UK land use projections and the implications for climate change mitigation and adaptation

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Executive Summary

This report reviews the evidence base on land use drivers, metrics and models to inform the Committee on Climate Change (CCC) on the implications of land use change for climate change mitigation and adaptation. In doing so we have developed a conceptual framework for assessing land use for agriculture, forestry and semi-natural habitats from a climate change mitigation and adaptation perspective. The work comprised mainly of a desk-based review of datasets, drivers and models but also included a stakeholder workshop to explore the pathways to a net zero emissions scenario from UK agriculture and land-use post 2050 and how land allocation (and impacts) might be modelled.

Drivers and pathways for land use and climate change

Drivers of land use can be indirect and direct, and affect both 'demand' for land (for a particular use) and 'supply' of land for land use change (LUC). Demand drivers can be grouped into the different categories of goods and services which land can supply, namely, resource needs (housing, food, water etc.), other ecosystem services (carbon sequestration, water management etc.) and biodiversity conservation. Supply drivers can derive from biophysical change to ecosystems which act as a constraint on land use, including climate change, and factors which release land e.g. sustainable intensification of agriculture or simply the abandonment of land.

Both demand for and supply of land are influenced indirectly by other drivers including demographics, economics, socio-politics, culture and technology. The interaction between different demands for land use reflects the tension between productive agriculture and the provision of wider ecosystem services, in addition to meeting demand for transport, housing etc. Climate change impacts on both the demand for and supply of land, by incentivising other uses (forestry, energy crops, flood management etc.) and limiting the areas available for productive agriculture (through access to water, extreme weather events etc.).

A framework was developed to map drivers against the main land use (or land cover) categories to identify key relationships. This has highlighted the importance of climate change as both a supply and demand driver and also the transient nature of both market and policy drivers. The interrelationship between drivers is complex and it is unrealistic to represent these interactions in a single model. On this basis, previous work such as the UK National Ecosystem Assessment (NEA), have used 'plausible scenarios' for indirect drivers and associated estimations of demand for different land uses and supply, to represent the outcome of a combination of drivers at a point in time. A scenarios approach would enable future land use patterns to be modelled to inform policy decisions on climate change mitigation and adaptation.

A stakeholder workshop was used to explore potential pathways for a particular scenario that is relevant to this policy area, namely achieving net zero carbon emissions in the agriculture and Land use, land-use change and forestry (LULUCF) sectors, post 2050. Multifunctional land use (integrated land management), improved technological efficiency and increasing carbon sinks (through afforestation and increasing soil carbon) were all identified as key pathways that could help the UK meet any potential net zero objective from agriculture and land-use. Synergies and trade-offs with other policy objectives was also considered important and these would need to be accommodated in a modelling exercise. Other key issues raised include the importance of defining boundary conditions and accounting scope (sector, national and international scales) and what degree of disaggregation is needed in modelling the considerable spatial variation within and across land systems.

Indicators for land use and land use change

A five tier framework for classifying land use metrics relevant to the work of the CCC was developed to provide high level linkage from the indicators of climate change mitigation and adaptation through the metrics to the underpinning datasets. The five tiers were: land cover (physical land type), land use, land management, land productivity and environmental quality.

There is sufficient data available on land cover, land use and land productivity for metrics in these categories to be derived for the UK as a whole, either directly or through combining different datasets, and for a reasonable level of spatial disaggregation (such as individual land parcels, 1km grid, 2km grid or 5km grid). The data coverage for metrics of land management is patchier with some gaps, particularly in terms of farm management practices for which data is only available for England and only for specific years. Given the importance of land management to climate change mitigation and adaptation, this will be a key gap to fill. In terms of environmental quality metrics, there is sufficient data to provide complete UK coverage for bird and butterfly metrics, but data is lacking for pests, diseases and pollinators, whilst data on habitat condition is poor outside of designated areas. For water and soil metrics there is complete UK coverage with a complete time series, apart from flood risk where a time series is not available.

To assess the impact of land use change on climate change mitigation and adaptation, a set of indicators was identified, based on the actions listed in the CCC's advice on the Fifth Carbon Budget and the advice of the Adaptation Sub-Committee (ASC) on adaptation in the agriculture and land-use sector. These indicators were then mapped to the metrics to determine which metrics would be required to provide information for the indicator. There were very few indicators where a single metric could be used to provide full information and the detail required to understand change in relation to climate change adaptation. It is likely that the indicators will require a composite metric derived from multiple smaller scale metrics to provide clear evidence of changing trends within the indicator.

Key gaps in the availability of metrics to produce indicators identified were related to farming practices (crop varieties, land drainage, novel crops), dietary change, water demand for habitats and species and diversity of tree species. To allow the CCC to assess the impacts of future land use scenarios, there will be a need to determine those indicators that are of greatest relevance and to then derive appropriate composite metrics to allow changes to the indicators to be assessed. Where the indicators rely on how farmland is managed, data on farming practices will need to be sourced to fill the existing gaps identified in this project.

Indicators of ecological condition were also mapped against a range of ecosystem services (market and non-market) under in different land uses. The analysis suggests that none of the indicators provides all the information on its own for any combination of land use and service or benefit. However, key indicators were identified, including those for soil quality, plant functional indices from the Countryside Survey and the condition of designated sites Cultural services (wild species diversity and environmental settings) have the greatest numbers of relevant indicators.

Review of models for allocation of land use

A review of existing models provides an overview of the existing modelling capability available for assessing the impacts of land use change on climate change mitigation and adaptation. The review focussed on models of land allocation because land allocation is a major input into models for assessment of impacts of land use change and it is therefore important to ensure that land allocation is appropriately represented. Where the land allocation models included impact assessment, the impacts assessed were included in the model description.

An initial rapid review of the literature revealed over 40 models relating to land use change. The models could be categorised into one (or more) of a number of key approaches: empirical regression models, econometric/spatio-econometric models, agent-based models or spatial placement (allocation only) models. In addition, a number of integrated frameworks were identified where models of the impacts of land use change are coupled with the allocation model. A significant advantage of an integrated framework is that feedback from the impacts can be incorporated into the allocation model.

From the initial assessment, eleven models were identified for more detailed review, representing a range of approaches to land allocation. The representation of key drivers in the models varied according to the aim of the model. Most driver categories (agronomic, cropping constraints, economics, land ownership and protected area constraints) were directly included within the model as key parameters, although the individual drivers included varied between the models. For policy drivers, the majority of models tended to represent these through scenarios or assumptions rather than having specified parameter values. The spatial resolution of the data required by the model varied from 100m squares up to 5km squares, with coverage ranging from regional/national scale through to global scale. Nearly all the models operated on an annual timeframe.

In terms of the needs of the CCC, the suitability of models is dependent on the drivers that need to be incorporated. As they currently exist, none of the models reviewed in detail provide the complete suite of approaches and impact assessments that would be required to model the land use scenarios under consideration by the CCC. Spatio-econometric approaches to land allocation tend to capture more key drivers than other models in both quantitative and qualitative forms. However, as the majority of spatio-econometric approaches use profit maximisation for land allocation, this may be a restrictive assumption and others should be considered, such as the use of profit-satisficing (requiring that a given level of profit is achieved) or even multiple factor maximisation/satisfaction approaches if it is felt that these would provide greater representation of land owner behaviour in the UK. Embedding a spatio-econometric approach within an integrated framework would not only allow assessment of impacts, but also enable feedbacks between impacts and land allocation to be included, which will be important when considering climate change mitigation and adaptation.

The majority of the reviewed models take land cover data, economic data and readily available farming practice information (such as fertiliser use) as inputs, all of which would be available from the datasets identified when developing the metrics and indicators. The resulting land allocation predicted by the models would provide an underpinning dataset that could be used to derive a detailed description of the impacts of that land use in terms of key climate change and mitigation metrics.

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1 Introduction and conceptual framework

1.1 Research purpose and report structure

Studies of future land use change suggest that there will be increased demand for land for bioenergy and food crops, but also for wider societal requirements such as housing, flood defence and natural capital. This tension between market-based and other ecosystem services may be abated by rational allocation of land (supply) to different uses and through sustainable intensification of agriculture, but land is largely privately owned and decisions are influenced by a range of market and policy drivers as well as the personal priorities of farmers and other landowners. Land use is also influenced by demand factors such as the degree of food waste and changing eating habits but again these drivers are reliant on consumer behaviour and public policy.

Land use decisions will both impact on climate change and be impacted by it. Food production is a major contributor to greenhouse gas (GHG) emissions but land can also store carbon in soils, while woodland is key to many renewable energy technologies which can displace high carbon fuels. For any given allocation of land to agricultural production, how that land is used and managed has a major bearing on GHG emissions, with ruminant livestock and nitrogen fertiliser being key contributors to the sector's carbon footprint. Technological developments and adoption of mitigation measures can help reduce emissions from agriculture but there is a risk that emissions are displaced to other countries if land use drivers favour other uses or lower agricultural production. Mitigation measures could also impact on other services land provides such as biodiversity, soil carbon stores and water availability. At the same time, a changing climate will also influence the opportunities for, and the economics of, land use. Planned adaptation to climate change is essential for both productive agriculture and the continued provision of other ecosystem services.

The Committee on Climate Change (CCC) has recognised the challenges facing land use in the UK in relation to the move to a low carbon economy and adapting to climate change. Based on the 2015 Department of Energy and Climate Change (DECC) business as usual projections, the land use change and forestry sector (LULUCF) is set to become a net source of emissions in the late 2020s, in the absence of increased woodland planting and inclusion of emissions from peat in the LULUCF inventory. In its review of sectoral scenarios for the Fifth Carbon Budget, the CCC estimate that LULUCF could reduce emissions by 2.4 $MtCO_2e$ by 2030 through increased afforestation and wider deployment of agro-forestry practices. It also acknowledges that the bioenergy sector is limited by land use and sustainability concerns (notably relating to indirect land use change - ILUC).

There is a need to understand how UK land use is likely to change in the future and the implications of changes in land use for mitigation of, and adaptation to, climate change in order for the CCC to provide reliable and accurate advice and analysis to the UK Government and Devolved Administrations.

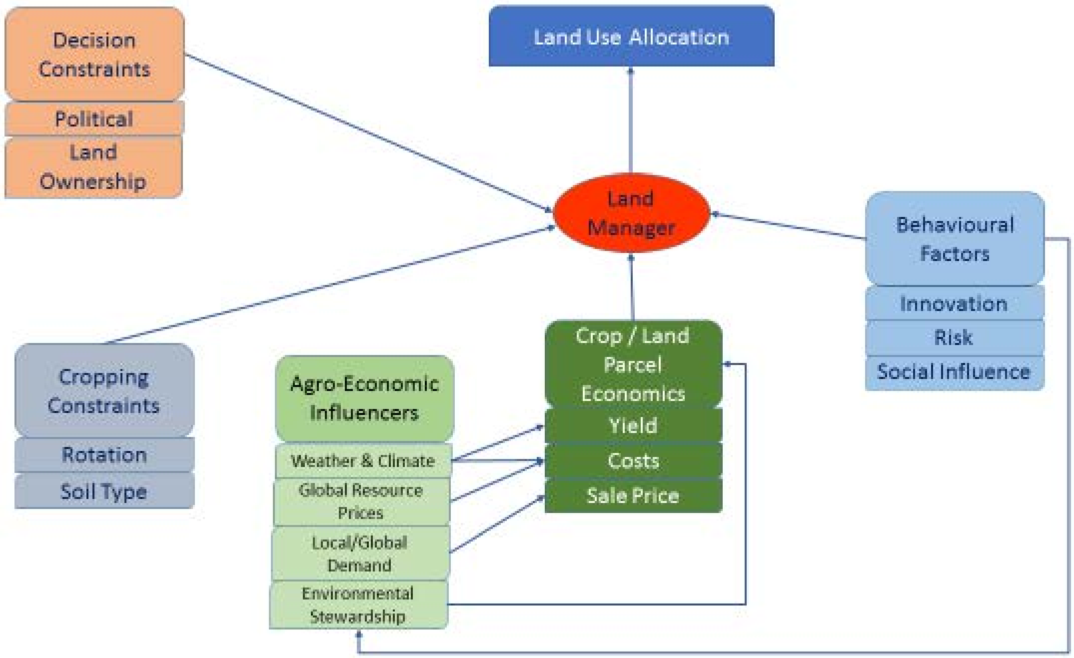
The aim of this project is to consider the drivers for land use in the UK and to scope the metrics available for modelling future changes in land use and management which are relevant to climate change mitigation and adaptation. In **Chapter 2** we set out a review of land use drivers, including a typology for drivers and an assessment of how they influence land use and management. In **Chapter 3** we consider the range of metrics available for land use, how they can be used as indicators of land use and its impacts and identify key data sources. **Chapter 4** provides a review of relevant modelling work in this area and how scenarios can be used to test how land use can be forecast in a range of market/policy contexts. In **Chapter 5** we review the models that are available for land allocation and the extent to which these accommodate climate change as both a driver and an impact factor. Finally in **Chapter 6** we summarise the outcomes of a stakeholder workshop and set out issues for the CCC to consider in taking forward a modelling exercise on land use and climate change.

1.2 Conceptual Framework

To provide a basis for assessment of land use models and component drivers, metrics and outputs, a conceptual framework was developed. This is based on work done by Skirvin *et al*. (2008) as part of Defra project IF0137, which identified the factors influencing land use change in UK arable crops. The conceptual framework assumes that agricultural/forested land use in the UK is an outcome of decisions made by individual land managers. These decisions can be influenced by a large number of factors, which can be grouped into a set of core categories (geographical, climatic, agronomic, economic, socio-economic, political and ecological) with interaction and feedbacks between the key influencing factors within these categories.

A modified version of the influence diagrams produced by Skirvin *et al*. (2008) was produced (Figure 1) by combining some of the influencing factors to provide key constraints and factors affecting an individual land manager's decision about how to use land.

Figure 1: Conceptual framework for land use modelling



The framework sets out the main influences on the land allocation decision, which lies ultimately with the land manager. It is helpful to consider the subsequent 'land system' as one that delivers a range of market and non-market outputs to meet private and social objectives. It is clear that there are a significant number of drivers and a complex interaction between them, so that the optimal allocation land is highly contested and difficult to model explicitly. The model also provides a basis for exploring the two way relationship between land use and climate change.

2 Current land cover and drivers of land use and land use change

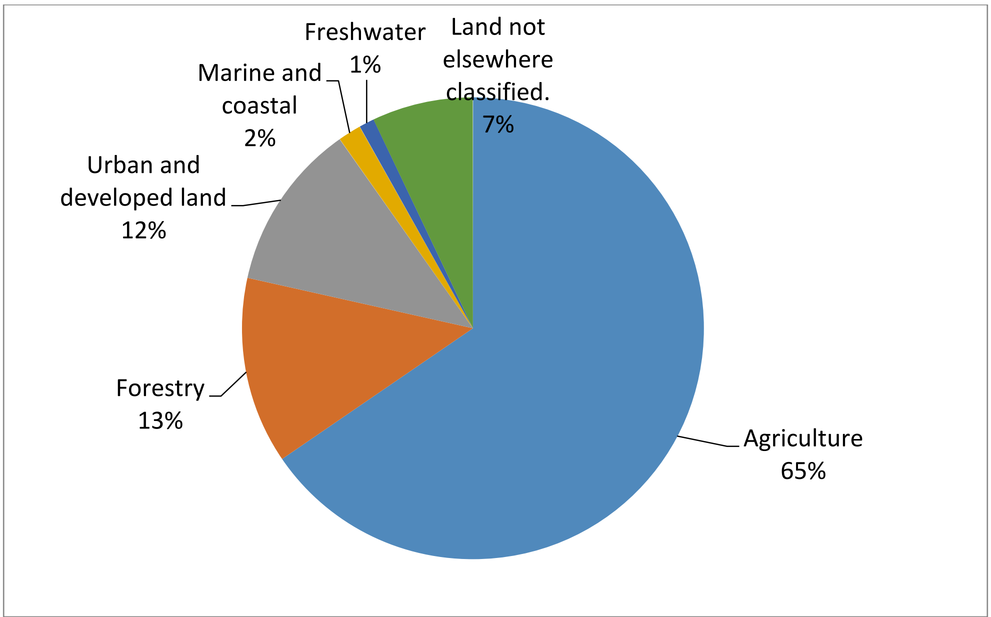
In this section we examine the different drivers of land use. We start by identifying current land cover and uses and then identify the drivers of these. We construct a framework for assessing the importance of each of the drivers in determining current use. We assess whether it is possible to identify all links between the different drivers and set out how current models of land use deal with these.

In order to assess how land might be used in the future, we identify key drivers from a brief literature review (Appendix 1), and score their relative importance in a matrix. This qualitative assessment addresses the relative importance of each driver in determining a particular land use and the disaggregation of land use needed to properly assess the impact of different drivers. The analysis also considers evidence of "structural breaks" which have led to significant, step changes in land use; patterns – for example technological changes in farm or chemical technology - and understanding how they can be predicted in future land use change models. Finally we consider the relative influence of private vs. public bodies in determining land use.

UK land use

We first need to consider how land is currently used in the UK. Figure 2 shows the distribution of land cover in the UK in 2010 and highlights the dominance of agriculture and forestry. Agriculture can be further disaggregated to mountains, moorlands and heaths, semi-natural grassland and enclosed farmland. In terms of change in land use and land cover, urban land use increased by 5% between 2000 and 2010 and forest area increased by 4%, while the area of agricultural land has remained fairly static (ONS, 2015).

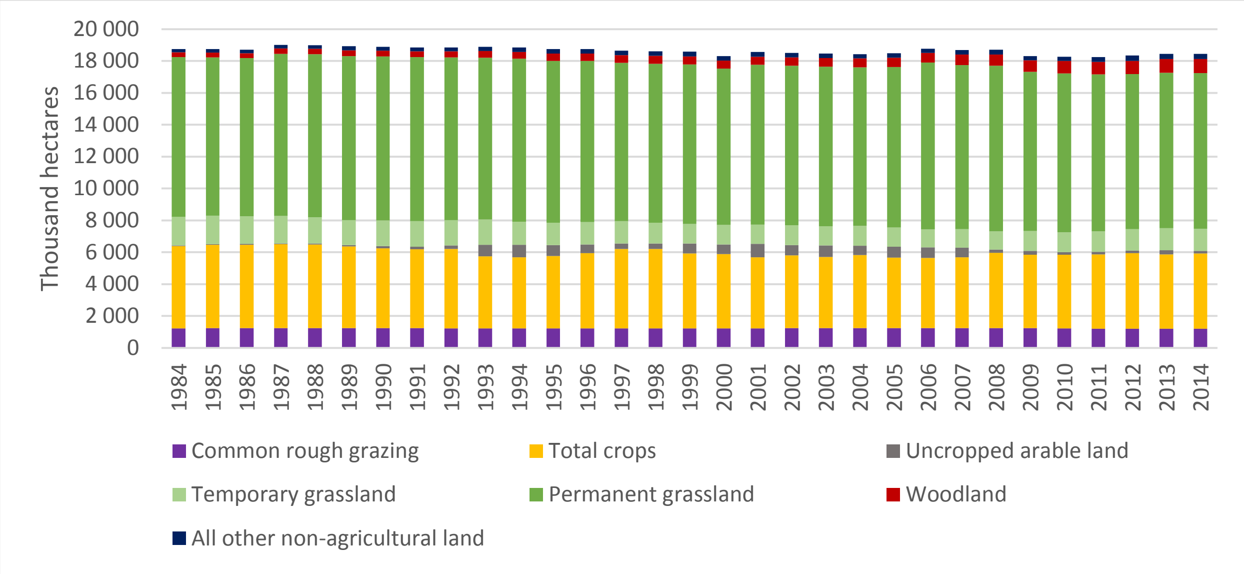
Figure 2: Land cover UK 2010 (23.4m ha)



Source: ONS experimental physical asset accounts for the UK

Within Agriculture, there are a number of broad categories of agricultural use of land. The trend in these over time is shown in Figure 3 and highlights the incremental nature of change and the predominance of permanent grassland, which represents 53-56% of total agricultural land use. Between 1998 and 2007, cultivated land area has decreased by over 550 thousand hectares, while the corresponding increase in the area of pasture and semi-natural grassland was about 295 and 155 thousand hectares respectively (ONS, 2015).

Figure 3: Balance of agricultural land uses over time (1984-2014)

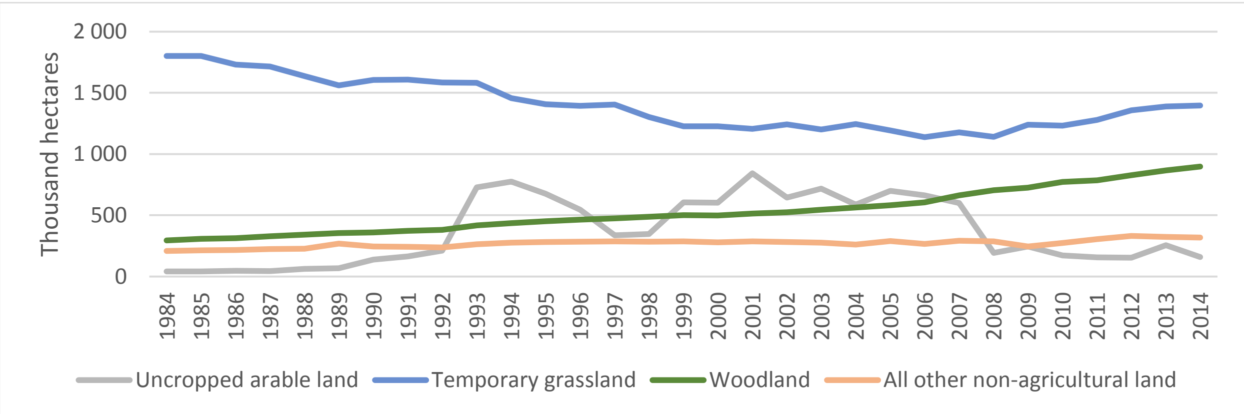


Source: Agriculture in the UK (2015)

Figure 4 focuses on land uses where change is evident and highlights some discrete patterns, notably:

- a steady increase in woodland area – threefold increase over 30 years
- a peak in uncropped arable land from 1993 to 2008 as a result of set aside
- a steady fall in temporary grassland during the 1980s and 1990s and a recovery since 2008

Figure 4: Change in key agricultural land use categories over time 1984-2014



Source: Agriculture in the UK (2015)

2.1 Identifying drivers

The literature suggests that it is important to distinguish between direct and indirect drivers of land use. Direct drivers include land for expansion of existing uses such as development or afforestation, while indirect drivers are those higher-level factors which affect this demand such as markets and population growth. It also has revealed that drivers of land use are not simply factors pulling land towards a particular use ("demand"), but also reflect factors which drive land away from its existing use and therefore make it available for other purposes ("supply"). The different drivers of supply and demand for land use are complex and can have impacts on different aspects of the land system. For example, the same indirect driver (e.g. technology) may be both a cause of land demand (e.g. for bioenergy) or land supply (e.g. via sustainable intensification). Drivers such as climate change are particularly complex as they are both direct and indirect drivers. Thus soil erosion and loss of woodland directly change land use, but humans respond to climate change and invasive species by introducing policies that incentivise land use change (e.g. new woodland, GM crops).

