between C in livestock feed and C in meat to consider carbon efficiency of livestock
- Is C4crop productivity (used by BIO) lower than C4natural (used by PAS)?
- Constrain based on proportion of national land area
- As 106 or 17 regions are handled, there are gaps in global coverage. Global area and total area do not match.
- In relation to handling of CGE output data
    - Handling of secondary forest output by AIMCGE
    - The production of bioenergy crops is not included and the price is based on 2005 in the calculation of profit
- Review of data used
    - VISIT data crop intensity, crop calendar, growth process
    - Classify Rammankutty's forage as pasture?
    - Double cropping is not considered when calculating fallow land maps

- Confirm that RCP and CGE output values match after calculating for the entire world
- Greenland is included in South America.

1.9 List of Symbols

Subscripts

g: grid cell number. All grid cells are assigned a serial number in order from 1.

i: Number that represents the vertical position of each grid cell on the map (i = 1–360

j: Number that represents the horizontal position of each grid cell on the map (j = 1–720)

l: Land use category

Other forest and grassland PRN_SEC

Table Land use categories and codes

Land Use Category	Code
Natural Forest	PRM_FRS
Wood Production Forest	HAV_FRS
Afforestation	AFR
Pasture	PAS
Rice	PDR
Wheat	WHT
Maize	GRO
Oilseed crops	OSD
Sugar crops	C_B
Bioenergy crops	BIO
Other crops	OTH_A
Grasslands	GL
Settlement	SL
Tundra, rock, water, etc.	OL

Symbols

GS : Grid size [°] (=0.5)

$D_{l,g}$: Grid cell g, diminishing returns due to expansion of land use category l (0–1) ($=\frac{1}{2 \cdot R_{l,g}}$)

$S_{l,g}$: Grid cell g, net profit per unit area for land use category l

$Q_{l,g}$: Grid cell g, adjustment cost per unit area for land use category l

$R_{l,g}$: Grid cell g, degree of diminishing returns due to expansion of scale of land use category l

$Z_{l,g}$: Grid cell g, target variable for land use category l

$Y_{l,g}$: Grid cell g, fractional area for land use category l (0 – 1)

LDM_l : Land demand for land use category l (exogenous variable)

CDM_l : Land demand for land use category l (Carbon equivalent weight) (exogenous variable)

$a_{l,g}$: parameter

b: parameter

β : parameter

γ : parameter

2. References

FAO. 2013. *FAOSTAT*. Retrieved from: http://faostat.fao.org/default.aspx.

Hurtt G C, Chini L P, Frolking S, Betts R A, Feddema J, Fischer G, Fisk J P, Hibbard K, Houghton R A, Janetos A, Jones C D, Kindermann G, Kinoshita T, Klein Goldewijk K, Riahi K, Shevliakova E, Smith S, Stehfest E, Thomson A, Thornton P, Vuuren D P and Wang Y P 2011 Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands *Climatic Change* 109, 1-2, 117-61.

IIASA. 2012. *Shared Socioeconomic Pathways (SSP) Database Version 0.9.3*. Retrieved from: https://secure.iiasa.ac.at/web-apps/ene/SspDb

Intergovernmental Panel on Climate C. 2006. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme. In Eggleston H S, Buendia L, Miwa K, Ngara T and Tanabe K (Eds.), IGES. Retrieved from: http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.htm.

Ito A and Inatomi M 2011 Water-Use Efficiency of the Terrestrial Biosphere: A Model Analysis Focusing on Interactions between the Global Carbon and Water Cycles *Journal of Hydrometeorology* 13, 2, 681-94.

Ito A and Inatomi M 2012 Use of a process-based model for assessing the methane budgets of global terrestrial ecosystems and evaluation of uncertainty *Biogeosciences* 9, 2, 759-73.

Masutomi Y, Takahashi K, Harasawa H and Matsuoka Y 2009 Impact assessment of climate change on rice production in Asia in comprehensive consideration of process/parameter uncertainty in general circulation models *Agriculture, Ecosystems & Environment* 131, 3-4, 281-91.

Monfreda C, Ramankutty N and Foley J A 2008 Farming the planet. Part 2: Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000 *Global Biogeochemical Cycles* 22, 1.

Sohngen B, Golub A A and Hertel T W 2009 The Role of Forestry in Carbon Sequestration in General Equilibrium Models.

UNEP-WCMC I a. 2015. *The World Database on Protected Areas (WDPA) [On-line], [May, 2015 of the version downloaded], Cambridge, UK: UNEP-WCMC. Available at:* www.protectedplanet.net.

WorldBank. 2014. *Unit Costs of Construction and Maintenance Works*. Retrieved from: http://siteresources.worldbank.org/INTROADSHIGHWAYS/Resources/338993-1122496826968/kmcosts.pdf

Appendix

Correspondence table for crop categories used by Monfreda et al. (2008) and this model

Land Use Category	Code	Monfreda et al. (2008) crop classification categories
Rice	PDR	
Wheat	WHT	
Oilseed crops	GRO	
Sugar crops	OSD	
Other crops	OTH_A	