Direct Drivers

Land use studies have generally classified demand for land use in the context of existing land use (agriculture, woodland, etc.) or in themes (food security, water management) and sometimes both at the same time. This is potentially confusing as these are not necessarily direct drivers, whilst land uses such as woodland may be meeting multiple needs. Our approach is to disaggregate demand drivers into the different categories of goods and services which land can supply. There are three broad themes:

- *Resource Needs*. Within this category are individual drivers such as housing, employment, infrastructure, food, timber, fuel, energy, water. What they have in common is that they are all resources whose economic value is explicit in the market.
- *Other Ecosystem Services*. This would include other services that provide a value to society but for which there is not necessarily a market value such as the regulating, cultural, supporting services which include carbon sequestration, water management, recreation, and others (see NEA conceptual framework in section 4.1).
- *Biodiversity Conservation*. This is sometimes thought of as an ecosystem service, but unlike others it is very difficult to ascribe its non-market value, and generally has a different set of indirect drivers that are not economic or demographic. As such it is better to represent as a separate theme.

The extent to which the land use drivers can be modelled in the allocation of land supply and ecosystem service demand requires that, at the very least, resource demands that cannot be provided by the same parcel of land should be disaggregated. However, land can also provide multiple services, for example woodland can produce timber, biodiversity, carbon sequestration and may also provide recreation or flood mitigation, depending on location. It is essential to map these conflicts and synergies, including any spatial dependencies, in any modelling exercise.

Supply of land to particular uses is more complex. There are factors that make land suitable or available for one use but not another, such as climate change, invasive species, and pollution/enrichment. These drivers affect the biophysical qualities of ecosystems and therefore act as a limiting factor in terms of what land uses are possible. However, as CISL (2014) pointed out, landowners may choose to release land for sale, lease or abandonment, thus causing a change of land use. Sustainable intensification may also be one of these drivers.

Supply drivers therefore fit into two broad themes:

- *Biophysical Change.* This includes biophysical change to ecosystems as a consequence of anthropogenic activity which acts as a constraint on alternative land use. This would be disaggregated into climate change, invasive species, and pollution/enrichment.
- *Land Release*. This could include explicit factors such as sustainable intensification or simply the abandonment of land. There can be multiple indirect drivers to this.

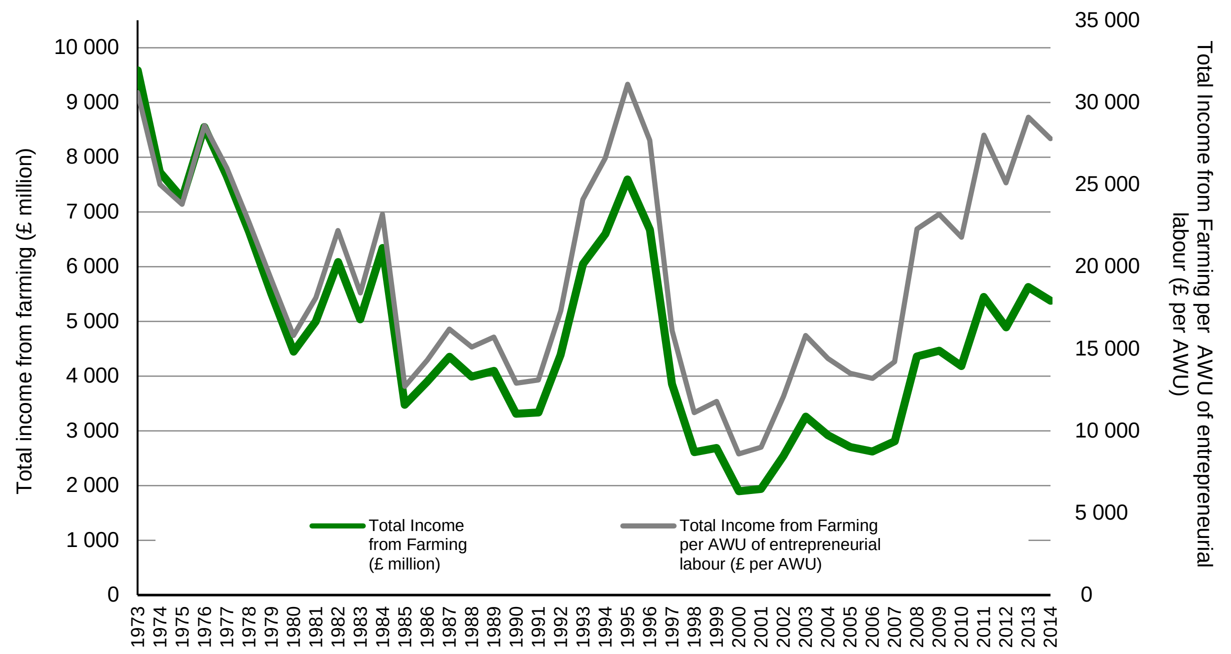
Indirect Drivers

The UK National Ecosystem Assessment (2011)[1] sets out a useful way to represent indirect drivers of land use. It includes the following:

- *Demographics*. Population growth, spatial distribution, age distribution, migration and ethnicity.
- *Economics*. Economic growth, consumer choice, market forces, industry size, globalisation.
- *Socio-politics*. Legislation, subsidies/grants (public/CAP or private).
- *Culture/Behaviour*. Knowledge, environmental attitudes.
- *Technology*. Innovation (chemicals, farm equipment), biotechnology, energy production technology, transport technology.

Within each broad category there may be specific themes that are important in their own right and may need to be given special attention, such as the Common Agricultural Policy (CAP). For example, an analysis of farm incomes over time illustrates very volatile returns in the sector, due largely to market and currency fluctuations (see Figure 5).

Figure 5: Long-term trends in farming income in real terms at 2013 prices; United Kingdom



Source: Defra Statistics

The notable spike in incomes from 1993-1996 reflects the introduction of direct subsidy payments under the CAP reform of 1992 and devaluation of sterling which inflated the value of both subsidies and produce. This economic volatility, together with a reliance on subsidies, encourages farmers to be risk-averse and is reflected in limited changes in agricultural land use over time. A more apparent driver is the impact of "structural breaks" such as the introduction of set-aside under the 1992 CAP reform, which impacted directly on land use by requiring a proportion of land not to be farmed. While much of the set-aside area was replaced by agricultural use after the policy ended, there has been some legacy impact, with around 150-250 thousand hectares of arable land left uncropped since that time.

[1] UK National Ecosystem Assessment (2011).

This example also illustrates the relative influence of private vs. public bodies in determining land use, emphasising that it is very difficult for public policy to accurately anticipate actual land use outcomes given the complex set of drivers facing landowners. Indirect drivers such as increasing global population (and demand for western diets) can be offset by others, notably an uncertain economic climate, as reflected in commodity food market prices, which have fallen back sharply since 2015. As such, drivers need to be considered over the long-term.

2.2 Mapping drivers

In order to assess how these drivers might lead to changes in land use in the future, we need to understand how they can be mapped against individual land use (or land cover) categories[2]. Disaggregating different land uses within enclosed farmland is necessary to determine ecosystem service impacts and would be expected to differentiate different broad crop types, livestock type and field boundary features. It may also be useful to differentiate organic from conventional land use as these have different drivers.

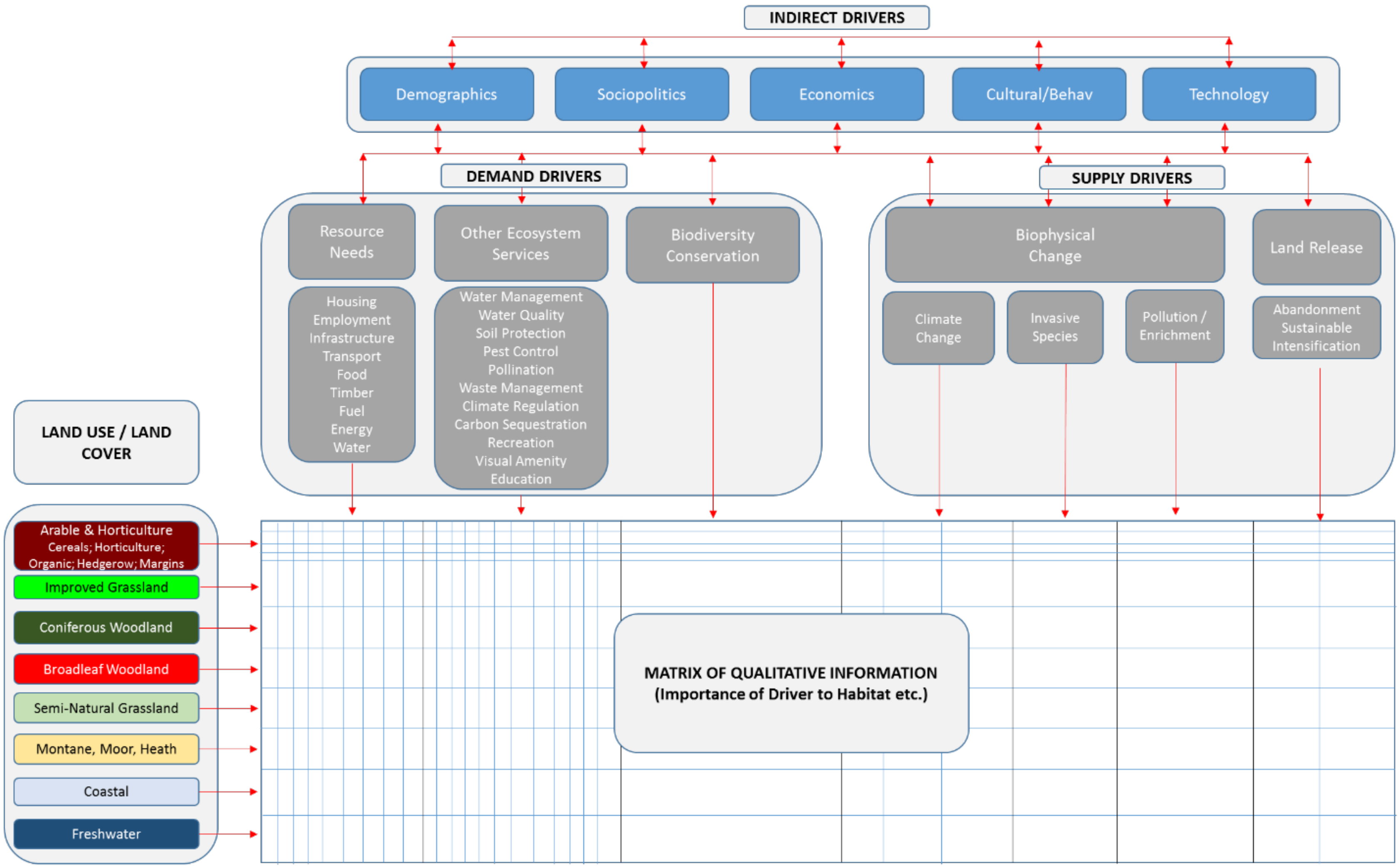
Figure 6 represents a schematic of what such a representation might look like. Mapping the link between the direct drivers and the habitats relies on a degree of expert knowledge and as such is subjective. This could be simplified by reducing the number of drivers to wider categories (e.g. housing/jobs/infrastructure could be "urbanisation"; other ecosystem services could be grouped into "regulating", "supporting", "cultural"; climate change could just be one driver even though it manifests itself in different ways).

It may also be feasible to show how indirect drivers relate to direct drivers. For example, a link could be made between "cultural/behavioural" (indirect) and "demand for food" (direct) through potential changes in diet. However, while the amount and type of meat consumed in the UK diet will affect demand for agricultural produce globally, the small scale of marginal changes at country level are unlikely to be reflected in global food commodity prices or necessarily impact on UK land use. Meanwhile CAP policies simultaneously provide demand for land for biodiversity conservation, GHG abatement and water quality purposes (regulation and agri-environment schemes) and limit land use change through payment of direct subsidies.

However, it is not feasible to map the interrelationship and interaction between drivers. Thus, changes to the UK diet such as a reduction in red consumption may not impact on land use if demand from overseas expands or trade increases. These factors are in themselves influenced by climate change and the availability or suitability of land. The indirect factors are also self-influencing: political decisions can influence economics and demography (e.g. economic growth and net migration), and of course these in turn influence policy.

[2] Land cover is determined by direct observation of the earth's surface and land use is a socio-economic interpretation of the activities that take place on that surface.

Figure 6: Framework for assessment of land use drivers against the main categories of land use



2.3 Analysis of drivers

The interaction between both demand and supply drivers and land use is explored in Table 1 and Table 2 respectively. This illustrates that some land use categories are more at risk from both demand and supply drivers, notably Arable and Horticulture and Improved Grassland. This reflects the tension between productive agriculture and the provision of wider ecosystem services and a reliance on technology to maintain total output. In particular, climate change impacts on both demand and supply, through incentivising other land uses (forestry, energy crops, flood management etc.) and also limiting the areas available for production through access to water, extreme weather events etc. Other land uses tend to gain at the expense of productive agriculture as they are more resilient to climate change and/or better able to provide relevant services (carbon storage, water management etc.).

In terms of relative importance of drivers in determining land use, drivers scoring +/- 2 are most important. Significant demand drivers include built environment, food security and climate regulation while climate change and sustainable intensification (technology) have the greatest capacity to influence supply. A distinction needs to be made between the strength of the driver and the scale of impact. For example, land abandonment is a significant driver but is only relevant to more mountainous and isolated areas of the UK. Other drivers such as provision of timber or diet change have weak links to UK land use as supply is dominated by global commodity markets.

In section 4 we consider the extent to which models include the key drivers of land use and their interactions. The next section looks at how we classify land cover/use and the key factors that we need to measure and identify to describe how land is used and the goods and services it provides.

Table 1: Mapping the influence of demand drivers on broad category land uses

Land Use (Level 1)	Built Environment (housing etc))	Provisioning Services				Regulating Services		Cultural Services	Biodiversity
		Food	Timber	Energy	Water	Air, soils & water	Climate		
Arable and Horticulture	-1	2	0	-1	-1	-1	-1	-1	-1
Improved Grassland	-1	1	0	-1	0	1	1	-1	-1
Semi Natural Grassland	0	0	1	-1	0	0	1	1	1
Woodland	0	0	1	0	0	1	2	1	1
Montane, Moor, Heath	0	0	0	0	0	0	1	1	1
Coastal	0	0	0	0	0	0	0	1	1
Urban/Developed	2	0	0	0	0	0	0	0	0

Key: Cells are scored from -2 (land use has strong negative impact on services) to +2 (land use has strong positive impact on services); a score of 0 means no effect. Cells are also colour coded according to the score as follows: -2; -1; 0; +1 and +2

Table 2: Mapping the influence of supply drivers on broad category land uses

Broad Land Use	Biophysical Change			Land Practice	
	Climate Change	Invasive Species	Pollution / Enrichment	Abandonment	Sustainable Intensification
Arable and Horticulture	-2	-1	-1	0	2
Improved Grassland	-1	0	-1	-1	1
Semi Natural Grassland	1	-1	1	1	0
Woodland	1	-1	1	2	1
Montane, Moor, Heath	0	-1	0	2	0
Coastal	-1	0	0	1	0
Urban/Developed	0	0	0	1	0

Key: Cells are scored from -2 (land use has strong negative impact on services) to +2 (land use has strong positive impact on services); a score of 0 means no effect. Cells are also colour coded according to the score as follows: -2; -1; 0; +1 and +2

3 Metrics and Indicators for land use and land use change

Any modelling exercise which aims to predict land use change requires a set of indicators and supporting datasets and metrics that quantify how land is used and the services it provides. This chapter considers the range of metrics available for quantifying land use in the UK and provides an assessment of the practicality of their use in projecting land use change.

3.1 Identification and classification of metrics

A framework for classifying land use metrics relevant to the work of the CCC was required to provide high-level linkage across all components of the project. This framework has five levels;

1. Land Cover. The first level is a broad classification of land cover (as opposed to land use). This level describes the physical land type such as forest, arable, grassland or open water and all metrics are area-based. This level is the only one to include developed land (since the focus of this project is on agricultural and semi-natural land covers) and provide full land area coverage of the UK.

2. Land Use. The second level classifies the land use where these metrics are relevant to the work of the CCC. Land use describes how people are *using* the land and is more likely to change in comparison to land cover. The focus for this level is on agriculture, forestry and semi-natural land covers, but it is acknowledged that there are many other land uses in existence. All metrics are area-based and examples include type of crop, type of farming and biodiversity designated areas.

3. Land Management. The third level describes the management practices being applied to level one land covers, further subdivided into management practices on agricultural land and on semi-natural land covers. Some of these metrics are area-based but some are quantified on a per-unit area basis. The latter are usually specified for a particular farm type and region, or a particular habitat type and can therefore be used in combination with level one or two metrics to produce area-based indicators with full UK coverage (if the data allow). These metrics mostly provide information for the climate change mitigation indicators, since different management practices have distinct implications for GHG emissions.

4. Land Productivity. The fourth level includes metrics on land productivity and ecosystem services. These metrics can relate to a particular land-use (e.g. crop yield) or be more general (e.g. carbon storage in soil). They can be used to provide data for indicators to monitor the productivity of the land in economic terms (resources and ecosystem services). These metrics mostly provide information for the climate change adaptation indicators, which include indicators of productivity.

5. Environmental Quality. The fifth level includes metrics that provide data for indicators of the environmental status of land. These are further subdivided into species-based metrics and other (habitat/soil/water) measures of quality. Some relate to specific habitats or features (e.g. condition of designated sites) and others are representative of the quality of wider landscapes or catchments (e.g. butterfly index; water quality status). These metrics mostly provide information for the climate change adaptation indicators and can be used to track trends in ecological condition of habitats as well as quality of soil and water, and flood and erosion risk (biophysical change).

For each of these categories, key metrics were chosen based on the data requirements for climate change mitigation and adaptation indicators and for biodiversity indicators. Each indicator was considered in turn and the most appropriate metrics to quantify it identified through discussion by key members of the project team, regardless of whether or not there was a known data source. This was an iterative process, completed over the course of the delivery of the component tasks. For example, if an additional data requirement was identified for a particular indicator that had not been included in the original list of metrics, this was added as an additional metric. The analysis is detailed in Appendix 2.

The metrics are a mix of quantitative data e.g. area of land, volume of goods/services and qualitative data e.g. habitat condition, soil biodiversity. In terms of robustness, the quality of data is variable. This is compounded when physical data is monetised to give economic values. Market-based metrics such as agricultural output are readily available but the value is highly variable over time, while for non-market goods and services there is additional uncertainty over value e.g. shadow values of carbon. These challenges are important when considering types of model in Section 4.

3.2 Land use metrics relevant to GHG mitigation and adaptation

In addition to identifying what metrics are available to understand land use, it is also necessary to consider how those metrics can be used to assess climate change mitigation or adaptation impacts. The Fifth Carbon Budget[3] identified a range of climate change mitigation and adaptation actions that needed to help UK agriculture reduce remissions and increase storage of carbon in order to achieve the target 15% further reductions in GHG emissions from the sector by 2030. It is therefore important that CCC is able to monitor trends in practice that contribute to climate change mitigation and climate change adaptation. For this task a matrix was set up using the metrics identified for land use against the indicators identified for climate change mitigation and climate change adaption in relation to land use, land use change and forestry. These indicators are based on the trends that need to be monitored as identified in the Fifth Carbon Budget report, as well as indicators identified in a number of indicator reports[4],[5],[6]. Each metric/indicator combination was assessed for whether or not the metric was able to provide information to support the indicator. The following scoring system for each metric was used:

- **0** – no relevance to the indicator,
- **1** – some relevance to the indicator, but needs to be used in combination with other metrics to fully support the indicator,
- **2** – relevant to the indicator, can be used to support the indicator in full without support from any additional metrics.

The matrix of indicator *vs* metric is provided in Table 3 for climate change mitigation[7] and Table 4 for climate change adaptation[8]. To identify which datasets are needed for each indicator, the metrics from this task were cross referenced to the matrix of dataset *vs* metric (see Appendix 2): this revealed the datasets that could provide the best options for spatially mapping each indicator. Once the metrics were scored, consideration was given to how metrics could be combined to give better support for each indicator, with the best combinations of metrics for each indicator discussed in detail in Appendix 3.

For the majority of the adaptation indicators the land cover/use metrics form a basis for being able to map any changes at a national level. However these metrics rarely provide the detail needed to

[3] CCC (2015) The Fifth Carbon Budget. The next step towards a low-carbon economy https://documents.theccc.org.uk/wp-content/uploads/2015/11/Committee-on-Climate-Change-Fifth-Carbon-Budget-Report.pdf (accessed February 2016)

[4] ADAS (2015) Indicator 2: Uptake of mitigation measures https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/448954/ghgindicator-2mitigation-29jul15.pdf (accessed February 2016)

[5] Eurostat (2012) Agri-environmental indicator – greenhouse gas emissions http://ec.europa.eu/eurostat/statistics-explained/index.php/Agri-environmental_indicator_-_greenhouse_gas_emissions

[6] CCC (2015) Adaptation indicators https://www.theccc.org.uk/charts-data/adaptation-indicators/ (accessed February 2016)

[7] Fifth Carbon Budget

[8] Fifth Carbon Budget

understand change in relation to climate change adaptation. Instead multiple smaller-scale metrics are likely to be needed to provide additional layers of information to provide clearer evidence of changing trends within an indicator. A decision for inclusion in the final model for each metric based on the availability and quality of the data will be required. More metrics could allow greater granularity of data, but may also require a highly complex set of assumptions that become unworkable once combined into a model.

3.3 Environmental quality indicators of land use

The indicators used to assess the ecological condition of different land uses and habitats at the UK and country level, and at Broad Habitat level, were reviewed and their capability for measuring temporal trends assessed. Key high level reports were reviewed and the relevant information extracted from them and presented in tabular form (Appendix 4). The current state of play with the development of soil quality indicators was assessed from the key publications.

A matrix was assembled to assess the ability of the key indicators to inform about the provision of ecosystem services (both market and non-market) in the three main land uses (agriculture, forestry and semi-natural habitat). Indicators were scored using a simple 3-point scale.

An overview of the drivers affecting key indicators, and synergies and trade-offs between different ecosystem services in relation to land use is presented in Appendix 4.

Links with services and benefits

The links between the indicators of land use and habitat condition and the economic services and non-market benefits of the three main land use types (agriculture, forestry and semi-natural habitat) are shown in Table 5.

Services and benefits are those cited in the UK National Ecosystem Assessment[9]. Indicators have been scored to show their capability for determining the ability of different land uses to provide each service or benefit. The scoring suggests that none of the indicators provides all the information on its own for any combination of land use and service or benefit. However, each indicator does provide some relevant information for at least one service or benefit. Soil quality indicators are informative across all land uses, and can contribute information on the potential provision of a range of supporting, provisioning, cultural and regulating services (although not for soil formation *per se*). Plant functional indices from the Countryside Survey are also among the most informative indices across all land uses. The condition of designated sites is also an important indicator in semi-natural habitats and forestry, while burning regimes on blanket bog and dwarf shrub heath are also highly relevant. Cultural services (wild species diversity and environmental settings) have the greatest numbers of relevant indicators.

[9] UK National Ecosystem Assessment Technical Report (2011) http://uknea.unep-wcmc.org/Resources/tabid/82/Default.aspx

Table 3: Matrix of climate change mitigation indicators against metrics

		Climate change mitigation indicator																			
	Metrics	Land area for planting trees (woodland & agri-forestry)	Different crop species	Different crop varieties	Reducing artificial N fertiliser use	Improved manure planning and application	Loosening compacted soils/ avoiding compaction and erosion	Minimum or zero tillage/ shallow ploughing	Winter cover crops/ undersown spring cereals	Stocking densities	Organic farming	Use of nitrogen fixing plants in grass leys	Upland & lowland peat – quality of peat / level of degradation / restoration	Reduction in heather burning	Agricultural land drainage	Land use change to lower input	Areas for novel crops	Need for dietary change	Emerging technologies	Increased soil carbon	Carbon storage - above ground
Land cover	Arable and horticulture area	1	0	0	1	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1
	Woodland area (broadleaved/ coniferous)	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1
	Improved grassland area	1	0	0	1	1	1			1		1			1	1		1		1	1
	Semi-natural grassland area	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1
	Rough grassland area	1	0	0	0	1	1	0	0	1	0	0	1	1	0	1	0	1	0	1	1
	Areas of other broad habitats	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	1
	Area of priority habitats	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1
Land Use	Crop area by type	0	2	0	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1
	Temporary grassland area	1	0	0	1	1	1	1	0	1	0	1	0	0	1	1	0	1	1	1	1
	Permanent grassland area	1	0	0	1	1	1	0	0	1	0	1	0	0	1	1	0	1	0	1	1
	Area of each farm type	0	0	0	1	1	1	1	1	1	0	1	0	0	1	1	0	0	0	0	0
	Area of buffer strips (along watercourses/ other)	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	Area of land under relevant agri-environment scheme options	1	0	0	1	0	0	0	1	1	1	1	1	1	0	1	0	0	0	0	0
	Area of biodiversity designated sites	0	0	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0	0	1	1
Management practices	Area designated as NVZ	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Mineral N fertiliser use per ha by crop / farm type/ region	0	0	0	2	1	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0
	Organic fertiliser use per ha by crop type/ farm type/ region	0	0	0	2	2	0	0	0	0	1	0	0	0	0	1	0	0	1	1	0
	Area under organic farming	0	0	0	1	1	0	0	0	0	2	1	0	0	0	1	0	0	0	1	0
	Pesticide use per ha by crop type/ farm type/ region	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0
	Proportion of UAA under zero/ min/ conventional tillage by crop type/ farm type/ region	0	0	0	1	0	1	2	0	0	0	0	0	0	0	1	0	0	1	1	0
	Proportion of UAA having fertiliser/ manure management plan by farm type/ region	0	0	0	1	1	0	0	0	1	0	1	0	0	0	1	0	0	1	1	0
	Percentage of temporary grassland sown with clover mix by farm size/ region	0	0	0	1	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
	Area with winter cover crop	0	0	0	1	0	1		2	0	0	0	0	0	0	1	0	0	0	1	0
	Number and volume of on farm reservoirs	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Stocking density by livestock type	0	0	0	0	1	1	0	0	2	0	0	0	0	0	1	0	0	0	0	0

	Uptake of precision farming technologies	0	1	0	1	1	0	1	0	0	0	0	0	0	0	1	0	0	1	0	0
	Plant breeding: varieties	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
	Livestock breeding: proportion of farms using high Profitable Lifetime Index or Estimated Breeding Value by size/ region	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
	Proportion of UAA applying manure in total and with immediate incorporation	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	1	1	0
	Irrigated area	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Area of functioning field drains	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
	Area of woodland in active management	1	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	1	1
	Area of woodland certified as sustainable managed																				
	Area of moorland burnt by habitat type	0	0	0	0	0	0	0	0	0	0	0	1	2	0	0	0	0	0	1	0
	Area of habitat restored	1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	1	1
Land Productivity/ Services	Crop yield by type	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1
	Grass yield by type	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1	0	0	1	1	1
	Timber yield by type	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Production of meat/ milk/ eggs by species	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Carbon storage in woodlands	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Carbon storage in soil																			1	
	Carbon storage in peat	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0
Quality Indicators	Indicator species population & distribution estimates (birds, butterflies, plants)	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	1
	Habitat condition (designated sites/ semi-natural grasslands/ crown condition of tree species)	1	0	0	0	0	0	0	0	1	0	0	1	1	0	1	0	0	0	1	1
	Soil biodiversity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	0
	Invasive species population & distribution estimates	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
	Habitat connectivity/ fragmentation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Soil type	1	1	1	0	0	1	0	1	1	0	0	1	1	1	0	1	0	0	0	0
	Soil erosion risk	1	0	0	0	1	1	0	1	1	0	0	1	1	1	0	0	0	0	1	0
	Soil organic matter content	0	0	0	1	1	1	1	1	0	1	0	1	1	0	0	0	0	0	1	0
	Soil P&K index	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Soil pH	0	0	0	0	0	0	0	0	1	0	0	1	1	0	1	0	0	0	0	0
	N, P & Z pollutant loads in freshwater	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Water quality status	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Flood risk	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Land capability for agriculture/ forestry grade	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	1

Key: Cells are scored from 0 to 2; 0 = not relevant, 1 = relevant but needs to be used in combination with others, 2 = highly relevant could be used as a stand-alone (note metrics that were not relevant to any of the indicators in the table have been removed) .

Table 4: Matrix of climate change adaptation indicators against metrics

Indicators		Water demand by agriculture											Flooding of agricultural land			Fertility of agricultural soils					
		Total water demand for					Vol. of abstraction									Area of agricultural land					
Metrics		Crop irrigation	Livestock	Forestry	Habitats	Species	Catchments at risk of water scarcity	All catchments	Amount of crop production in climatically unsuitable areas	Number of farms implementing water efficiency measures	On-farm water storage capacity	Improved water quality	Area of ALC 1-3 land reliant on drainage	Agricultural losses from flooding/waterlogging	Proportion of EA flood asset systems protecting agricultural land	Covered by crops at high-risk of soil erosion	Covered by crops at low-risk of soil erosion	losing soil organic carbon, by grade	Converted to development, by grade	Under minimum/no tillage, by grade	Covered by soil conservation measures
Land cover	Arable and horticulture area	1	0	0	0	0	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
	Woodland area (broadleaved/ coniferous)	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Improved grassland area	0	1	0	0	0	1	1	0	1	0	0	1	1	1	1	1	1	1	0	1
	Semi-natural grassland area	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Rough grassland area	0	1	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Areas of other broad habitats	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Area of priority habitats	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Land Use	Crop area by type	1	0	0	0	0	1	1	1	1	0	1	0	1	0	2	2	1	0	1	1
	Temporary grassland area	0	1	0	0	0	1	1	0	1	0	0	1	1	1	1	1	1	1	0	1
	Permanent grassland area	0	1	0	0	0	1	1	0	1	0	0	1	1	1	1	1	1	1	0	1
	Area of each farm type	1	1	0	0	0	1	1	0	1	1	0	0	0	0	0	0	0	0	1	1
	Area of buffer strips (along watercourses/ other)	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	0	0	1
	Area of biodiversity designated sites	0	0	0	1	1	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	Area of land under relevant agri-environment scheme options	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
Management practices	Area designated as NVZ	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Mineral N fertiliser use per ha by crop type/ farm type/ region	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Organic fertiliser use per ha by crop type/ farm type/ region	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Pesticide use per ha by crop type/ farm type/ region	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0

	Proportion of UAA under zero/ min/ conventional tillage by crop type/ farm type/ region	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	2	1
	Proportion of UAA having fertiliser/ manure management plan by farm type/ region	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Area with winter cover crop	0	0	0	0	0	0	0	0	0	0	1	0	1	0	1	1	0	0		1
	Irrigated area	1	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Number and volume of on farm reservoirs	2	0	0	0	0	1	1	0	0	2	0	0	0	0	0	0	0	0	0	0
	Stocking density by livestock type	0	1	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
	Abstraction volume by use	1	1	1	0	0	2	2	0	0	0	0	0	0	0	0	0	0	0	0	0
	Number of farms implementing water efficiency measures	0	0	0	0	0	1	1	0	2	0	0	0	0	0	0	0	0	0	0	0
	Uptake of precision farming technologies	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Proportion of UAA applying manure in total and with immediate incorporation	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
	Area of functioning field drains	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0
	Area of moorland burnt by habitat type	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0
	Area of woodland in active management			1			1	1													
	Area of habitat restored	0	0	0	1	1	0	0	0	0	0	1	0	1		0	0	0	0	0	0
Land Productivity	Crop yield by type	0	0	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
	Grass yield by type	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	Production of meat/ milk/ eggs by species	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
	Water availability	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Flood assets	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Quality Indicators	Indicator species population & distribution (birds, butterflies, plants)	0	0	0	1	1	0	0	0	0	0	1	0	0		0	0	0	0	0	0
	Habitat condition (designated sites/ semi-natural grasslands/ crown condition of tree species)	0	0	0	1	1	0	0	0	0	0	1	0	0		0	0	0	0	0	0
	Soil erosion risk	0	0	0	0	0	0	0	0	0	0	1	0	0		1	1	0	0	0	1
	Soil organic matter content	0	0	0	0	0	0	0	0	0	0	0	0	0		0	0	1	0	0	0
	Flows	1	1	1	1	1	0	0	0	0	0	0	0	1	0	1	1	0	0	0	0
	N, P & Z pollutant loads	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
	Water quality status	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0
	Flood risk	0	0	0	0	0	0	0	0	0	0	0	0	2	0	1	1	0	0	0	0
	Land capability for agriculture grade	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	0
	Conversion to development	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	

Key: Cells are scored from 0 to 2; 0 = not relevant, 1 = relevant but needs to be used in combination with others, 2 = highly relevant could be used as a stand-alone (note metrics that were not relevant to any of the indicators in the table have been removed).

Table 4 (continued)

Indicators		New pests and diseases						Climate suitability of tree species						Ecological condition of farmed countryside				
		Incidence			Area						Agricultural land			number of farmland				
	Metrics	Pests	Pathogens	Weeds	Invasive non-native species	Woodland affected by wildfires	Woodland being sustainably managed	Proportion of timber trees planted in areas likely to be suitable in 2050	Proportion of woodland in active management	Diversity of tree species	Targeted agri-environment schemes (HLS)	Non-targeted agri-environment schemes (ELS)	ELS options identified as priority for climate change	Bird species in decline	Butterfly species in decline	Bat species in decline	Pollinator species (i.e. wild bees) in decline	Fragmentation of habitats due to agriculture
Land cover	Arable and horticulture area	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1
	Woodland area (broadleaved/ coniferous)	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0	0	1
	Improved grassland area	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1
	Semi-natural grassland area	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
	Areas of other broad habitats	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
	Rough grassland area	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
	Area of priority habitats	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1
Land Use	Crop area by type	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Temporary grassland	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1
	Permanent grassland	1	1	1	1	0	0	0	0	0	1	1	1	1	1	1	1	1
	Area of buffer strips (along watercourses/ other)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Area of land under relevant agri-environment options	0	0	0	0	0	0	0	0	0	2	2	2	0	0	0	0	1
	Area of biodiversity designated sites	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1
Management practices	Pesticide use per ha by crop type/ farm type/ region	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Area under organic farming	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Area with winter cover crop	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Plant breeding: varieties	1	1															
	Area of moorland burning by habitat type	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Area of woodland affected by wildfires	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0

	Area of woodland certified as sustainably managed	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0	0	0
	Area of woodland in active management	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0	0	0
	Area of habitat restored	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	1
Productivity	Crop yield by type	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Grass yield by type	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Timber yield by type	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Quality indicators	Pollinator species number and distribution	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1
	Farmland bird species number/ distribution	0	0	0	0	0	0	0	0	1	0	0	0	2	0	0	0	1
	Farmland bat species number/ distribution	0	0	0	0	0	0	0	0	1	0	0	0	0	0	2	0	1
	Farmland butterfly species number/ distribution	0	0	0	0	0	0	0	0	1	0	0	0	0	2	0	0	1
	Incidence & prevalence of pests and diseases	2	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Habitat condition & diversity	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1
	Soil biodiversity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Invasive species population & distribution	1	1	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0
	Habitat connectivity/ fragmentation	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2
	Climate projections	0	0	0	0	1	0	1	0	0	0	0	1	0	0	0	0	0

Key: Cells are scored from 0 to 2; 0 = not relevant, 1 = relevant but needs to be used in combination with others, 2 = highly relevant could be used as a stand-alone

Table 5: Links between indicators of ecological condition and the economic services and non-market benefits under in different land uses.

Agriculture

		Plant species richness	Bird & butterfly foodplants	Plant functional types	Farmland birds	Farmland butterflies	Structural condition of hedgerows	Structural condition of walls	Soil biological indicators	Soil chemical indicators	Soil physical indicators
Supporting	Primary production	0	0	1	0	0	0	0	1	1	1
	Soil formation	0	0	0	0	0	0	0	0	0	0
	Nutrient cycling	0	0	1	0	0	0	0	1	1	1
	Water cycling	1	0	1	0	0	1	0	1	1	1
Provisioning	Crops, livestock, fish	1	0	1	0	0	0	0	1	1	1
	Trees, standing vegetation, peat	0	0	1	0	0	1	0	1	1	1
	Water supply	0	0	1	0	0	0	0	0	0	1
	Wild species diversity	1	0	0	0	0	0	0	1	1	0
Cultural	Wild species diversity	1	1	1	1	1	1	0	1	1	1
	Environmental settings	1	1	1	1	1	1	1	1	1	1
Regulating	Climate regulation	0	0	1	0	0	0	0	1	1	1
	Pollination	0	1	0	0	1	0	0	0	0	0
	Detoxification & purification	0	0	1	0	0	0	0	1	1	1
	Hazard regulation	0	0	1	0	0	1	1	1	1	1
	Noise regulation	0	0	0	0	0	0	0	0	0	0
	Disease and pest regulation	0	0	0	0	0	0	0	1	1	1

Forestry

		Plant species richness	Bird & butterfly foodplants	Plant functional types	Condition of designated sites	Woodland certified as sustainably managed	Woodland birds	Woodland butterflies	Crown condition of key tree species	Tree pests and pathogens	Soil biological indicators	Soil chemical indicators	Soil physical indicators
Supporting	Primary production	0	0	1	0	0	0	0	0	0	1	1	1
	Soil formation	0	0	0	0	0	0	0	0	0	0	0	0
	Nutrient cycling	0	0	1	1	0	0	0	0	0	1	1	1
	Water cycling	0	0	1	1	0	0	0	1	0	1	1	1
Provisioning	Crops, livestock, fish	0	0	0	0	0	0	0	0	0	1	1	1
	Trees, standing vegetation, peat	1	0	1	1	1	0	0	1	1	1	1	1
	Water supply	0	0	1	1	1	0	0	1	0	0	0	1
	Wild species diversity	1	0	0	1	0	0	0	0	0	1	1	0
Cultural	Wild species diversity	1	1	1	1	1	1	1	0	0	1	1	1
	Environmental settings	1	1	1	1	1	1	1	1	0	1	1	1
Regulating	Climate regulation	0	0	1	1	1	0	0	1	1	1	1	1
	Pollination	0	1	0	1	0	0	1	0	0	0	0	0
	Detoxification & purification	0	0	1	1	1	0	0	1	1	1	1	1
	Hazard regulation	0	0	1	1	1	0	0	1	1	1	1	1
	Noise regulation	0	0	0	0	0	0	0	0	0	0	0	0
	Disease and pest regulation	0	0	0	0	0	0	0	0	1	1	1	1

Semi-natural habitat

		Plant species richness	Bird & butterfly foodplants	Plant functional types	Condition of designated sites	Condition of non-statutory semi-natural grasslands	Breeding birds: grassland specialists	Burning regimes on dwarf shrub heath	Burning regimes on blanket bog	Sediment supply	Soil biological indicators	Soil chemical indicators	Soil physical indicators
Supporting	Primary production	0	0	1	0	0	0	0	0	0	1	1	1
	Soil formation	0	0	0	0	0	0	0	1	0	0	0	0
	Nutrient cycling	0	0	1	0	1	0	1	1	0	1	1	1
	Water cycling	0	0	1	1	0	0	1	1	0	1	1	1
Provisioning	Crops, livestock, fish	1	0	1	1	1	0	1	1	0	1	1	1
	Trees, standing vegetation, peat	1	0	0	1	1	0	1	1	0	1	1	1
	Water supply	0	0	1	1	1	0	1	1	1	0	0	1
	Wild species diversity	1	0	0	1	1	0	0	0	0	1	1	0
Cultural	Wild species diversity	1	1	1	1	1	1	1	1	0	1	1	1
	Environmental settings	1	1	1	1	1	1	1	1	0	1	1	1
Regulating	Climate regulation	0	0	1	1	0	0	1	1	0	1	1	1
	Pollination	0	1	0	1	1	0	0	0	0	0	0	0
	Detoxification & purification	0	0	1	1	1	0	1	1	0	1	1	1
	Hazard regulation	0	0	1	1	1	0	1	1	1	1	1	1
	Noise regulation	0	0	0	0	0	0	0	0	0	0	0	0
	Disease and pest regulation	0	0	0	0	0	0	0	0	0	1	1	1

Key: 0 = contributes no information, 1 = contributes some information but other indicators needed, 2 = contributes all the information needed.

4 Modelling land use and climate change

In Section 2 we set out the different drivers of land use and the complex inter-relationships between them. The key purpose of this is to explore how different land use models use this information in order to predict how land might be used in the future and to be able to assess the different impacts of these decisions. In Section 3 we set out the different metrics that would be needed for a full assessment of the mitigation and adaption impacts of changes in land use. This chapter considers how the metrics and drivers identified in previous sections can be used to develop a framework for predicting land use.

The first task is to consider the parameters and range of values associated with different land use drivers, using the framework developed in Chapter 2. The aim is to represent what is known about driver action and interaction, and how these effects would be captured in the metrics identified in Chapter 3. Climate change is an important driver of land use, both directly and indirectly, so this exercise will also capture its action and interaction. The analysis relies on key sources in the literature, complemented by expert opinion.

The knowledge base on driver action is known to be more established than that on interaction, which can become highly complex when considering multiple drivers over time. To simplify this, previously published studies have developed scenarios to represent possible future land use outcomes. The second part of the task identifies the range of scenarios that have been developed from a brief review of relevant literature on UK land use future scenarios.

The following reports have been reviewed:

- Cambridge Institute for Sustainability Leadership (CISL) (2014). The Best Use of UK Agricultural Land.
- Government Office for Science (2010). Land Use Futures.
- UK National Ecosystem Assessment (NEA, 2011). Chapter 25 – “Scenarios: Development of Storylines and Analysis of Outcomes”.
- Nakicenovic *et al*. (2000). Special Report on Emissions Scenarios. CUP, Cambridge.
- Office for Science and Technology (2002). Foresight Futures 2020. Revised scenarios and guidance.
- Morris *et al.* (2005). Agricultural future and implications for the Environment. Defra Project IS0209: Technical Report.
- Rounsevell *et al.* (2005). Future scenarios of European agricultural land use II. Projecting changes in cropland and grassland. *Agriculture, Ecosystems and Environment* 107, pp117-135.
- Rounsevell *et al.* (2006). A coherent set of future land use scenarios for Europe. *Agriculture, Ecosystems and Environment* 114, pp57-68.
- Rounsevell & Reay (2009). Land use and climate change in the UK. *Land Use Policy* 26 (S), pp160-169.

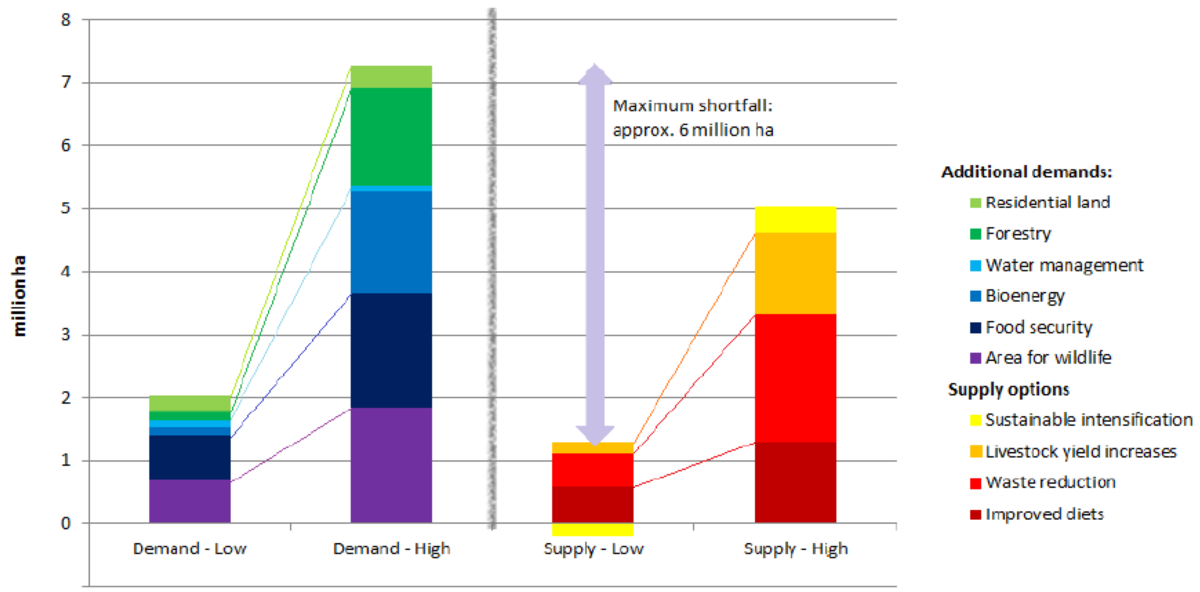
- Audsley *et al.* (2008). The impact of future socioeconomic and climate changes on agricultural land use and the wider environment in East Anglia and North West England using a metamodal system. *Climate Change,* 90 (1-2), pp57-88.

4.1 Methodological approaches for scenario development

The review identified two different types of scenario analysis. The most commonly used approach in the studies reviewed involves generating alternative storylines or scenarios for plausible future worlds, focussing mainly on indirect drivers. Storylines diverge by assuming society prioritises different values at opposite ends of conceptual axes that represent key indirect drivers. The Special Report on Emissions Scenarios (SRES) and Foresight Futures 2020 (Foresight) approach simplifies the drivers to just two (global/local and economy/environment), which in turn have implications for other indirect drivers such as demography, technology, and economics. Land Use Futures (LUF) considers three axes, but only develops three storylines. The NEA does not take a hierarchical approach to storyline development, and instead maps out drivers and possible trends in drivers and looks for common themes that link. The result is still a set of scenarios that are based on different values, but one which allows for a broader range of values to be considered.

A second approach varies the parameters associated with specific drivers to generate extreme scenarios that examine the land use response to particular stresses. In the CISL work, the potential changes in agricultural land resulting from low and high demands on agriculture and low and high supply of land are considered for each driver in isolation and then in combination. This results in additional demands for land versus different supply options. In Audsley et al, the model integrates the effect of many drivers but a number of scenarios are generated by varying respective parameters to build a picture of possible future outcomes. The CISL framework is shown in Figure 7 below.

Figure 7: CISL High-Low Demand-Supply model to estimate UK 2030 land use requirement



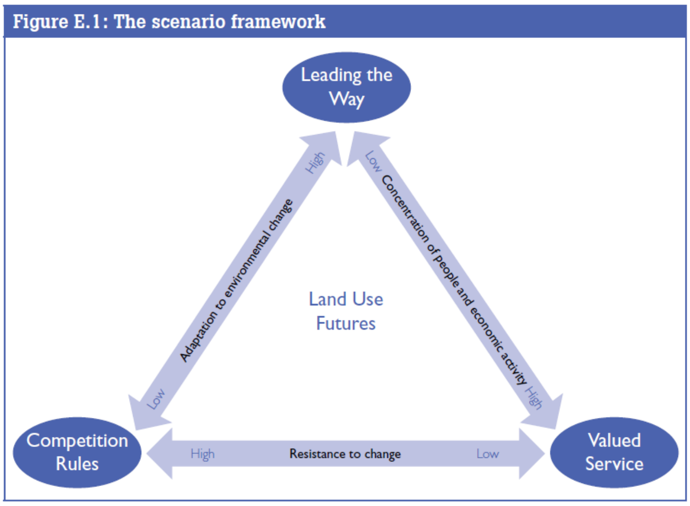
Source: CISL, 2014

The Foresight Futures, Land Use Futures and UK NEA frameworks are shown below in Figure 8.

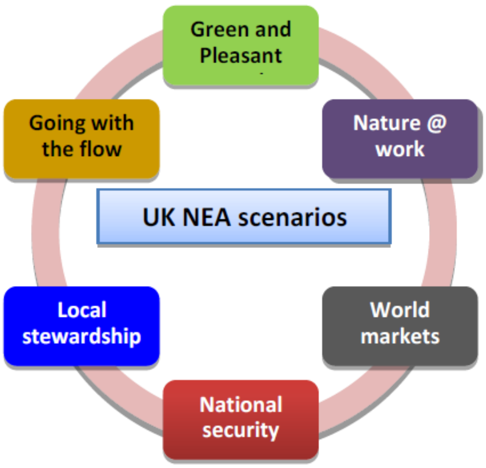
Figure 8: Example frameworks for scenarios on future land use

(a) Foresight Futures: 2020 Revised scenarios and guidance - Four UK futures scenarios (Office for Science and Technology, 2002)

(b) Land Use Futures: Making the most of land in the 21st century - three driver, three scenario model (Government Office for Science, 2010)



(c) UK NEA: Operationalising scenarios - Morphological Analysis approach to generate six scenarios (UK NEA, 2011)



Drivers incorporated

The scenario analyses use some or all of the indirect and direct drivers identified in Chapter 2 on both the demand and supply sides. For storyline based approaches, the focus is generally on how some or all of the indirect drivers change, with further assumptions made on what the impact will be on direct drivers. Different outcomes for CAP policy (abolitionist, supportive or reformist) are incorporated. Technological change is also an important driver, with many scenarios based on improvements in crop and livestock yields. Where the scenarios are used to generate future land use patterns, the direct drivers (e.g. demand for housing, crop productivity) are then incorporated.

More recent analyses have incorporated climate change variables into the scenarios considered, generally by overlaying different extremes of temperature and precipitation. The Land Use Futures work is unique in that it considers society's response to climate change (and change more generally) as a fundamental driver in differentiating future storylines. The NEA also looks at other direct drivers which affect habitats (rather than land use *per se*) such as invasive species and pollution.

Driver interaction

Apart from the CISL work, all the scenarios generated assume some interaction between drivers. In many of the studies, a hierarchy is used to model interactions, with societal and governance variables considered to be the most fundamental. These can impact on direct drivers (e.g. changing the demand for meat) or on other indirect drivers (e.g. changing the outcome for economic growth, population dynamics, technological progress and CAP policy), which in themselves influence the direct drivers. In the NEA, the morphological approach used captures synergies between different drivers (direct and indirect) by associating them together into scenarios linked by a common theme.

The extent to which this interaction is quantified varies with some studies developing a narrative with hypothetical outcomes presented by the authors. Others use expert opinion to parameterise the extent to which each driver then operates.

Common themes

There is considerable commonality between the SRES and Foresight storylines, both of which imagine four distinct future outcomes driven by societal values on globalisation and sustainability. The NEA authors note that many other scenario analyses studies (done for purposes other than investigating future land use) can be mapped back to the broad 2 by 2 matrix developed in SRES and Foresight. Although the NEA breaks with this pattern by adopting a different approach, there is still a certain correspondence between scenarios which is acknowledged in the report. Land use futures takes a different approach and is the only study reviewed that considers the response of society and its institutions to change, and in particular environmental change, as key drivers on which to build alternative storylines.

There appear to be some common themes emerging across the scenarios analysed. In the storylines generated that reflect plausible future worlds, agricultural land decreases in most scenarios. This is even true in scenarios where population growth is modelled as high. Improvements in technology and changes to the CAP are the main drivers of this. Even a world with higher food security concerns does not appear to result in a higher demand for UK agricultural land.

Assessment of models and gaps

Rounsevell & Reay (2009) review the relationship between land use and climate change, and draw on some other studies done in the context of developing scenarios for future land use that have not been mentioned above. They note that scenario analysis is generally based on assumptions about future changes in drivers, rather than verified facts and that data can often be of poor quality, leading to significant variation in the range of land use estimates from similar scenarios. They also note that many of the drivers which contribute to the models are poorly understood, in particular technological change and policy reform. Rounsevell *et al* (2006) raise similar caveats about the subjectivity of scenario interpretation and the high reliance on assumptions to underpin model development. The authors also note models themselves are typically spatially constrained (e.g. UK/Europe) so cannot take into account variables outside this area (e.g. demand from Asia). Equally the models are typically static and calibration assumes only that historic relationships will still hold into the future.

Some of these concerns are also reflected in the NEA, in particular how the different scenario outcomes for each driver might be better quantified, and whether all the uncertainties have been considered in the range of scenarios built. The authors also caution on the use of the NEA scenarios divorced from the process by which they were developed. Decision-makers should ensure that the questions they wish to use scenarios to answer reflect those they would need to ask themselves.

4.2 Implications for land use and climate change modelling

The studies reviewed vary in terms of geographical scale and methodological approach taken, with some attempting to build a range of plausible future world storylines and others considering a range of extremes which might be used to judge resilience or vulnerability to specific drivers. The scenarios consider a wide range of drivers, though a number of assumptions are made on which to base the quantitative element of their effect. However, once the quantities have been approximated then they are used as inputs to various models to produce possible future land use allocations. Climate change scenarios are included as cross-cutting themes that are often independent of other variables.

Maximising food production is considered in the CISL study although spatial distribution is not indicated. Other scenario analysis suggest that this will not be a strong driver, or that it will be offset by technological improvements to crop and livestock yields, so more can be produced from less land. Even where food security is a major driver, there appears to be no additional land use requirement. Climate change response has been considered as a driver in more recent work, in particular the Land Use Futures study. The scenarios explored here are considered as a narrative rather than for land use allocation, although broad predictions are made for variables which could be incorporated into a model.

The process of scenario development is equally as important as the actual scenarios produced. The questions asked during workshops or surveys and the opinions and assumptions of stakeholders are critical components. The CCC's requirement is quite unique and does not exactly reflect the purposes behind the development of scenarios used in these studies. As such, there is an opportunity to pose different questions in the context of food security and climate change response as part of a fresh scenario generation process to facilitate the next stage of this study.

Table 6: Review of scenario-based approaches

Scenario Exercise	Scale	Methodological Approach	Themes / Drivers	Interaction
SRES	Global	2 * 2 social value axes	Global vs local; sustainability vs growth; Technology	Hierarchical approach: Cultural / socio-political determines demographics, economics, technology
Foresight Futures	UK	2 * 2 axes	Community vs individual; Autonomy vs interdependence	Hierarchical approach: Cultural / socio-political determines demographics, economics, technology
Rounsevell et al (2005)	Europe	Modified SRES (food production only); Demand vs Supply	*Demand*: population, consumer preferences, market liberalisation, and EU enlargement. *Supply*: productivity (technology, management, temperature, precipitation, CO_2)	Demand and supply drivers interact in simple model (but scenarios focussed on single land use category)
Rounsevell et al (2006)	Europe	Modified SRES (broader land use focus)	*Urban* -> population (demographic trends, housing demand); GDP, *inter alia* *Agriculture (food + bioenergy)* -> as R et al (2005) *Forest:* No specific driver – assume current national trends continue (mainly abandonment of ag land) *Protected area:* policy/legal; recreation/tourism	Simple hierarchy used to assume priority between land uses Protected (designated) areas>urban>cropland> grassland>bioenergy crops>commercial (unprotected) forest land>not actively managed
Morris et al (2005)	UK	Modified Foresight (+ 4 additional scenarios for crop technical change)	Agricultural and rural policy; Food markets and prices, Environmental policy; Farmer attitudes / motivation; Agricultural production and farming systems	Economic equilibrium model.
Audsley et al (2008)	UK	Modified Foresight (+ UKCIP02 climate change) – scenarios (stressed to extreme)	Agricultural production; bioenergy production; Yield improvement; Input costs (fertiliser, water, labour etc); water availability/efficiency; set-aside; CAP subsidy; temperature and precipitation	Each scenario generates different parameter inputs for each driver
Land Use Futures	UK	Workshops;	Climate change adaptation; Societal resistance to change; Population dispersion / concentration	Narrative driven
NEA	UK	Survey; Morphological Analysis; (ecosystem/land cover focus)	*Indirect*: demographic, economic, socio-political, cultural / behavioural, scientific / technology *Direct*: LUC, pollution / enrichment; resource exploitation; climate change invasive species;	Commonality between drivers captured in morphological analysis. Bayesian Belief Network used to determine future LU or LUC
CISL	UK	Literature Review; Stress test	*Demand*: population (built environment), bioenergy targets food security; biodiversity protection; woodland cover, water management *Supply*: crop productivity; livestock productivity; food waste reduction; change in diet	Not considered

5 Current models to predict land use in the UK

The aim of this component of the work was to provide an overview of existing models used to predict land use patterns in the UK now and in the future. There were two stages to the work. The first stage was a rapid review of the literature to identify modelling approaches and models that are or have been used to model land use and/or land use change (LUC). From this rapid review, a shortlist of models was identified. In the second stage, the shortlisted models were reviewed in greater detail to assess their in order to provide a judgement on their suitability for use in the development of a modelling framework for assessing the impacts of potential future land use changes in the UK.

For the rapid review of models of land uses and/or land use change, refereed publications, reports and working documents were selected using three approaches:

- Extracting references from published reviews of land use models,
- Following up references to models from published papers on a model of interest (often referenced due to synergies for potential integration with other models, or else for comparison as an alternative approach)
- Searching for the following terms on Web of Science and Google Scholar:
    - 'Land use change model'
    - 'Agent-based land use model'
    - 'Land use model agriculture'.

From these sources, models were categorised into different approaches and their ability to capture key drivers and influencing factors, based on a conceptual framework for modelling land use change to produce a shortlist of models to be examined in more detail. The full list of the references used in the rapid review is provided in Appendix 6.

5.1 LUC Modelling Approaches

The rapid review phase identified a number of key categories of modelling approaches that are or have been used to model LUC at national, European or global scale. Below we describe the main approaches and their ability to capture the key types of major drivers of LUC that were identified in section 2 of this report.

Empirical regression models

Empirical regression models (e.g. Chaudhuri & Clarke, 2012; Sorel *et al.*, 2010) generally focus on spatial and biophysical drivers. The drivers are parameters that can be measured in a gridded landscape, such as soil type, population size and distance to road. A regression equation is usually fitted to historic data on both the drivers and land use to derive a relationship that describes the importance of the different drivers in determining land use. Predictions are then made by changing the value of the drivers using scenarios and predicting the land use under the scenario conditions. This type of model is most frequently used in modelling at a local/regional scale, particularly as models of urban development.

Empirical regression models are limited in their ability to predict beyond the near future (Brown *et al.*, 2004), due to the lack of inclusion of non-physical drivers such as economics, and because the effect of each driver can vary over time. In addition, spatial autocorrelation can limit the applicability of these models at a global scale, as the effect/relative importance of each physical driver varies between different parts of the world.

Econometric and spatio-econometric models

These models (e.g. Bateman *et al*, 2014; Britz *et al.*, 2014; Holman et al., 2016) focus predominantly on economic drivers, often predicting changes in demand for a mix of products (for example as a result of increasing population or GDP), which then drive changes in land-use as required to meet that demand. These models are often based on the principle of profit-maximisation, and are mostly 'equilibrium models', which keep supply and demand in equilibrium. For example, if demand for a product decreases, the price for that product decreases and as a result the supply decreases to bring the system back into equilibrium.

These models need to be developed with a method for determining the relative influence that each of the key drivers has on profit and hence land use. In several of the models, this is done through a regression of historic driver data against historic land use. This potentially limits the predictive capability of these models as using historical data means that the models cannot necessarily account for novel land uses or predict accurately outside of the range of variation in the historical data (Wainger *et al*., 2007).This limitation is ameliorated to some degree by the use of broad land use categories (e.g. arable, grassland, forestry) rather than individual crops.

Economic models are most frequently used at a global or sub-global scale, usually with a top-down approach and with profit-maximisation based on crop yields. However, economic models often do not take into account spatial constraints and variations in yield beyond quite a coarse sub-global scale, if at all. A number of economic LUC models have been adapted to include a more detailed representation of spatial variation and constraints, leading to the development of spatio-econometric models.

Spatio-econometric models take into account both biophysical and economic drivers and are used at a variety of scales and with varying sophistication in representing the biophysical environment. These models are generally driven by an economic (and sometimes political/social) model of demand and usually assume profit-maximisation for an average farm, but take account of some biophysical constraints in predicting how land-use responds to changes in demand. For example, biophysical constraints may limit the potential yield of a crop in an area or increase the costs of growing it. These constraints are included in the profit-maximisation calculations which determine how much supply responds to demand.

Agent-based models

Agent-based models (e.g. Berger, 2001; Izquierdo *et al.*, 2003; Valbuena *et al.*, 2010) assume that there is a population of "agents" who individually make decisions on how to allocate land according to an individual set of rules. Many agent-based models include both social and economic factors, and sometimes include spatial and biophysical constraints. These models are developed to give a bottom-up approach, predicting land-use change at the level of the decisions made by individual land managers. These land managers can be influenced by economics, policy and social factors, and have to work within the constraints of the land that they own (for example, soil type and suitability for particular crops) and the resources available to them.

Most agent-based models are driven by the assumption that land managers make decisions based on profit-maximisation, or constrained profit-maximisation (for example land managers may not have perfect knowledge of the yield or price that they will achieve for a crop, or behavioural constraints such as an individual perception of risk).

These models vary in their representation of the landscape managed by individual agents within the model. Some models allocate each agent within the model land parcels of an equal size and quality as a starting point, whereas others take more account of heterogeneity in land ownership – this can have a substantial impact on the outcome of the simulation.

Limitations include difficulty in scaling models up beyond a local scale due to the computational power required to simulate the decisions of large numbers of agents, and the need for data on land manager characteristics to allow the model to represent a realistic landscape and agent population. However, this limitation can be overcome to some degree by using a typology of agents and using an average of multiple runs of a simulation to describe the average behaviour of an agent of a particular type. This average behaviour can then be used to replace the full agent-based approach for larger areas.

Allocation models

Allocation models distribute pre-defined percentages of cropping or land-use across a landscape (where the percentage has been provided by a model or scenario), usually with reference to biophysical constraints such as climate and soil type, and sometimes taking account of temporal constraints such as what is currently grown in a location and the practice of crop-rotation (e.g. Hilst *et al*., 2012; Veldkamp *et al*., 1999). The method of allocation may be statistical/probability-based, or driven by optimising yield, average farm profit or nitrate runoff. In addition allocation can be top-down where the most suitable land use is selected first and then the overall land use is adjusted to ensure that supply of a particular land use does not exceed demand. The second approach is bottom up where land uses are assigned in a specific order (i.e. for the first land-use the most suitable locations are chosen until supply equals demand, then the second land use is considered, and so on until all land-uses are allocated).

Often the allocation is based on a suitability approach, where multiple biophysical and other factors (e.g. proximity to transport) are used to define the suitability of an area for a given land use. These suitability models are commonly derived through an analysis of historical land use, with the limitation that it is therefore difficult to include novel land uses. This limitation can be overcome through the use of expert opinion to determine the suitability of particular areas for novel crops.

Integrated frameworks

Integrated frameworks (e.g. Lavalle et al., 2014; Schneider & Schwab, 2006; Stehfest et al., 2014) link a number of models together to gain the benefit of modelling the drivers represented in each model and also of assessing impacts of the land use change. For example, economic models can be used in conjunction with allocation models where the economic models predict changes in land use demand, and allocation models distribute the changes across a landscape, taking account of biophysical constraints.

Frameworks may include iteration over a number of time steps and feedback between models from each time step. For example, the land-use change from one step determines the supply of a crop or product, which may then feed into a global economic model to determine the demand for the next time step. However, most frameworks will have some models that do not accept feedback. For example, climate models that influence crop yields may not accept feedback from land-use changes.

The capability to capture the feedback effect of land-use change on economics and other factors that themselves influence land-use change is very helpful in making projections for the future. However, the linking of models does carry some risks, for example that some components of a framework may be extrapolated beyond the individual model's range (spatial or temporal) of validity, and careful consideration must be given to avoid this. In addition, many of the integrated frameworks are designed to work on large spatial scales with a significant number of simplifying assumptions.

5.2 Selection of models for review

To develop the shortlist of models for detailed assessment, the approach used, the ability of the model to include the key components of the conceptual framework (Figure 1), and the spatial scale at which the model operated were assessed and used as selection criteria. In addition, the popularity of the model (or its approach to land allocation) was taken into account when determining the models to include on the shortlist (Table 7). The shortlist includes models that cover a range of geographical scales (national, European and global); key references for each model can be found in Appendix 7.

The models included were chosen to be representative of the range of approaches used to model LUC and also of the most common models currently used to investigate LUC at a range of spatial and temporal scales. The models selected provide approaches to inclusion of many of the important factors influencing LUC identified in the conceptual framework. Some of the models listed are well-established, tested over many years and are widely used, whilst others are more recent developments but offer new approaches or consider factors not represented in other models.

These models were taken forward for a more detailed structured assessment of their ability to represent and predict land use change, accounting for their ability to capture and integrate the key drivers identified in Chapter 2, the strengths and weaknesses of the approach used, the scale at which the modelling takes place and the ability to utilise datasets identified in Chapter 3.

5.3 Review of the shortlisted models

Each of the models in the shortlist was reviewed in more detail, explicitly examining the method used to allocate land, the inputs, outputs and drivers that are used in the model and the impacts that are assessed by the model. In addition, the strengths of the model and the main assumptions (weaknesses) of the model were identified. The full review for each of the models is provided in Appendix 7 with a list of the main inputs, drivers and impacts assessed in Appendix 8.

It is important to note that most of the shortlisted models were developed with a specific purpose in mind (see Table 7) and the inputs and drivers included in the models are a reflection of the original purpose of the model. As a consequence, the spatial context and resolution is driven primarily by the purpose of the model and the spatial resolution of available input data (or the spatial resolution of output data form models used to provide inputs) for the land allocation model (Verburg *et al*., 2013). With appropriate data, it should be possible for most of the models to be used at the UK scale (or even regional scale) with a resolution of at least 1km square.

A summary overview of the drivers included in each of the shortlisted model, the spatial and temporal scales of each of the models and their approach type is provided in Table 8. From this table it can be seen that only the agent-based models (FEARLUS, MP-MAS and Valbuena *et al*. (2010) include all of the driver categories identified in section 2 of this report (albeit with some drivers included indirectly through scenarios). The other models do not include behavioural drivers, but apart from CAPRI (which does not include cropping constraints) do include all the non-behavioural drivers either directly or indirectly through scenarios.

Table 7: Shortlist of models reviewed in more detail and reasons for inclusion

Model name	**Model category**	**Reason for inclusion & core use**
FEARLUS	Agent-based model	Models a range of social, economic and biophysical factors. Developed to allow application of agent-based models to land use decision and has been used to assess decision relating to protection of water quality.
MP-MAS	Agent-based model	Innovative representation of agent population, detailed representation of spatial factors with feedback. Developed to replicate human decision making in agriculture and has been applied to case studies of land use change in Thailand, Chile and Ghana.
Valbuena *et al.* (2010)	Agent-based model	Typology of agents to simplify heterogeneity in the population of decision makers. Developed to simulate individual farmer decision making in terms of selection of farm practices and has been applied to a case study in the Netherlands.
EUFASOM	Integrated framework	Representation of different sectors impacting on land-use: forestry, bioenergy and agriculture. Developed to investigate the competition between land for forestry, food and non-food agriculture within the context of meeting renewable energy targets.
LUISA	Integrated framework	Framework of well-established models with many drivers of land-use change. Developed to provide ex-ante evaluation of European and national policies that impact on land use. It has been applied to the whole of the European Union.
IMAGE	Integrated framework	Framework of models with many drivers of land-use change, e.g. global economics, climate. Well-established. Developed as a dynamic integrated assessment framework for the analysis of global change. Has been used to provide scenario studies for the Intergovernmental Panel on Climate Change, the United Nations Environment Program and Organisation for Economic Co-operation and Development.
TIM	Spatio-econometric model	Puts economic value on land used for recreation, allowing value to non-land-managers (such as nearby urban populations) to be taken into account in policy planning. Developed to identify optimal ways for implementation of multi-objective policy changes. Has been used to assess the scenarios in the National Ecosystem Assessment
CLIMSAVE	Spatio-econometric model	Representation of spatial variability in biophysical constraints in crop model, enabling modelling of the impacts of climate change on crop yield and thus land-use. Developed as an exploratory tool for the complex issues surrounding impacts, adaptation and vulnerability to climate change. Applied to Europe and Scotland.
CAPRI	Spatio-econometric model	European focus, incorporates global economic drivers and models of crop, livestock and forest sectors. Well-established. Developed to assess the impact of the Common Agricultural Policy at European, national and sub-national scale.
CLUE	Allocation model	Widely used including in some important frameworks. Allocation based on probability, taking into account spatial and temporal constraints. Developed to simulate land use change using empirically quantified relations between land use and its driving factors. It has been applied to a wide range of case studies and underpins the LUISA and IMAGE frameworks.
PLUC	Allocation model	An alternative approach to CLUE that uses a bottom-up method for allocation of land use. Allocation is based on both biophysicial, economic and social suitability information. Developed to assess future developments in land availability for bioenergy crops. It has been applied to case studies in Mozambique and Brazil.

Table 8: Summary of drivers included in the shortlisted models and their spatial coverage, spatial resolution and temporal resolution

		Drivers / Influencing factors								
Model	Model Type	Agronomic	Economic	Behavioural	Cropping Constraints	Land ownership and protected area constraints	Policy constraints	Spatial Coverage	Spatial resolution	Temporal resolution
FEARLUS	Agent-based	Direct	Direct	Direct	Direct	Direct	Indirect	Regional	User defined	Annual
MP-MAS	Agent-based	Direct	Direct	Direct	Indirect	Direct	Indirect	Regional	100m or user defined	Annual
Valbuena et al (2010)	Agent-based	Direct	Indirect	Direct	Direct	Direct	Indirect	Regional, potentially national	100m	Annual
EUFASOM	Integrated framework	Direct	Direct		Direct	Direct	Direct	European, National	National	5-yearly
LUISA	Integrated framework	Direct	Direct		Direct	Direct	Indirect	European, National, Regional	100m	Annual
IMAGE	Integrated Framework	Direct	Direct		Direct	Direct	Direct	Global, sub-global	10km	Annual
TIM	Spatio-econometric	Direct	Direct		Direct	Direct	Indirect	National, Regional	2km	Annual
CLIMSAVE	Spatio-econometric	Direct	Direct		Direct	Indirect	Indirect	Europe, National, Regional	5km	2020 & 2050
CAPRI	Spatio-econometric	Direct	Direct			Direct	Direct	European, National, Regional	Variable (highest = 1km)	Annual
CLUE	Land Allocation Only	Direct	Indirect		Direct	Indirect	Indirect	European, National, Regional	1km (100m)	Annual
PLUC	Land Allocation Only	Direct	Indirect		Direct	Indirect	Indirect	European, National, Regional	1km	Annual

Table 9: Summary of functionality of the models reviewed

	FEARLUS	MP-MAS	Valbuena *et al* (2010)	EUFASOM	LUISA	IMAGE	TIM	CLIMSAVE	CAPRI	CLUE	PLUC
Range of drivers modelled (High – 4 or more drivers in most categories (table 8), Low (1 or 2 drivers in up to 4 categories)	Low	Low	Low	Medium	High	High	High	Medium	High	Low	Low
Global (G), national (N) or local (L) scale drivers	N + L	All	N + L	All	All	All	N + L	All	All	N+L	N+L
Range of impacts considered {High - >8, Low - <=3)	Low	Low	Low	Low	High	High	Medium	Medium	Low	Low	Low
Competition between different land use demands (Yes/No)	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Feedback from impacts to land use (Yes/No)	No	No	No	No	No	Yes	No	No	No	No	No
Monetisation of environmental impacts (Yes/No)	No	No	No	No	No	No	Yes	No	No	No	No
Key allocation assumption [1]	PS	PM	-	CE + PF	CE	CE	PM + PF	PM	CE + PM	S	S
Climate change can be incorporated (Yes/No)	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Timescale	Not stated	25 years[+]	Not stated	To 2050	To 2050	To 2100	To 2060	To 2050	To 2050	N/A	N/A
In active development (Yes/No)	No	Yes	No	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes
Publicly Available or Downloadable (Yes/No)	Yes	Yes	No	No	No	No	No	No	No	Yes	No

[1]PM = profit maximisation, PS = Profit Satisficing (aspirational level of profit achieved), PF = perfect foresight, CE = competitive equilibrium, S = Suitability (may include economics)

Note that the table provides an overview of the published functionality of the models reviewed, and that many of the approaches used to develop the reviewed models could be adapted to include further spatial scales, temporal scales, drivers and impacts.

The majority of the models operate on an annual timescale, apart from CLIMSAVE & EUFASOM. However, CLIMSAVE is an online meta-model of several models and the underpinning full models can and do operate on an annual timescale. The spatial context and spatial resolution is where there is the most variation, with spatial contexts from regional through to global and spatial resolutions from 1 hectare (100m square) through to 10km squares. Table 9 provides a summary of the functionality of the reviewed models, the detail of which is provided in Appendix 7. This overview highlights the published functionality of the models but many of the approaches used in these models could be adapted to include further spatial scales, temporal scales, drivers and impacts.

All of the shortlisted models make some assessment of the suitability of an area for land use based on a combination of bio-physical (agronomic, cropping constraints), socio-economic and other factors. Most of the models include the interactions between these drivers to allow allocation to account for competing demands for land use (Table 8). The precise drivers included in the suitability assessment vary between the models (see Appendices 7 and 8), but more importantly, also vary between applications of the same model to different geographical locations. Therefore, there is the potential to adapt any of the models to the specific set of driving factors that CCC wish to investigate by selecting a specific set of drivers to be included in the suitability assessment for the land allocation components of the models. The main caveat will of course be the availability of suitable data to be used as inputs to the suitability assessments.

In terms of assessing impacts from changes in land use, all of the models have been developed with some form of assessment in mind. However, it should be noted that the assessment of impacts, particularly in relation to climate change, is usually done using a separate model from the model that predicts land use. In some cases the assessment models have been integrated with the land allocation model (e.g. FEARLUS-W and TIM). In other models, the outputs from the land allocation model are used within several impact models as part of a framework of assessment, occasionally with feedbacks between the assessment and the land allocation (e.g. IMAGE, LUISA, CLIMSAVE, and EUFASOM). Important factors to consider in selecting a model for future work on land use change and its implication for climate change mitigation and adaptation.

None of the models reviewed were explicitly designed to answer questions regarding the impacts of land use change on adaptation to and mitigation of climate change, apart from CLIMSAVE, but this is restricted to a specific set of scenarios with well-defined assumptions. Therefore, none of the models (as currently published) will fully meet the needs of CCC and any future work will need to include a process for either the selection of an appropriate modelling framework and the development of a model, or the modification of existing models in order to provide a robust approach to land allocation and assessment of the impacts of land use changes in terms of climate change mitigation and adaptation.

All of the shortlisted models have components or approaches that could potentially be beneficial to CCC. The integrated frameworks provide a number of advantages in that impact models have already been linked to the land allocation models, but suffer from the fact that they are less accessible than some of the other models. The agent-based approaches would allow the incorporation of farmer behaviour into the models, but care would need to be taken to ensure that the models were able to be scaled to national level without adversely affecting their performance and run times. In addition, the agent-based models would need investment in terms of representing the biophysical factors and constraints affecting land use. CLUE and PLUC could form the basis of the development of a new model, but would need investment in terms of the development of approaches to determine the demand for land within the UK, accounting for biophysical factors and constraints. CLIMSAVE is a tool based on meta-modelling of the results of a whole suite of detailed models. To adapt this to meet CCC's needs would be possible, but would require the original models to be run using a set of scenarios developed by CCC and then the results of these scenarios to be aggregated through meta-modelling. CAPRI and TIM would both require investment in adding approaches to assess impacts as they currently only have a limited range of impact assessment. TIM would be extremely useful for assessing an overall optimal strategy as it is able to monetise environmental impacts, but investment would need to be made to ensure that appropriate monetisation approaches were used along with appropriate constraints on land-use change.

In order to include mitigation of climate change, there would be a need to have sufficient detail in the models to enable the implementation of different farm management practices to be represented. Currently, although CAPRI and EUFASOM include some management practices, all of the models would need modification in order to include mitigation practices in detail.

In determining how to progress this work, CCC might wish to consider the following questions when making a decision about which model or models to use:

1. *A model or a tool?*

   The first question is whether a model or a tool would be the most suitable way forward. CLIMSAVE is a good example of the production of a tool based on detailed models. Meta-models that capture the behaviour of the full models under a range of conditions have been used to produce a tool that allows the user to modify input assumptions (within a set range). CCC should consider whether they wish to have a model run for a defined set of scenarios or whether it would be more beneficial to have a tool based on a model that would allow in-house exploration of scenarios and the assumptions within the scenarios, including the relative importance of different drivers.

2. *How accessible are the models?*

   This question relates to determining how easy it will be to use the model and potentially modify it. For example, FEARLUS, MP-MAS and CLUE are able to be downloaded and then modified or adapted by modellers who were not originally involved in the development of the model. In contrast, IMAGE is owned by the PBL Netherlands Environmental Assessment Agency and due to its complexity could only be modified or adapted by PBL.

3. *Is the model being actively developed?*

   If a model is under active development, then there is a much higher potential to be able to modify the model to suit the needs of CCC through engagement with the model developers. Of the models in the shortlist, IMAGE, MP-MAS, LUISA, CAPRI, CLUE, TIM and CLIMSAVE (now IMPRESSION) appear to be actively being developed, and of these the latter two are being developed by researchers in the UK.

4. *Should land-use decisions be based on profit maximisation or not?*

   There are a number of approaches within the shortlisted models to determining which land use is most suitable for a particular location. For those models that explicitly account for economics, profit maximisation is the most common approach. Profit maximisation assumes that a land manager will always place the most profitable land use on a piece of land in order to get the highest return. In the CLIMSAVE model, profit is included, but constraints can be placed on the land use so that an area will not always be assigned the most profitable land use. Finally, there is the option to assume that land managers are satisficing (as done in FEARLUS), where an aspiration level of profit is set and then the allocation works to select land uses that attempt to meet the aspiration. Which of these approaches is most appropriate will depend on the level of detail that it is felt necessary to include in order to represent how land use will change and whether sufficient data is available to allow incorporation of one of these approaches into the modelling.

5. *Should the model assume perfect knowledge for land use decisions?*

   Within the models, one of two assumptions is made regarding the selection of land use that of perfect knowledge or that of imperfect knowledge. Under the assumption of perfect knowledge the land use decision is made with the future sale price known (i.e. the perfect decision is made with regards to profit maximisation, based on inputs of sale prices from scenarios or models). In reality, perfect knowledge is not available and a land use decision would be made with an estimate of the potential profit. Within the shortlisted models CLIMSAVE and MP-MAS explicitly assume imperfect knowledge as part of the land use allocation process.

6. *How much data manipulation and analysis will be required before the model can be run?*

   As whichever model(s) is(are) chosen will require some adaptation in order to be able to meet the needs of CCC, then consideration will need to be given to the amount of time that will be required in adapting the model(s) to meet CCC's needs and the manipulation and analysis of data to provide inputs to the model(s). All of the models have included a degree of analysis of data for the definition of land suitability used within the land allocation models. FEARLUS and CLUE are both frameworks that require the user to define the structure of the land allocation model for themselves. This would require data analysis and time to ensure that the appropriate drivers are included with correct weightings for driving land use. In addition data analysis may be required to derive typologies of land managers for decision making (in the case of agent-based models) or the analysis of economic, population or other data for the development of scenarios based on trends in social and economic drivers. In the integrated frameworks, a large amount of data has to be analysed and manipulated to ensure that each of the models in the framework that use external input data receives this input data in the correct format and at the correct spatial and temporal resolutions.

Finally, we would recommend that the results of the modelling work are expressed relative to a baseline that has been predicted from the same model. This not only allows the results to be expressed in relative terms (e.g. percentage change in land uses) but also means that if there are any significant assumptions in the model, then these have been applied to the baseline as well as the scenarios so the outputs are consistent across the scenarios and baseline.

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6 CCC UK land-use workshop

The purpose of the workshop was to provide a forum for the CCC to informally explore with key stakeholders the feasibility of modelling possible land use pathways in the context of climate change mitigation and adaptation. In order to provide a focus for discussions, a scenario was presented which envisaged net zero GHG emissions from the UK agriculture and land-use sectors post 2050. The core question asked at the workshop was "*what future uses of UK land could help reach net zero emissions in the agriculture and LULUCF sectors post 2050, while ensuring resilience to the impacts of climate change?*"

The workshop was held on 26 April 2016 at Imperial College, London and a total of 23 delegates attended from 19 organisations. The event was chaired by Sir Graham Wynne (member of the CCC's adaptation committee) and facilitated by CCC and ADAS staff. The delegates covered a range of interests including experts on agriculture and forestry, food policy, land use modelling, natural capital and ecosystem services. The agenda and a full list of delegates who attended are detailed at Annex 9.

6.1 Baseline understanding

The Climate Change Act established a target for the UK to reduce its emissions by at least 80% from 1990 levels by 2050. This target represents an appropriate UK contribution to global emission reductions, consistent with limiting global temperature rise to as little as possible above 2°C.

The CCC has built various scenarios for reducing emissions on the path to 2050, with their central estimate meeting the UK 2050 target in the Climate Change Act. In the agriculture sector this assumes the following actions: increased take-up of crops and soils measures that mainly target the reduction of N_2O through improved efficiency of fertiliser use (e.g. use of cover crops and improved manure management practices); livestock measures targeting animal diets, health, and breeding that reduce methane; effective waste and manure management, including anaerobic digestion; and improvements in the fuel efficiency of stationary machinery.

The scene was set in an introduction by the CCC on issues for climate change mitigation and adaptation in the agriculture and LULUCF sectors. Key points raised with regards to climate change mitigation and adaptation in the agriculture and LULUCF sector were:

Mitigation

- There has been an 18% reduction in agricultural GHG emissions in the UK since 1990.
- Based on the 2016 national inventory, UK agricultural GHG emissions in 2014 accounted for 49 $MtCO_2e$, or 9.5% of total UK emissions.
- In the 5th Carbon Budget the LULUCF sector is a net carbon sink of ~9 $MtCO_2e$ in 2014 (this does not include all emissions from upland and lowland peat).
- Projections[10] to 2030 in the absence of low carbon policies (e.g. GHG abatement and afforestation) suggest that agriculture emissions will increase by 2% and the LULUCF sector will become a small net carbon source by 2030.
- Best estimates suggest that agriculture will account for a larger share of UK emissions by 2030 at 14-16%, up from 9.5% in 2014. This is due to other UK sectors decarbonising at a greater rate than the agricultural sector.
- The CCC estimate that abatement measures could mitigate emissions in the agricultural sector, with potential savings of 8.5 $MtCO_2e$ by 2030.

[10] Based on DECC UEP (2015)

- The CCC project that the LULUCF sector could turn from a net carbon source to a net carbon sink by 2030 through mitigation measures such as afforestation (planting around 15,000 ha/year) and increasing agroforestry from 1% to 1.6% of agricultural land.
- It is recognised that other sectors (e.g. Power and Transport) reflect a greater proportional potential for mitigation abatement measures than for example buildings, industry and agriculture, due to more cost-effective abatement options.
- By 2050, it is anticipated that agriculture will account for almost 30% (43.5 $MtCO_2e$) of total UK emissions (estimated at 147.6 $MtCO_2e$).

Adaptation

- Climate change provides opportunities in the form of extended the growing season and milder winters, with the potential for improved productivity of crops, grasslands and forestry. There also may be opportunities for more widespread growing of novel crops and for areas that are currency marginal, due to climatic constraints, to become more viable for agricultural use.
- At the same time, climate change can be expected to exacerbate a number of key limiting factors that may make it difficult to realise the potential opportunities from longer growing seasons. This will especially be the case if international mitigation measures are unsuccessful in restricting mean global temperature rise to below 2^oC.
- Drier summers and changing precipitation patterns are likely to increase water scarcity and aridity in parts of the UK, with eastern and south eastern regions most vulnerable to water shortages.
- Projections of increased soil aridity suggest that under a high emissions scenario by the 2050s, soil droughtiness will drive the downgrading of Agricultural Land Classification (ALC), with considerably less land available at grades 1-3a and increases in land at grade 4.
- Projections of reduced water availability for abstraction suggest that under a high emissions scenario by the 2050s, abstraction demand in central and eastern England will increase, with many areas increasing by more than 200%.
- Increases in winter precipitation and sea level rise will increase flood risk in the UK, both from coastal and fluvial flooding, but also from surface water flooding during extreme rainfall events.
- A 1m sea level rise will put pressure on around 20% of coastal defences in England, making them highly vulnerable to failure and putting an additional 2,100 km^2 of land at risk of inundation.

6.2 Working towards net zero emissions

The recent COP21 climate agreement in Paris set a globally agreed ambition to restrict global temperature rise to less than 2°C by the end of the century. However the Paris Agreement does not specify how to deliver the target on a sector by sector basis.

In the UK, the CCC and others have set out plans to address climate change mitigation up to 2050 through the Climate Change Risk Assessment and Carbon Budgets, however, there is a need to go beyond this to eventually meet global net zero emissions.

It is recognised that there are a vast range of ways to address mitigation in the agriculture and LUCLCF sector, but also an urgent need to prioritise activities, with current estimates indicating a third of UK emissions will come from this sector by 2050, unless measures and policies are implemented in the next few decades. This will have implications on agriculture and LULUCF sectors in terms of potential future uses of land, particularly with regards to the importance of maintaining food security without negatively impacting on emissions reductions.

This workshop provided a scoping exercise for the CCC to explore possible pathways to net zero emissions. The 'best' pathway to eventually reaching net zero emissions is complex and dependent on the perspective taken for optimal land uses, which strive for self-sustainability and food security without compromising the environment, both in the UK and overseas.

6.3 Perspectives on 'best' pathways

The first breakout session aimed to understand the factors to consider in specifying pathways and constraints on land use under a net zero emissions scenario. Delegates were asked to consider the following question, taking into account any synergies and trade-offs they felt were key for success:

"*What are the possible pathways to reaching net zero emissions from UK agriculture/LULUCF*"?

Delegates were each asked to individually record the following on Post-It notes:

1. Two main **synergies** between climate change mitigation and other land use objectives;
2. Two main **trade-offs** between climate change mitigation and other land use objectives;
3. Two criteria to decide the **best mitigation pathway**;
4. The best pathway for climate change mitigation.

The aggregated responses to each question are outlined below:

Synergies

The delegates individually identified a number of synergies that would likely result from using land in a more productive way that incorporates mitigation (and in some cases adaptation) measures:

- The **restoration of natural habitat** was highlighted as a key synergy by the majority of delegates for enhancing natural carbon sinks, restoring peatlands, increasing biodiversity, improving water quality, whilst also providing greenspace.
- **Afforestation** also came out as a key synergy for providing carbon sequestration as well as a range of ecosystem services including tourism and recreation, flood prevention and bioenergy in productive woodlands.

Other important synergies highlighted by the delegates include: c**hanging diets** which result in lower meat consumption, reducing food waste and improved animal welfare; **greater economic and environmental resilience** of farming through multi-functional land use and diversification; **intensification of agricultural production** which meets food demand with proportionally lower GHG emissions; and mitigation and adaptation measures for **improved soil management** which increase soil function, reduce erosion and improve flood resilience.

Trade-offs

A number of trade-offs were identified by the delegates which resulted from using land for mitigation measures instead of conventional agriculture:

- A high proportion of delegates identified a **reduction in agricultural land for food production** and reduced **food security** as a direct trade-off where land is used for afforestation, bioenergy crops, recreation, ecosystem conservation and urban expansion.
- A number of delegates identified reducing livestock production as a means to quickly reduce agricultural emissions and in particular methane, although it was noted that this would create a trade-off between **reduced methane emissions for increased nitrous oxide**

emissions, if for example livestock systems are replaced with e.g. arable systems to ensure food security.

- In addition, a small number of delegates noted **landscape change** as a trade-off for land sparing and changed land use.

Other trade-offs discussed included: i**ncreased costs for farming and consumers** associated with low-carbon farming and changed agricultural management practices; **a loss of conventional wildlife friendly farming** where there was afforestation; and **greater conflict** over farming, **reduced timber production** and changing **research priorities** (e.g. GM) as a result of changes in the LULUCF sectors.

Criteria to decide 'best' mitigation pathways

A wide range of criteria to decide the best mitigation pathway were identified by the delegates. The following criteria are shown in order of the most mentioned first:

- **Meeting multiple objectives** and demonstrating multi-functional land use which enables gradual change on the land available.
- Mitigation potential through **carbon efficiency per unit output**, which is synergetic with global emission reductions.
- Mitigation potential alongside the **ability to enhance biodiversity**, increase ecosystem services and meet environmental indicator targets.
- Ensuring **best fit with public values**, culture and current trends which ensure public acceptance and engagement.
- The **economic cost**, impact on trade and cost-benefit of land used for mitigation purposes compared with current land use.

Other criterion identified by delegates include **resilience to climate change**; **maximising food production** and maintaining a reasonable degree of home grown food; ensuring the UK efforts to reduce emissions **does not displace emissions overseas**, either through increased land use or increased GHG emissions intensity; **negative impacts are minimised**; and the ability of a pathway to increase soil organic matter, **reduce erosion** and **prevent flood risk**.

Best pathway

The delegates identified a wide range of pathways to enhance climate mitigation with varying levels of attributes and constraints. These are discussed in section 6.4.

6.4 Factors to consider in specifying pathways

Following the 'Post-It note' exercise, delegates discussed "*what were the possible pathways to reaching net zero emissions from UK agriculture/LULUCF*" in their three groups. These discussions elaborated on the individual perspectives previously recorded, identifying areas of agreement, as well as areas of difference, indicating areas which might need to be addressed when approaching the topic for developing a useful model.

Five key pathways were identified by the groups, which also emerged as the key pathways in the Post-It note assessment, indicating consistency between individual views and group discussion. A number of key factors raised by the delegates which may help, or prevent a pathway from reaching net zero emissions from UK agriculture/LULUCF were also identified for the pathways. The five key pathways identified are as follows:

(i) Dietary change

There was a clear consensus among the participants at the workshop that reducing ruminant meat production in the UK would be the fastest way to meeting net zero emissions, with the majority of methane emissions coming from livestock. However, it is consumption that drives emissions and there is a risk that these are displaced abroad. As such, changing dietary patterns in the UK culture would therefore be fundamental to this pathway, with a change from ruminant meat products to pig or poultry meat or plant-based diets. Land sparing associated with reduced grazing was a key element of this pathway which would allow for increased habitat restoration and other uses.

Boundaries for food security should take account of the context a growing global population. Alongside this, it is important to consider the impacts of climate change on global food supply, as production in some regions may become less favourable, amplifying the risks of supply failing to meet demand with knock on effects for UK food security.

(ii) Multifunctional land use

Multifunctional land use was identified by most participants as a potential pathway to net zero emissions. This is based on the concept of land in productive agriculture (and other land uses) being managed to provide other functions simultaneously, such as biodiversity and other ecosystem services.

The ability to use land for multiple purposes, at a range of spatial and temporal scales, was stated as a crucial element for efficient use of land in the future in order to balance the needs and demands of the other sectors (e.g. power, transport etc.). However, this would require site-specific land management based on a sound understanding of how land use could change in a specific area, as larger-scale regional aggregation of land statistics which only provide general indications of dominant land use.

It was noted that in order to plan long-term food security and land use, fishing, freshwater and marine resources need to be incorporated into any pathway to maintain sustainability of all food production.

(iii) Increased carbon storage

Afforestation, increased agroforestry and energy crops were noted by delegates as demonstrating a route to create carbon sinks, increase biodiversity and provide clean energy through the production of perennial (biomass/bioenergy) crops. Increasing soil organic carbon was also seen as an important strategy.

While woodland was seen as an important carbon sink, there is a substantial time lag between planting and peak carbon sequestration. Using land for both agriculture and forestry (i.e. on field boundaries, margins, corners etc.) was suggested as an effective way to both improve agricultural resilience, reduce net emissions and improve soil restoration. Delegates felt that agroforestry would be an easier and more efficient use of land than simply converting agricultural land to woodland (afforestation).

It was suggested that it is currently difficult to measure trends in soil carbon although the latest evidence indicates that changes in land management practices on cropland has little impact on carbon content. There is potential in the long-term to create a carbon sink from restoring peatlands and while there could be a temporary short term spike of methane emissions, this does not outweigh the long term benefits. Some delegates noted the opportunity for immediate benefits from the restoration of degraded peatland habitats and deep peat soils, in both the uplands and lowlands. This would reduce current and on-going CO_2 emissions from the loss of peat carbon, as well as potentially create new carbon sinks in the future.

The delegates noted that flood resilience is very important and must be considered in future land use, particularly with regard to trade-offs and synergies between urban land use and farming, carbon storage and tourism, etc.

(iv) Enhanced technological efficiency

Enhanced efficiency for crop and livestock production through adoption of technology was suggested as a potential pathway to zero net emissions from agriculture. The main focus was felt to be in promoting the sustainable intensification of agriculture, leading to a reduction in the land required for production and potentially proportionally reducing emissions. Research and development was felt to be a key aspect in this approach, alongside land management and agri-tech interventions to reduce emissions intensity. Delegates suggested that technological improvements can greatly increase farm productivity, however, this may not lead to reduced emissions without a supporting policy as farmers will simply increase production rather than use spare land for mitigation priorities. Improved measurements and monitoring of methane and nitrous oxide would be required to better understand agricultural emissions to allow the development of efficient agriculture. The roll-out of the new 'smart' agriculture inventory, which will use country-specific emissions factors will go some way to reducing the level of uncertainty in this area and help identify the most efficient technologies.

Knowledge sharing and best practice are key to influencing agricultural activities at a farm level, e.g. sustainable intensification of farming. The role of R&D will be fundamental for driving this in the long-term. New products, ideas and services e.g. genetic modification (GM), artificial meat or artificial milk could affect the demand from agricultural land.

(v) Alternative production systems (closed loop and off-farming)

Closed loop production systems, where actions are taken to avoid, reduce, reuse or recycle waste could be adopted within farming systems to minimise external inputs and contribute to meeting zero net emissions. It was suggested that this will be crucial for moderating land use in the future, and would involve replacing produce or systems which have a high waste footprint with other produce that can provide a more efficient use of resources with reduced GHG emissions.

A more radical approach to food production, 'off farming' (i.e. industrial indoor production of algae, vegetable and fish protein, etc.) was also identified as a means to release land pressures via high efficiency production (with abatement systems).

General factors to consider across all pathways

Some factors appeared to be common across all of the pathways identified as part of the discussions.

- <u>Global context</u>: It was felt that a successful pathway would need to create sustainable production which provides food security in the long term. This would require the management of boundaries in any particular pathway to determine whether food should be grown outside of the UK and the carbon implications of importing it, which may have ramifications for global emissions. The overall feeling was that UK actions should not adversely affect agricultural production overseas and some emphasis was put on a dual approach to assess and incorporate both local and international implications for future land use to meet the needs of the UK, as availability of certain produce may change due to climate, social and political changes in other nations.

- Safeguarding animal health and welfare was felt to be important in public perceptions of meat production and any changes to livestock systems to reduce climate impacts should accommodate this.
- Allowing for extreme weather events was deemed an important constraint to any pathway, given that such events can damage or reduce efficiency of crop (and livestock) production. As extreme weather events are projected to increase under climate change, there is need to improve understanding about their impacts on particular farming systems and for determining climate adaptation measures.
- It was recognised that there is a need to define clear land use metrics and indicators which can be used to measure changes in land use, both now and in the future. This includes the value of land (economic, social, environmental or other) and further work is needed in this area. The need for multi-objective assessment was clearly recognised and it was felt that determining a pathway to deliver net zero emissions needs to balance what a perfect future might look like in terms of land use, and plausible reality of what could and is achievable, based on the current status of land and projected timescales.
- The importance of farmer behaviour in delivering pathway actions and the assumption that it can be influenced and/or managed. In practice, farmer responses may not always be rational and policy initiatives need to allow for both “profit seekers” and “environmental advocates”.
- The delegates noted that land sparing through more productive agriculture (higher yields with less land) can release land for other mitigation and adaptation/resilience measures. However, without a policy drive, it is more likely that spare land would simply be used to grow more crop, therefore creating higher emissions and reducing resilience. It was recognised that UK and EU policy plays a crucial role in land use and practices. For climate-focused pathways to be successful, the Common Agricultural Policy (CAP) and wider Research and Development (R&D) are key to encouraging change in current agricultural practices.

6.5 Considerations for modelling land use in the context of net zero emissions

The second breakout session aimed to understand the key requirements for modelling each of 3 selected pathway approaches, namely i) technological efficiency of agriculture; ii) multi-functional land use; and iii) maximising carbon sinks. Delegates were asked to consider five key questions within their groups:

a) What are the most appropriate spatial and time scales?
b) What are the most important factors to be included in determining land allocation? (Global economy, farmer behaviour, policy, crop yields)
c) What management practices that don’t affect land use should be included in the model? (E.g. adding covers to slurry storage tanks and reservoirs)

d) What are the most important impacts to include in the model?
e) What interactions/feedbacks from impacts to drivers & land use should be included?

(i) Technological efficiency of agriculture

The concept for this pathway is that improved technological efficiency will lead to reduced emissions from agricultural production and will reduce land use.

The group discussed the scale at which the modelling should take place and suggested that for precision farming a 10m resolution is required as heterogeneity is an important aspect in ensuring that optimal decisions are taken. There is a need to ensure that the right things are grown in the right place and both water catchment and soil properties are taken into account when making decision about land use. However, a broad brush national picture will also be required.

There are a number of constraints that would need to be accounted for when considering technological efficiencies. A cost-benefit approach will be needed to determine whether a particular technological improvement will be taken up and implemented, particularly if the changes are not economically efficient. Policy scenarios may be required to incentivise the uptake of economically disadvantageous technologies which provide environmental benefits. There was a question as to how fit for purpose existing models are as they operate at scales of 2km, and so can provide only a broad overview of the landscape. The global economy was seen as a major constraint.

It was felt that a number of management practices that do not directly affect land use would also need to be considered, including managing animal health through breeding and genetics in relation to stocking densities and yields. There was a need to consider issues around waste management as this would potentially have impacts on the demand for feed and energy and indirectly influence land use via demand for these commodities. The increasing move to on-farm energy generation could lead to more efficient use of energy and also changes in land use to provide feedstocks for on-farm energy generation plants.

The group discussed key impacts of improved production efficiency that need to be measured:

- **Soil erosion** was felt to be a significant impact that would need to be considered, particularly as it can have knock-on impacts for water quality and soil carbon.
- **Pesticide usage** was also considered to be an impact that would need to be measured for this pathway.
- The effect on **food commodity price** would need to be considered as there was the potential for more efficient production to lead to greater demand through reduced prices and this would then impact on land use and the ability to achieve zero net carbon emissions.
- **Water quality** was felt to be a significant impact that would need to be measured, particularly in relation to run-off from agricultural land uses. It is important to determine whether improved efficiency led to improved use of nutrients and reduced diffuse pollution impacts.
- The impact on **biodiversity** would also need to be considered to ensure that improved efficiency did not negatively affect biodiversity and landscape connectivity.

Finally the group considered whether there were any significant interactions and feedbacks that would need to be considered. The balance between imports and exports and the potential impacts of improved efficiency on crop prices were considered to be important feedbacks that would need to be included within any model of this pathway. In addition, concern was raised over the potential for double counting to occur.

ii) Multi-functional land use

Multi-functional land is based on land being used for more than one purpose, either at a given time, or within a defined time period, such as a crop rotation. The group agreed that this concept was defined as the use of a landscape to deliver multiple objectives and a range of outputs, e.g. food production, non-food services and ecosystem services. Some examples include:

- Sheep grazing on the same field as solar panels or wind turbines.
- Switching between food crops and energy crops in a crop rotation.
- Agroforestry where both agricultural activities, forestry (and biodiversity) are combined.
- Afforestation which incorporates tourism or other societal benefits.

There was a wide range of views with regards to the most appropriate spatial and temporal scales of analysis, which varied depending on individual perspectives of multi-functional land use. A model developed to consider the multi-functional land use pathway would need to consider both short (annual) and long (decadal) changes in temporal patterns of land use. A multi-scale analysis would be required for processes occurring across different spatial scales. The group suggested fine-scale, landscape-scale and coarse-scale analysis would be crucial in any model.

A number of important factors and constraints were recognised in the group which would add complexity and uncertainty to any model, with one delegate suggesting there are just too many variables to make any model useful. In general, a good understanding of and the incorporation of key drivers affecting model outputs would provide indicative scenarios. Farmer behaviour was the core suggestion by the group as the most important factor to be included in determining land allocation. This would enable a simpler model of defining land use change with greater clarity, given that behaviour was seen as crucial in determining which land use options are selected. However, it was noted that this would also need to manage constraints, such as the assumption that farmers make rational decisions, the act of random behaviours, behavioural constraints and responses to local market conditions.

A number of land management practices was highlighted by the group, mainly in relation to mitigation and adaptation synergies. It was suggested that mitigation and adaptation could run in parallel, i.e. through organic or extensive farming systems. However, it can be difficult to capture these multi-functional attributes in a model, since some systems (e.g. organic farming) do not necessarily set specific objectives rather inherently deliver a range of functions favourable to mitigating or adapting to climate change.

The breakout group concluded that current allocation models were unlikely to be sufficient for modelling this pathway and the CCC should perhaps look at other countries' farming systems to gather insight where appropriate. In the absence of suitable examples, one method for assessing multi-functional land use would be to establish what can be practically achieved, and then work backwards from there to understand the actions needed to achieve the outcome.

(iii) Maximising carbon sinks

The aim of this pathway is to determine the largest carbon sink that could be achieved when accounting for other constraints on land use, with particular emphasis on achieving this in a way that provided resilience to climate change and the most value to other ecosystem services. The group agreed that there were a number of constraints that would need to be considered as part of this pathway, which included:

- Food production (the % of UK demand that would need to be satisfied by UK production)

- Bioenergy production (the % of UK bioenergy demand that would need to be satisfied by UK production)
- No export of emissions outside of the UK
- No net loss of local biodiversity

The group identified afforestation and the use of perennial crops as the major methods by which carbon storage could be increased. The group felt that this pathway would need to be modelled using an annual time step and that the timescale over which the pathway should be assessed would need to be at least 50 years. There is a need to consider both above-ground and soil carbon, accounting for both slow turnover and fast turnover processes that affect storage of carbon.

Most of the discussion focused on the important impacts for inclusion in the modelling. As part of the discussion, it was suggested that the majority of afforestation was likely to occur in areas of low agricultural productivity, which would potentially have significant impacts on upland systems. It was suggested that the importance of cultural and social aspects would need to be given a high level of importance in assessment of this pathway as work in Scotland has shown that afforestation in hill farming areas can potentially fragment local communities, with significant negative impacts on the cultural and social aspects of these communities.

In addition to assessing the social impacts of approaches to increasing carbon sinks, it was also felt that the impacts on biodiversity would need to be considered as increasing woodland cover, whilst likely to benefit woodland biodiversity, might adversely impact on the biodiversity of, for example, arable species. However, there was potential to increase the connectivity of the landscape through appropriately placed woodland.

Changes in flood risk due to afforestation of upland areas was also raised as a key impact to be considered when assessing this pathway.

The latter part of the discussion focussed on the factors that could be used to influence land use in order to achieve increased carbon storage. The group suggested that carbon incentivisation could be a useful approach. Other potential factors that would influence the success of this pathway would be changes in input and output prices, such as fertilisers, labour, machinery and crop prices. Finally there was a suggestion that technology change would also need to be considered, with the use of closed loop systems allow a move to the regeneration of soil carbon through appropriate management of manure applications and crop residues.

6.6 Summary

The core question asked of the stakeholder group was "*what future uses of UK land could help reach net zero emissions in the agriculture and LULUCF sectors post 2050, while ensuring resilience to the impacts of climate change*?" The response highlighted a general consensus on a number of pathways, namely, multifunctional land use (integrated land management), improved technological efficiency and increasing carbon sinks (through afforestation). However, it was clear that these pathways should not be considered in isolation and that any assessment should consider the degree to which the pathways contribute towards other objectives (environmental, economic, social and political) in order to determine synergies and trade-offs. A common basis for defining impacts in terms of ecosystem services would seem to be essential.

The complexity of determining the impacts of land use and land use change and the feedbacks and interactions with national and global drivers was identified as a key issue. This highlights the importance of having clear boundaries for defining what is counted, in what sector(s) and on what spatial (and temporal) scale to provide a clear indication of the potential impacts at a global level.

There is a need to be clear about whether the aim is to determine what can be achieved under a set of given (current and potential future) constraints, or whether we are trying to identify what the future could be with appropriate policy incentives and regulation.

The discussions regarding the pathways and modelling identified a number of uncertainties, such as future climate and extreme weather, changing demand for food and energy, and global trade that need to be addressed when considering the pathways to net zero emissions. It was questioned whether existing models and approaches could cope with the high degree of complexity, interactions and feedback to provide meaningful outputs. Despite this, it was felt that models that capture key drivers and behaviours with appropriate metrics could provide indicative scenarios that would help in determining whether the target of net zero emissions post 2050 could be achieved.

The workshop has highlighted the complexity involved in addressing the question of how to achieve net zero emissions post 2050 from the agriculture and LULUCF sectors. There is some question as to how useful current models can be in addressing this issue, although the potential for using simplified models with defined boundaries to address a number of “what if?” scenarios has been suggested as a means of identifying pathways that can work under a range of possible futures.

Appendix 1: Review of literature on drivers for land use change

A limited number of key reports were identified in the original project methodology document, including Cambridge Institute for Sustainability Leadership (CISL) (2014); The Best Use of UK Agricultural Land, HM Government (2012); The UK Climate Change Risk Assessment Evidence Report (CCRA); UK National Ecosystem Assessment (NEA) (2011) and CE Delft (2008). Agricultural land availability and demand in 2020. A global analysis of drivers and demand for feedstock, and agricultural land availability.

Identifying Drivers

Land Use Futures identifies six major drivers as: demographics, economic growth, climate change, new technology, societal preferences, and policy/regulation. It then considers how these relate to nine specific demands created by the six major drivers that drive certain land uses (water resources, conservation, agriculture, woodland, flood risk management, energy, residential/commercial, transport infrastructure, and recreation). The authors acknowledge that the major drivers and the sector specific demands are interlinked in a complex web of synergistic and antagonistic effects that are difficult to model. Instead they used an expert workshop approach to help develop three possible future scenarios "Leading the Way", "Valued Service", and "Competition Rules" which reflect different economic and demographic outlooks, different attitudes to environmental change, and different levels of resistance to change. The scenarios can then be translated into expected land use demand by sector.

CISL looks not just at demand pressures, but also what factors influence the extent to which land can become available to alleviate these pressures (which they call "supply"). Demand pressures are: residential/commercial/infrastructure, bioenergy, food security, wildlife/habitat protection, woodland cover, water management infrastructure. Supply alleviation drivers include, sustainable intensification in arable and livestock systems, food waste reduction, and changes in eating habits. CISL also builds scenarios based on low and high levels of demand pressure and supply alleviation. These are not used to explicitly predict land use change, but are used to identify potential shortfall of land in likely and worst case scenarios.

The CCRA approach only looks at climate impacts on agricultural land, forests and natural habitats. Impacts in particular are identified in terms of productivity, soil moisture deficit, coastal erosion, flooding, invasive species, new crops, change of timing of seasonal events. It is useful for identifying direct effects of climate on habitats but only some can be considered actual changes in land use (e.g. coastal erosion, flooding).

The NEA approach looks at drivers of change in ecosystems and the consequences for the ecosystem services which these areas provide. Ecosystems are represented as UK broad habitats (enclosed farmland, semi-natural grassland, mountain/moor/heath, woodland, freshwaters, coastal margins, marine, and urban). The framework unlike *Land use futures* or CISL, differentiates between direct and indirect drivers of change. The direct drivers include, land use change[11], pollution/enrichment, resource exploitation, climate, and invasive species. These in themselves are influenced by indirect

[11] The assessment is nominally of land cover (the biophysical composition) rather than land use (how people actually use it). However, these concepts are very closely related, and for many agricultural and forest land covers are virtually indistinguishable. Indeed, because the NEA also looks at non-market ecosystem services, even semi-natural habitats can be thought of having a "land use", albeit not one always acknowledged in an economic relationship

drivers which include, demographics, economics, socio-politics, cultural/behavioural, and scientific/technological.

In order to demonstrate these relationships, consider the example of house building. This is a direct driver of land use / land cover because it is the actual process which causes the change from, say, enclosed farmland to urban. However, there are many indirect drivers which influence how many and where additional houses are built, such as demographics (population growth), economics (affordability), and planning regulation/legislation (Green Belt, Natura 2000, zoning of brownfield land). Climate change is also an indirect factor here, pushing development away from coasts and floodplains.

It is relatively straightforward to isolate each indirect driver and understand how it influences the direct driver. However, as with *Land use futures*, the authors acknowledge the complexity of understanding how these factors interrelate especially over space and time. Rather than trying to build an unwieldy model where each direct and indirect driver can be independently adjusted, the UK NEA also uses scenarios (six in total) to predict future land cover. Again, these are derived from postulating different socio-political, cultural and economic trends and represent a range of visions, some of which are more extreme than others.

CE Delft is a global study of drivers of agricultural land use. The study identifies the main drivers for land use as, food and feed, wood, bioenergy/biofuel and other products. Within food/feed they identify biggest driver as food intake / diet choice but other factors such as markets, policy, food security, sustainability, technology also mentioned as drivers.

Each report brings something different to consider. *Land use futures* identifies the high level drivers but does not discuss how they interact and which ones are direct or indirect. CISL looks at more direct drivers and differentiates factors which affect land availability (supply) as well as those which simply look at demand, but there is no explicit mapping of higher level (indirect) factors that influence these. The CCRA approach gives information on climate impacts but only looks at drivers of habitat quality and not necessarily land use. The UK NEA approach makes the direct/indirect distinction, and goes beyond drivers of land use to look directly at land cover (those these are strongly related. CE Delft approach is highly concise but only focuses on productive land and uses which are related to production.

Importance of Drivers

Land use futures does not explicitly score each driver in terms of its importance to each land use. Instead, it works through each of the nine land use areas and provides a mixture of qualitative and quantitative information about the past, current and future effect that various factors are likely to have on that land use. It is not clear from the report exactly how this information was translated, via the workshop, into the projections for land use developed in each of the three scenarios.

Each individual broad habitat chapter of the UK NEA provides qualitative and quantitative information on the main drivers affecting that habitat, which in many cases means factors influencing land use. The relevance (yes/no), trend (increasing/decreasing), and evidence (much/limited) base for each driver is scored, though only at the broad habitat level. A summary infographic for all eight broad habitats is presented which shows importance and trend of the five direct driver groups identified in Chapter 3. A similar infographic also shows the relationship between the direct drivers and ecosystem service provision.

The CISL report uses a variety of references to estimate additional demand and supply of land from each driver. These create a low and high change in land use demand for each theme for 2030 against a reference year of 2005. Many of these are themselves built on scenarios developed in other reports or papers (e.g. DECC 2050 pathways, UK NEA scenarios etc.). This provides implicit information about the absolute and relative importance of individual drivers, but it does not indicate how they might interact.

CE Delft provides a global indication of likely land area requirement for each productive land use for 2020, derived from a brief literature review. The 2020 numbers are largely interpolated as many of the underlying papers actually model to 2050 or other years, but these numbers are also shown. Again, these can be used as an indicator of absolute and relative importance, but information on interaction is absent. In addition, the drivers reflect global aggregate conditions which may differ from UK specific drivers, so should be used with some caution.

Structural breaks, disaggregation, and public-private influence

All the reports make some reference to structural breaks such as the mechanisation of farming, the introduction and reform of the CAP, and the response to climate change. However, none describe exactly how these should be considered in future land use models. Instead, the UK NEA, *Land Use Futures* and CISL get around this problem and the challenge of how different drivers interrelate by developing scenarios. These show a range of plausible future worlds including some more conventional and more extreme outcomes. The extreme outcomes help imagine the impact of big structural shifts, however unlikely they may seem given the current outlook.

The general approach to disaggregation of land use categories across the literature surveyed is to look at broad and competing uses such as: agriculture (food crops and livestock), energy crops, woodland, urbanisation, infrastructure, water management, etc. The UK NEA looks at habitats rather than land use explicitly. Some of the analysis does go beyond the broad habitat level and looks at drivers of use for certain crops or certain types of woodland, though much of this information is not represented in the summary infographics.

The literature does not provide information to model the relative influence of public and private bodies in determining land use.

Appendix 2: Land use metrics and data sources

Identification and classification of metrics

A framework for classifying land use metrics relevant to the work of the CCC was required to provide high-level linkage across all components of the project. This framework has five levels;

1. Land Cover. The first level is a broad classification of land cover (as opposed to land use). This level describes the physical land type such as forest, arable, grassland or open water and all metrics are area-based. This level is the only one to include developed land and provide full land area coverage of the UK.

2. Land Use. The second level classifies the land use where these data are available and relevant to the work of the CCC. Land use describes how people are *using* the land and is more likely to change in comparison to land cover. The focus for this project is on agriculture, forestry and semi-natural land covers, but it is acknowledged that there are many other land uses in existence. All metrics are area-based and examples include type of crop, type of farming, biodiversity designated areas.

3. Land Management. The third level describes the management practices being applied to level one land covers, further subdivided into management practices on agricultural land and management practices on semi-natural land covers. Some of these metrics are area-based but some are quantified on a per-unit area basis. The latter are usually specified for a particular farm type and region, or a particular habitat type and can therefore be used in combination with level one or two metrics to produce area-based indicators with full UK coverage (if the data allows). These metrics mostly provide information for the climate change mitigation indicators, since different management practices have different implications for GHG emissions.

4. Land Productivity. The fourth level includes metrics on land productivity and ecosystem services. These metrics can relate to a particular land-use (e.g. crop yield) or be more general (e.g. carbon storage in soil). They can be used to provide data for indicators to monitor the productivity of the land in economic terms. These metrics mostly provide information for the climate change adaptation indicators, which include indicators of productivity.

5. Environmental Quality. The fifth level includes metrics that provide data for indicators of the environmental status of land. These are further subdivided into species-based metrics and other (habitat/ soil/ water) measures of quality. Some relate to specific habitats or features (e.g. condition of designated sites) and others are representative of the quality of wider landscapes or catchments (e.g. butterfly index; water quality status). These metrics mostly provide information for the climate change adaptation indicators and can be used to track trends in ecological condition of habitats as well as quality of soil and water, and flood and erosion risk.

The metrics were chosen based on the data requirements for the climate change mitigation and adaptation indicators (Task 2) and the biodiversity indicators (Task 3). Each indicator was considered in turn and the most appropriate metrics to quantify it identified through discussion by key members of the project team, regardless of whether or not there was a known data source. This was an iterative process, completed over the course of the delivery of all three tasks. For example, if an additional data requirement was identified for a particular indicator that had not been included in the original list of metrics, this was added as an additional metric.

Identification of data sets

The key data sets that quantify these metrics were identified through a combination of existing knowledge and internet searches on relevant keywords. There are a number of known internet dataset metadata and download repositories that the team were aware of and used as a starting point. These included:

- www.data.gov.uk;
- www.magic.gov.uk;
- www.geostore.com/environment-agency;
- www.landis.org.uk;
- esdac.jrc.ec.europa.eu;
- www.gov.uk/government/collections/structure-of-the-agricultural-industry;
- www.nbn.org.uk;
- lle.wales.gov.uk/home?lang=en;
- gateway.snh.gov.uk/natural-spaces/;
- www.doeni.gov.uk/articles/download-digital-datasets;
- www.gis.naturalengland.org.uk/pubs/gis/gis_register.asp;
- www.countrysidesurvey.org.uk/

Each country in the UK was given equal consideration when identifying datasets, and datasets that covered the whole of the UK were sourced where possible as these are more likely to have spatial consistency across the four countries. Most of the identified datasets had a spatial component or could be integrated with other datasets to give them a spatial component.

Data sets were categorised by functional type. These types were;

- Land Cover Maps. Data sets of this type mostly provide information for the *level one metrics*. They attempt to provide a continuous spatial coverage of land cover across the whole of the mapping extent and are derived from classification of remote sensing data, trained and validated with ground-truthed data. Typically these types of data sets are updated on a less regular basis than some other types, due to the large amount of effort required in producing the data set and the fact that land cover is not usually subject to rapid change.

- Habitat Maps. These types of data are mapped inventories/ surveys of particular habitats of priority for conservation or monitoring. They map land cover but do not provide full spatial coverage. Typically they are updated fairly infrequently due to the effort involved in producing them. They mostly provide information for the *level one metrics*.

- Land Use. These data sets are either national area-based statistics on agricultural land use; land use maps derived from remote sensing or from statistical disaggregation of official statistics or registers of agricultural land uses. Typically they are updated on an annual basis in order to track changes in agricultural land use. They mostly provide information for the *level two metrics*.

- Land-based Designations. These data sets describe areas officially designated for protection from degradation, from a water quality and/or biodiversity perspective. They are updated as needed, but not on a regular basis. They also provide information for the *level two metrics*.

- Land Management. Data sets of this type provide information on the management practices applied to agricultural land and some other habitats. The agricultural management data mostly comprise survey data that is stratified in such a way that it can be scaled up to national level. These data sets are typically updated on a regular basis, some annually, in order to track trends in management practices. They provide data for the *level three metrics*.

- Environmental Monitoring.
- Productivity. These are data sets that provide information on financially-related production measures (e.g. yields) or the capability of the land for production of high yields. The yield data are typically updated annually. They provide data for the *level four metrics* and the *level five metrics*.
- Water Resources. Data sets of this type include all data sets relating to water resources including flooding, water availability and water quality. They provide data to measure certain ecosystem services for *level four metrics* (water availability; flood assets) and also measures of water quality/ flood risk for *level five metrics*.
- Soil Resources. Data sets of this type include all data sets relating to soil resources. They provide data to measure certain ecosystem services for *level four metrics* (carbon storage in soil and peat) and also measures of soil quality for *level five metrics*.
- Environment and Species Monitoring. Data sets of this type include long-term species monitoring data, monitoring of invasive species, pests and diseases and monitoring of habitat/ resource condition. Typically these data sets arise from national long-running monitoring projects, some encompassing a wide range of environmental metrics. They mostly contribute to *level five metrics* but some contribute to a number of metrics across all levels.

Each dataset identified as potentially providing information for one or more of the identified metrics was reviewed in a systematic way and the results of this review collated into a spreadsheet. The review covered the following aspects;

- Type of dataset (e.g. land cover maps; surveys of agricultural practice)
- Owner of the dataset/ dataset provider
- Derivation of data (e.g. derived from remote sensing; survey)
- Description of the dataset
- Metrics (identified for this project) that can be quantified from the data
- Coverage (e.g. Europe; United Kingdom). The scope of this project is UK and many data sets are country-specific.
- Spatial consistency – i.e. is the methodology for data collection and/or the originating data sets consistent across the territory covered? For country-specific data sets it is likely that there will be inconsistencies in methodologies and therefore data between different UK countries for the same metric.
- Time period over which data has been collected – as well as quantifying the areas of land under different land uses, information on rate and direction of change is important to monitor the impacts of climate change and link land use change to changes in key drivers.
- Frequency of update (e.g. annual; as needed; never)
- Best spatial resolution – i.e. the minimum size of land parcel mapped or the maximum scale of mapping used. The ideal level of spatial resolution varies depending on the metric and how it is to be used.
- Purpose of creation – it is important to know the purpose of creation so a judgement can be made as to its accuracy and whether it is fit for the purpose of land use modelling.

- Usage limitations – limitations identified from the dataset report or metadata (e.g. recommended for national to regional use only).
- Accessibility – in terms of licencing requirements and fees as well as stipulations about how it can be used/ disseminated.
- Sample size (if derived from survey data) to give an indication of confidence in the scaled-up results.
- Peer reviewed/ validated? Some data sets' reports and metadata provide information on accuracy and validation procedures. Methodologies published in peer reviewed journals are likely to be more robust.
- Reference/ URL – web link to data set description/ download site or a report/ paper reference.

Due to the large number of potentially useful data sets and the time and budget limitations for this task, the review is not comprehensive for every data set and is not exhaustive in terms of the data sets identified. The information available on each data set varied widely and there remain some gaps in the data review spreadsheet where evidence for certain aspects could not be found.

Following completion of the data set review, the findings with regards the metrics that each dataset/ group of datasets could provide was entered into a matrix of dataset vs. metric. Each cell was scored as;

0 - does not provide data for the metric;
1 – provides some data for the metric (e.g. partially addresses metric or provides data for part of the UK);
2 – provides all data for the metric in all UK countries

A synthesis of datasets was included in the matrix using the following scoring system;

UK coverage (0=no; 1=yes)
Quality (0=poor/ unknown; 1=average; 2=good)
Accessibility (0=not accessible/ unknown; 1=licence fee/ limitations to use; 2=open licence)
Number of metrics covered (sum of metrics scored as 1 or 2 for the dataset)

A synthesis of metrics was included in the matrix using the following scoring system;

Data completeness (0=no data; 1=some data; 2=complete data for UK)
Trend analysis (0=no time series; 1=limited time series; 2=complete time series)
Uncertainty (0=very uncertain; 1=some uncertainty; 2=little uncertainty)

Assessment of metrics

The identified metrics and the datasets that support them are shown in 'Task 1 matrix.xlsx'. The review of the datasets is provided in 'Task 1 dataset review.xlsx'. The metrics and the availability and quality of data sets to provide sufficient information for the metrics at UK scale are discussed by framework level below.

Level 1: Land Cover

Metrics of coverage of broad land cover categories in the UK include;

- Arable and horticulture area

- Woodland area (broadleaved/ coniferous)
- Improved grassland area
- Semi-natural grassland area
- Rough grassland area
- Areas of other broad habitats (by type)
- Area of priority habitats (by type)

These metrics are well represented by the identified data sets with little uncertainty, certainly at a more aggregate level. Time series data, with the exception of agricultural land covers, is limited as the sorts of data sets that provide the other land cover data are updated infrequently.

CEH land cover maps are derived from satellite data, ground-truthed with data collected from *Countryside Survey*. The broad land covers classes are broadleaved woodland; coniferous woodland; arable and horticulture; improved grassland; rough grassland; neutral grassland; calcareous grassland; acid grassland; fen, marsh and swamp; heather; heather grassland; bog; montane habitats; inland rock; salt water; freshwater; supra-littoral rock; supra-littoral sediment; littoral rock; littoral sediment; saltmarsh; urban; suburban. The advantage of these classes is that they are equivalent to the UK Biodiversity Action Plan Broad Habitat classification and can therefore be directly related to condition assessments of these habitats. These data sets have full UK coverage but the more detailed versions require licencing.

CORINE land cover is also derived from satellite data. It has European coverage and has the advantage of being freely available. Spatial resolution is poorer than *CEH land cover*. Mid-detail land cover classes are urban fabric; industrial, commercial and transport units; mine, dump and construction sites; artificial non-agricultural vegetated areas; arable land; permanent crops; pastures; heterogeneous agricultural areas; forests; shrub and/or herbaceous vegetation association; open spaces with little or no vegetation; inland wetlands; coastal wetlands.

The reliance of these land cover maps on interpretation of remote sensing data, albeit using ground-truthing, means there are discrepancies (sometimes large) between arable area calculations from these continuous land cover data sets and scaled-up surveys of agricultural land use. For example, the 2007 *June Survey of Agriculture and Horticulture in England and Wales* reports 4,385,076 ha of arable land and 5,572,081 ha of grassland (permanent and temporary). The *2007 Land Cover Map (LCM)* estimates there to be 5,509,800 ha of arable land and 4,410,600 ha of improved grassland in England & Wales. This may be partly due to temporary grass and uncropped land being included in the LCM 'Arable and Horticulture' class. In addition, the spectral variability of this class is greater than any of the other classes due to the wide range of crops and differences in growth stages between images.

Annual surveys of agriculture and horticulture have the advantage of providing an annual, statistically robust time-series for the UK, but only for agricultural land covers. These survey statistics have been used to produce seamless mapping at 1km scale (*ADAS Land Use database*) and 2km scale (*EDINA agcensus*). The EDINA version is more regularly updated and covers England, Wales and Scotland. These derived datasets attempt to overcome the discrepancies found in data derived from remote sensing through the use of land allocation algorithms that constrain the arable area to that reported in the relevant June census.

Habitat inventories do not provide seamless maps, but delineate areas of specific habitats, either priority habitats for conservation or woodland. The only habitat to be mapped in a consistent manner across the UK is ancient woodland. *Priority habitat inventories* are available for England, and to some extent for Scotland. *The National Forest Inventory* has GB coverage. These data sets are all readily accessible.

Level 2: Land Use

Metrics representing agricultural and semi-natural land use in the UK include;

- Crop area by type
- Temporary grassland area
- Permanent grassland area
- Area of each farm type
- Area of buffer strips (along watercourses/ other)
- Area of land under relevant agri-environment scheme options
- Area designated as NVZ
- Area of biodiversity designated sites

These metrics are well represented by the identified data sets at the UK scale with little uncertainty, with the exception of sub-field features such as buffer strips and other small areas taken out of production for environmental protection. Areas of agricultural crops have complete time-series data. Other metrics have limited time-series.

Annual surveys of agriculture and horticulture provide all of the necessary data for the UK for crop area by type, temporary and permanent grassland area, and area of each farm type. They are updated on an annual basis. Every ten years a census rather than a survey is completed. Statistics are readily available at local or unitary authority level, although figures for some crops will be suppressed at this scale to avoid disclosivity. The *ADAS land use database* and *EDINA agcensus* provide seamless mapping of crop types and grassland areas; the latter is updated regularly. Bioenergy crops can be identified by GIS data on *Energy Crops Scheme agreements* in England and to some extent via the *Land Parcel Identification System*. The latter has full UK coverage, but its quality is average and accessibility difficult.

Land Cover Plus: Crops is a new product allied to Land Cover Map, which uses satellite data to identify individual crops. The intention is to update this annually. It is superior to other datasets in that it provides parcel-level data, but does not include as many crops as the annual surveys.

Sub-field features such as buffer strips and other areas of land under relevant agri-environment scheme options are identified at parcel scale in GIS datasets of *Environmental Stewardship Scheme/ Woodland grant scheme agreements/options*. These are only available for England however, and do not identify the exact location of the feature. *Countryside Survey* is a fully stratified and randomised environmental UK-wide monitoring survey that provides some information on level 2 metrics including crop areas and buffer strips.

The national GIS datasets *of Sites of Special Scientific Interest (SSSIs)* provides the necessary data for the metric 'area of biodiversity designated sites'. All sites designated under European law (SPAs, SACs, Ramsars) are also SSSIs. These are readily accessible and are updated as needed.

Level 3: Land Management

Metrics representing how the agricultural, forested and semi-natural land is managed in the UK include;

- Area designated as NVZ
- Mineral fertiliser use

- Organic fertiliser use
- Area under organic farming
- Pesticide use
- Tillage practices
- Fertiliser/ manure management plan
- Temporary grassland sown with clover mix
- Area with winter cover crop
- Number and volume of farm reservoirs
- Stocking density
- Uptake of precision farming technologies
- Plant breeding: varieties
- Livestock breeding: quality
- Manure application technique
- Irrigated area
- Water abstraction volume for agricultural use
- Number of farms implementing water efficiency measures
- Area of functioning field drains
- Area of woodland affected by wildfires
- Area of woodland in active management
- Area of woodland certified as sustainably managed
- Area of moorland burnt by habitat type
- Area of habitat restored
- Frequency of moorland burning by habitat type

Only nine of these metrics have complete data for the UK. These are area under NVZ; area under organic farming; pesticide use; tillage practices; area with winter cover crop; stocking density; manure application technique; area of functioning field drains and area of woodland certified as sustainably managed. Most have some degree of time series data, with complete time series data available for fertiliser use; area under organic farming; pesticide use; fertiliser/ manure management planning; stocking density; plant breeding: varieties; abstraction volume; area of woodland affected by wildfires; area of woodland in active management; and area of woodland certified as sustainably managed. Most of these metrics have some degree of uncertainty due to the fact that they are derived from survey data. The area designated as NVZ; stocking density; plant breeding: varieties; area of woodland in active management and area of woodland certified as sustainable managed are all considered to have little uncertainty.

Survey data are key data sources for the majority of these metrics. The *Farm Practices Survey (FPS)* provides information for 14 metrics, all but one of which is level 3. There is an irregular time-series for metrics derived from this data source as the questions asked vary year on year. The FPS also only covers England. The *Survey of Agricultural Production Methods (SAPM)* was a one of survey that covers the whole of the UK, to satisfy EU reporting requirements. It provides information for 6 of the metrics and had to meet certain precision requirements. More specific surveys include the *British Survey of Fertiliser Practice (BSFP)*, the *Pesticide Usage Survey (PUS)* and the *Irrigation Survey*. The PUS is UK-wide and has a regular time-series of data. The BSFP does not cover Northern Ireland but also provides a regular time-series. Accessibility of data from surveys of agricultural practice are mostly good, and can be linked to spatial information on crop areas and farm types to provide area-based metrics.

Other data sets relating to agricultural land management are the *Seed certification data* for plant varieties, which covers England and Wales but has an unknown update frequency; the *Planting and Variety survey*, about which there is little information; the *annual surveys of agriculture and horticulture* for stocking densities and the mapping of *extent of drainage in agricultural soils*. The latter covers the whole UK but is derived from survey data of varying quality between countries.

The metrics on management practices on woodland and semi-natural land covers can be estimated from a variety of data sources. There is a data set on the *number and area of woodland fires*, but this only covers GB and is only available at a country level. There are a couple of identified scientific studies on the *extent of vegetation burning for game management*, one covering Great Britain, but accessibility to these data is uncertain and there is limited time series data. The *CEH Land Cover Maps* also claim to identify area of burnt heather. There is a good quality dataset on the area of certified woodland that covers the whole UK, but the data are only readily accessible at a country level. The area of habitat restored could be estimated from a number of data sets including *Environmental Stewardship Scheme agreements/ options* for Higher Level Stewardship restoration options; condition assessments of *SSSIs/ ASSIs*; and *Countryside Survey* data. The area of woodland in active management could also be estimated from a number of data sets including the *National Forest Inventory*; *Woodland Grant Scheme agreements/ options; Land Use/ Cover Area frame Statistical Survey (LUCAS)* and *Countryside Survey*.

Level 4: Land Productivity

Metrics representing the productivity of agricultural, forested and semi-natural land within the scope of this study include;

- Crop yield by type
- Grass yield by type
- Timber yield by type
- Production of meat/ milk/ eggs by species
- Water availability
- Carbon storage in woodlands
- Carbon storage in soil
- Carbon storage in peat
- Flood assets

Most of these metrics have complete data for the UK, with the exception of water availability; carbon storage in woodlands and flood assets. Five have a complete time series (crop yield; grass yield; timber yield; production of meat/ milk/ eggs; carbon storage in woodlands). The others have no time series data available. There is some level of uncertainty associated with the measurement of all of these metrics.

Key data sets are the *farm business/ accounts surveys* for the agricultural production metrics, for which there is one for each UK country, although the content of the surveys varies between countries and the spatial disaggregation is regional at best. At least two UK countries repeat this survey annually. *Forestry statistics on UK-grown timber provide* an annual time series of data for timber yield for the UK, but are only provided at the country level at present.

For ecosystem services, data for the water availability metric could be obtained from GIS data of *surface water networks* as well as catchment-scale classifications of *water resource availability*. The latter only covers England and Wales. Carbon storage in woodlands could be estimated from the *National Forest Inventory*. Carbon storage in soil and peat could be taken from the UK map of *topsoil* *carbon stock*, which is very relevant, peer-reviewed and available at 1km resolution. It does not, however, provide a time series. The *BioSoil project*, which was based on soil sampling on forested land and has coverage of Great Britain, could also provide a data source for soil carbon storage and has the potential to become a monitoring programme in the future. *Countryside survey* also provides measurements of organic matter content of soil. Locations of *flood defences* in England and Wales are available under licence and will gradually be added to.

Level 5: Environmental Quality

Metrics representing the quality of agricultural, forested and semi-natural land within the scope of this study include;

- Pollinator species number & distribution
- Incidence/ prevalence of pests and diseases
- Invasive species population/ distribution
- Farmland bird species/ distribution
- Farmland bat species/ distribution
- Farmland butterfly species/ distribution
- Woodland bird species/ distribution
- Woodland butterfly species/ distribution
- Breeding birds: grassland specialists species/ distribution
- Butterflies: grassland specialists species/ distribution
- Plant species richness
- Number of farmland bird/ butterfly food plant species
- Condition of designated sites
- Habitat connectivity/ fragmentation
- Crown condition of key tree species
- Structural condition of hedgerows
- Structural condition of walls
- Condition of non-statutory semi-natural grasslands
- Sediment supply
- Land capability for agriculture/ forestry
- Soil type
- Soil erosion index
- Soil organic matter content
- Soil P&K index
- Soil pH
- Soil biodiversity
- Flows
- N, P & Z pollutant loads in freshwater
- Water quality status
- Flood risk

Most of the species-related metrics have complete data for the UK, a complete time series and little uncertainty, particularly the bird and butterfly data that are collated from a long-standing network of sample squares throughout the UK and are regularly used as indicators of habitat quality. Pollinator species, bats, invasive species and pest and disease species distributions are less certain and do not have complete UK coverage or a complete time series. Data on plant species richness have UK coverage but limited time series and some uncertainty.

Metrics of condition of designated sites, water flows, N, P & Z pollutant loads in water and water quality status all have UK data with complete time series and little uncertainty. Soil metrics all have UK coverage and some have a complete time series, but all have some uncertainty due to the relative sparsity of sampling sites and the spatial variability of soil. Data for the flood risk metric are available for the UK, but with no time series and some uncertainty. Metrics on the condition of various habitats and features outside of the designated site network do not have complete data for the UK, have limited time series and some uncertainty. No data source was identified for sediment supply. Land classification datasets are only available for Great Britain and are somewhat dated, therefore their metrics are very uncertain.

Surveys of environmental quality such as *LUCAS* and *Countryside Survey* provide a detailed assessment of habitat extent and condition, and provide information on a time series (albeit with years between successive surveys) for 3 and 11 level 5 metrics respectively. They are fully stratified and randomised but as they are surveys they can only provide robust estimates at the level of stratification (e.g. landscape character areas). Countryside Survey has not been updated since 2007. Connectivity/ fragmentation of natural habitats can be inferred to some extent from habitat maps such as *Priority Habitat inventories* and the *National Forest Inventory*, and there are also some model outputs available specifically quantifying habitat connectivity for functional groups of species. Habitat connectivity was a UK biodiversity indicator until 2013, but it has not been updated since 2007 since it relied on data from Countryside Survey. In 2015, CEH, JNCC and Defra investigated the possibility of using the level of synchrony in the fluctuations of annual population counts of butterflies as a proxy of connectivity. The exploration used data for four species of butterfly associated with woodland, collected through the *UK Butterfly Monitoring Scheme* (UKBMS). Population synchrony has been shown to be an effective measure of functional connectivity. Other datasets that provide information for environmental quality metrics include *SSSI/ASSI* datasets, which have information on habitat quality and species diversity.

With regards water-based quality metrics, *flood risk maps* are mostly derived from modelling but are not known to be available for Northern Ireland. Accessibility to these maps is variable and they give an estimation of flood risk at one point in time. Datasets on *gauged flows* and *water quality monitoring* are available but not always for the whole UK. Accessibility varies, with lower quality datasets usually being more accessible. For soil related metrics, *national soil maps* and *national soils inventories/ monitoring* data are available for all UK countries but require licencing. The latter give a limited time series of data for monitoring trend in certain soil parameters at sampled locations. More frequent monitoring data for soils are available via the UK Environmental Change Network (ECN), but only for irregularly spaced individual sample sites across the UK. European soils data are available free of charge but are based on lower resolution mapping. A number of derived products have been released that seamlessly map particular attributes of soil such as carbon stock and erodibility. *LUCAS* and *Countryside Survey* environmental monitoring projects also collect some soil attribute data.

Appendix 3: Climate change mitigation and adaptation indicators

This section provides detailed analysis of the required metrics and how they could be combined for each climate change mitigation and adaptation indicator.

Climate change mitigation indicators

Land area for planting woodland

A combination of different land cover / use metrics would be needed to identify areas for tree planting. There are specific metrics that show the *woodland area* and *area of woodland in active management* that already exist. These would provide a baseline of what is already planted, but for new plantings other land uses would need to be considered for conversion, including *arable and horticulture area* and the different types of *grassland areas*. These would provide some information on where land could be accessed for planting, but would not refine *what* land could be used for planting. The 'what' could be supported by information from metrics such as *land capability for agriculture/forestry grade*, with assumptions made about what grades of land could be considered relevant to target for woodland planting, e.g. exclude grade 1 and 2 on the basis of its importance for food production. Additional refinement could be given by considering *soil type* and *erosion risk* metrics, with soil type guiding where land might be better suited to trees than crops and erosion risk maps identifying areas that might benefit from having increased tree plantings to lower the risk. There are other constraints put on tree planting where it may conflict with the biodiversity or landscape value of an area – these could in part be identified through the use of some of the land cover / use metrics such as *area of priority habitats* and *area of biodiversity designated sites*.

Farming practices – different crop species

This indicator could be directly measured using a single *crop area by type* metric.

Farming practices – different crop variety

There were no obvious metrics that allowed for the assessment of the crop variety indicator. Partial information might support this indicator for certain crop species, from metrics relating to *plant breeding: varieties* (e.g. rates of certified seed sold for broad acre crops such as cereals, oilseeds and pulses). *Soil type* information could be used to give some indication of which varieties would be best suited to a location, but additional metrics on *varietal requirements* would be required to link to soil type.

Nitrogen mitigation – reducing artificial nitrogen (N) fertiliser use

Reducing artificial nitrogen fertiliser use could be measured directly (e.g. rate of nitrogen per hectare) or indirectly through changes in practice that are likely to lead to reductions in artificial N fertiliser use such as improved nutrient planning. The *mineral N fertiliser use by crop* metric is highly relevant and could be used as a standalone metric to understand if fertiliser use in a specific crop is declining. To understand how this impacts at a national level this information would need to be combined with metrics on *crop area by type* or *improved grassland area* and *area of each farm type* at a regional scale.

Additional supporting information on *organic fertiliser use* could be applied to understand whether overall usage was reduced or just switched from artificial to organic sources of nitrogen. There are a number of other metrics that could also provide evidence to support this indicator such as;

- *Proportion of UAA under zero/ min-till/ conventional tillage practices* – this would need to be supported by a metric or assumptions on fertiliser usage under different tillage systems and areas of relevant land uses
- *Proportion of UAA having a fertiliser or manure management plan* – this metric could provide an indication of the proportion of crops expected to receive optimal fertilisation, but would not give a scale of change
- *area under organic farming* – organic farms do not use artificial nitrogen and therefore changes in the organic area could be used as a metric to indicate whether the area treated with artificial N was increasing or decreasing
- *area with winter cover crop* – cover crops are planted to minimise leaching and therefore maintain soil nitrogen between main crops. The use of a cover crop should therefore reduce the artificial N requirement of the following crop
- *uptake of precision farming technologies* –if precision farming technologies such as GPS steering, yield mapping and N-sensors are applied correctly, they should result in reductions in applied artificial N since the timing and location of applications will be better targeted
- *yield* and *soil organic matter content* could both provide some evidence to support this indicator, but alone would be insufficient.

Nitrogen mitigation – improved manure planning and application

Improved manure planning and application could be measured directly (e.g. *rate of nitrogen per hectare*) or indirectly through changes in practice. *Organic fertiliser use by crop* metric is highly relevant and could be used as a standalone metric to understand if manure use in a specific crop is changing. To understand how this impacts at a national level this information would need to be combined with metrics on *crop area by type* or *grassland area*. Metrics that actually provide detail on the practices such as having a *fertiliser / manure management plan*, *uptake of precision farming technologies* and *proportion of UAA applying manure in total and with immediate incorporation* will all provide evidence to support the improved manure planning and application indicator, but would need to be used in combination with organic fertiliser use per hectare and crop area metrics. The *soil organic matter content* and *soil P&K index* metrics could be used to indirectly demonstrate the effectiveness of manure applications in improving soil structure and fertility.

Farming practices - Loosening compacted soils / avoiding compaction and erosion

This indicator is relevant to *arable, grassland* and *forestry land uses* and therefore the land cover / use metrics for each of these will be relevant to help spatially locate where actions can occur. There are then a number of metrics that could be combined to give evidence of changing practices to address this indicator such as;

- *Proportion of UAA under zero/ min-till/ conventional cultivation* – as tillage type can be used to identify risk of compaction / erosion

- *Area of buffer strips* – buffer strips will not actually prevent soil erosion from occurring, but they can be used to help capture the eroded soil and prevent it from entering water courses through surface runoff. Would need to be combined with an *erosion risk* metric to identify if the strips are suitably located.

- *Area under winter cover crop* – winter cover crops can protect against soil erosion and therefore their use in high risk areas can reduce erosion risk. Certain cover crop species are also deep rooted, which can help aid improvements in soil structure[12].
- *Stocking density by livestock type* can be used as a metric to support this indicator, with higher stocking density associated with increased compaction, poaching and erosion risk[13].
- *Soil type, soil erosion risk* and *soil organic matter content* metrics can all be used in combination to provide evidence of areas at risk (with sandier soils more prone to erosion and clay soils at risk of compaction especially if the soil organic matter content is low)[14].
- *Flood risk* can also be used as a metric to provide evidence to support this metric, with compacted soils likely to increase the risk of flooding as water infiltration is reduced and therefore surface water flow increased.

Minimum or zero tillage / shallow ploughing

Tillage of soils is limited to the *arable area (including temporary grassland*) therefore land cover / use metrics for those land uses will provide spatial information on the areas that are likely to be cultivated. These metrics will need to be combined with a metric of *proportion of UAA under zero tillage / min tillage / conventional tillage*. The tillage metric could be used alone to support an indicator of proportion of land that is under each cultivation type, but the *crop area by type* and *area of each farm type* metrics will be required to help spatially map that data.

Winter cover crops / undersown spring cereals

A specific metric of *area with winter cover crops* is needed to measure this indicator directly. *Land area under relevant agri-environment schemes* will provide information on those cover crops or undersown cereals that are included in agri-environment schemes, but not all crops will be included in these schemes. *Soil type, soil erosion risk* and *soil organic matter content* metrics could be used to identify where the use of cover crops / undersown spring cereals could be beneficial, or whether they have had an impact, but would not tell you where they are. The *crop area by type* metric may provide some information about the use of cover crops or undersown spring cereals indirectly, e.g. through giving the area of spring cropping that can be used to interpret maximum areas that could be applicable for over winter cover crops or undersown.

Stocking densities

A direct metric of *stocking density* could provide evidence for a simple indicator looking at whether stocking density was increasing or decreasing, however in order to know where those changes were occurring this would need to be linked to land cover / use metrics for the grassland types. Additional supporting evidence could be provided by metrics including; *grass yield by type* (higher yielding grassland could be expected to sustain higher stocking densities than a low yielding grassland), *habitat condition and diversity* (higher stocking densities may impact on habitat condition and therefore this could be used as indirect evidence of changes in stocking density), *soil type and*

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[12] AHDB (2015) Opportunities for cover crops in conventional arable rotations. http://cereals.ahdb.org.uk/media/655816/is41-opportunities-for-cover-crops-in-conventional-arable-rotations.pdf (accessed February 2016)

[13] NWRM (2015) Reduced stocking densities http://nwrm.eu/sites/default/files/nwrm_ressources/a12_-_reduced_stocking_density.pdf (accessed February 2016)

[14] Defra (2013) Managing soil types https://www.gov.uk/guidance/managing-soil-types (accessed February 2016)

erosion risk (these metrics could provide evidence as to where increased stocking density are resulting in increased erosion risk or vice versa).

Organic farming

The most relevant metric for this indicator is a direct metric of the *area under organic farming*. This could be supplemented by metrics on *mineral fertiliser use* (which is not applied to organic farms and therefore any changes in area treated could provide indirect evidence of changes in organic area), *percentage of temporary grassland sown with clover mix* (organic agriculture uses nitrogen fixing plants to build fertility in grass leys, however this metric may not distinguish between leys that are organic and conventional) and the *area of land under relevant agri-environment scheme options* (there are a number of the agri-environment scheme options that are organic specific and therefore this could be used as evidence to support the indicator).

Use of nitrogen fixing plants in grass leys

A direct metric measuring the *area of nitrogen fixing plants in grass leys* would be the most relevant to this indicator, but the best available that could be identified from survey data was *percentage of temporary grassland sown with clover mix.* To apply this information spatially a land cover / use metric for the *area of temporary or permanent grassland* would be required in addition to the *area of each farm type*. Additional supporting evidence could be provided by the following metrics; *area having fertiliser manure* (this would be expected to decline where nitrogen fixing plants were included in the ley), *area under organic farming* (organic production typically uses nitrogen fixing crops as part of the fertility building process, this would not capture those areas of grassland that are not organic, but include nitrogen fixing plants), *area of land under relevant agri-environment scheme options* (there are some options that promote the use of nitrogen fixing plants in grass leys, and this data would capture those, but not all nitrogen fixing leys would be included in agri-environment schemes) and *grass yield by grass type* may be able to give some supporting evidence indirectly.

Upland and lowland peat – quality of peat / level of degradation

Land cover / use metrics such as *rough grassland area, area of priority habitats and area of biodiversity designated sites* could all be used to identify where peat lands are, especially when used in combination with *soil type* and *soil organic matter metrics*. Changes in soil organic matter or *carbon storage in peat* metrics could be used to help identify whether degradation or restoration was occurring. Additional evidence on the quality of the peat land would be provided by metrics on *indicator species population and distribution* (e.g. presence of certain species indicate levels of degradation/restoration), *area and frequency of moorland burning by habitat type* (where heather is present on peat burning can lead to degradation[15]), various *habitat condition* metrics*, area of habitat restored* and *area under relevant agri-environment scheme options*. In addition *water availability* could be used to provide evidence on condition of peat as higher water tables are associated with improved peat quality[16][17].

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[15] Brown, L.E., Holden, J. & Palmer, S.M., 2014. Effects of Moorland Burning on the Ecohydrology of River basins. Key findings from the EMBER project. University of Leeds – http://www.wateratleeds.org/fileadmin/documents/water_at_leeds/Ember_report.pdf (accessed February 2016)

[16] Allott T, Evans M, Lindsay J, Agnew C, Freer J, Jones A & Parnell M (2009) Water Tables in Peak District Blanket Peatlands. *Moors for the Future report number 17*.

Reduction in heather burning

A similar set of metrics could be used for heather burning as for quality of peat. The most relevant of these metrics would be the *area and frequency of moorland burning by habitat type* which could provide good evidence of changes in the area burnt, but would need to be linked to the land cover metric *areas of other broad habitats* for spatial mapping.

Agricultural land drainage

There are no directly relevant metrics available on agricultural land drainage, instead a combination of *land use / cover metrics (arable, grassland and crop area by type*) to give location of potential drainage with other metrics indicating levels of drainage would be required. These other metrics include *area of functioning field drains* (which would give area of drained land), *land capability for agriculture/ forestry grade* (would give an indirect indication as undrained land is likely to be of a lower grade than drained land) and *indicator species population and distribution* (as certain species will favour drained or undrained land). *Soil type* and *soil erosion risk* metrics will aid in identifying locations where land drainage is needed / used.

Land use change to lower input systems

There are multiple metrics that are needed to measure this indicator as there are multiple elements that go into making up a low input system. In order to map spatially, all the metrics on *land cover/use* are relevant, with the changes between different land cover / uses being relevant for identification of some of the lower input systems (e.g. increase in the area of spring crops is evidence of lower inputs on arable areas). *Area under organic farming* will give evidence of low input systems, but it will not capture all low input systems, as there will be some 'conventional' systems that are using lower inputs too. In addition metrics that provide evidence on *rate of mineral and organic fertiliser use, pesticide use, cultivation system (area under zero / min-till / conventional tillage), irrigated area* (reductions in irrigation indicate lower inputs) and *stocking density* will all provide evidence on whether there are reductions in inputs. Indirect evidence could also be provided by the following metrics;

- *area with winter cover crop* (these crops can reduce nitrogen leaching and therefore the requirement for mineral N in the future crop, however this metric does not capture whether or not the farmer actually reduces the following inputs),
- *uptake of precision farming technologies* (more accurate application should reduce input requirements),
- *yield* (lower input systems may impact on yield, but should be aiming to maintain yield with lower inputs)
- biodiversity metrics such as *habitat connectivity/ fragmentation, soil biodiversity, area of habitat restored* and *area under relevant agri-environment scheme options* could all provide indirect evidence to support an indicator of reduced inputs.

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http://www.moorsforthefuture.org.uk/sites/default/files/documents/MFF%20RR17%20Water%20Tables%20in%20Peal%20District%20blanket%20peatlands.pdf (accessed February 2016)

[17] Evans M, Allott T, Holden J, Flitcroft C and Bonn A (2005) Understanding gully blocking in deep peat. *Moors for the Future Report no 4*
http://www.moorsforthefuture.org.uk/sites/default/files/documents/MFF%20RR04%20%5BMain%5D%20Evans%20M%202005%20Understanding%20gully%20blocking%20in%20deep%20peat.pdf (Accessed February 2016)

Areas of novel crops

There are few metrics that can be used to provide evidence for an indicator of area of novel crops. Land cover / use metrics for *crop area by type* may help – but if the area of novel crops is very low this may not pick up the area of novel crops. *Land capability for agricultural grade* and *soil type* could be used to identify locations where the crop might be grown, but would not provide information on how much is grown where.

Need for dietary change

There are no direct metrics that provide evidence for dietary change. The *land cover /use metrics* could be used to provide some indirect evidence e.g. if meat consumption decreased you might expect a reduction in grassland area and an increase in arable area – but there could also be other drivers that would influence this change, e.g. increased efficiency of livestock production or market changes.

Emerging technologies

There are a range of emerging technologies that could be considered with regards to climate change mitigation. Examples include the precision application of inputs and improvements in crop and livestock genetics, therefore metrics that capture changes in these are relevant to this indicator. Indirect evidence could be accessed from metrics such as *mineral fertiliser use per ha by crop type* (with the assumption that precision nitrogen application could reduce total rates or improved varieties could reduce input requirements) and *crop yield by type* (with improved genetics assumed to help improve crop yield).

Increased soil carbon

Soil carbon levels are influenced by the type of vegetation present (e.g. annual crops vs perennial crops) and the management of those crops, therefore l*and cover / use metrics for all crop, grassland, woodland* and *habitat types* are relevant for this indicator in order to know what vegetation type is where and what changes are occurring. This data will need to be supported by evidence on how the soils are being managed so metrics such as *organic fertiliser use by crop* (use of organic fertiliser can increase soil carbon content) and *type of cultivation* (area under zero / min / conventional tillage – with more intensive cultivation associated with reductions in soil carbon content)[18].

Carbon storage above ground

All the *land cover /use metrics* for *arable, grassland and other habitats* would provide evidence to support the carbon storage above ground indicator, as they will give information on the type of vegetation that is present in the location. These will be the most relevant metrics along with *carbon storage in woodland*. However, additional evidence about the productivity of the area could be provided by metrics on production such as *crop yield by crop type, grass yield by type, timber yield by type* and *land capability for agriculture grade* – although where the crop is harvested this carbon is only very transiently stored. More robust evidence on the longer term carbon storage in vegetation would be supported by metrics on *indicator species population and distribution, habitat condition* metrics and *area of habitat restored* as these will provide greater detail on the type of species present, which can be linked to carbon storage potential.

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[18] Bhogal A, Chambers B, Whitmore A & Powlson D (2009) The effects of reduced tillage practices and organic material additions on the carbon content of arable soils. *Summary Report for Defra Project SP0561* http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=2&ProjectID=15162 (accessed February 2016)

Climate change adaptation indicators

Water demand by agriculture

Total water demand for – Irrigation

The most relevant metrics for water demand for irrigation is *abstraction volume* and *irrigated area*. These metrics could be supported with more specific detail on the *number and volume of on farm reservoirs* as this gives evidence of the amount of water that is being stored to be used for irrigation, however there are people who use irrigation from other sources, e.g. mains water, direct extraction from a water body, so this will not capture all water available for irrigation. The *flows metric* would provide evidence of whether there is sufficient water available in a river system for abstraction for irrigation. Combining this with a metric on *irrigated area* would enable a link to be made between water availability and demand for irrigation. Land cover/ use metrics *for crop area by type* and *arable area* would enable spatial mapping of that information.

Total water demand for – Livestock

As with irrigation the most relevant metric for this indicator is *abstraction volume for agricultural use*, specifically the agriculture (excl. spray irrigation) component of annual water abstraction estimates. To understand its impact on livestock, the metric would need to be combined with land cover /use metrics on *grassland* and also *stocking density* metrics to understand where the livestock are and how many are in each location.

Total water demand for – Forestry

As with the other water availability indicators the *abstraction volume* metric is highly relevant, but will need to be linked to land cover / use metrics for *area of woodland in active management* to make it relevant specifically to the forestry sector.

Total water demand for – Habitats and species

For habitats and species there is no directly relevant metric. Land cover / use metrics on *woodland area*, *semi-natural grassland area, areas of other broad habitats, areas of priority habitats* and *area of biodiversity designated sites* will provide data on areas and locations of various natural habitats. Other metrics that could provide evidence for this indicator are the species quality metrics and habitat-related quality metrics as these will all impact on the water demand from a habitat.

Volume of abstraction from catchments at risk of water scarcity and all other catchments

This indicator would require at its simplest catchment boundaries and the two metrics *water availability* (to identify areas of scarcity) and *abstraction volume* (to represent demand). These metrics could be supported by other metrics such as the land cover / use metrics *(crop area by type, habitat etc.*) to help identify areas with increased water demand based on land use. In addition, other metrics could provide additional insight into the water demands in a catchment such as *irrigated area, number and volume of on farm reservoirs* and *number of farms implementing water efficiency measures*.

Amount of crop production in climatically unsuitable areas

There are two main metrics to support this indicator *climate* and *crop area by type.* These metrics will tell you what crop types are being grown in areas with different climates. Note that the *climate* metric is not included in the review of datasets because it is not a measure of land use, but the UK

Climate Projections project from the Met Office[19] would provide the necessary climate data. Interpretation would then be needed to determine which climates were suitable for which crops to then identify if they were being grown in a suitable climatic area. Additional information on *crop yield by type* could be used to understand the volume of production in each area.

Number of farms implementing water efficiency measures

A single metric of *number of farms implementing water efficiency measures* could be used to support this indicator. Additional metrics on *crop area by type, arable area* and *grassland area* could be used to aid in the spatial mapping of this information.

On-farm water storage capacity

This indicator could be fully supported by a single metric capturing *number and volume of on farm reservoirs.*

Improved water quality

Improving water quality can increase the availability of water for other purposes, such as for irrigation or livestock. The main metrics that measure water quality are *N, P & Z pollutant loads in freshwater* and *water quality status*. Other metrics that are relevant are the land cover /use metrics for *arable and horticulture area, improved grassland area, crop area by type* and *area of biodiversity designated sites*. Overlaying these there are a range of metrics that can be used to give evidence into the impact of agriculture on water quality. There are those that provide evidence for a reduction in pollutants likely to reach water. These metrics include ones that can contribute to reductions in nitrate and phosphate in water such as *mineral N fertiliser use per hectare by crop, organic fertiliser use per hectare by crop, having a fertiliser /manure management plan, timing of fertiliser /manure application, stocking density, uptake of precision farming technologies* and *applying manure in total and with immediate incorporation.* In addition, metrics that monitor *pesticide use per hectare by crop* can provide information on risk of pesticide contamination, whilst *area of buffer strips, area with winter cover crop* and *area of land under relevant agri-environment scheme options* can help to identify areas where surface runoff and pollution should be reduced. Other metrics can give an indication of whether the water quality is actually good such as *indicator species population and distribution* and measures of *habitat condition.*

Flooding of agricultural land

Area of ALC 1-3 land reliant on drainage

There are three main metrics that can be used to provide information on this indicator. The first is the *land capability for agricultural grade* which provides information on agricultural land classification (ALC) this would then be overlaid with the *area of functioning field drains*. These two metrics would provide most of the information needed to support this indicator, although additional information could also be provided spatially using the *arable area* and *grassland area* metrics that would enable drainage and ALC to be aligned with land use.

Agricultural losses from flooding/waterlogging

The *flooding risk* metric is highly relevant and could be used as a standalone metric to show the proportion of agricultural land at risk of flooding. In order to map this information spatially land cover / use metrics such as *arable area, grassland area* and *crop by crop type* could be used. In

[19] http://ukclimateprojections.metoffice.gov.uk/

order to understand agricultural losses a slightly different set of metrics would be needed alongside those identifying areas at risk. The *crop area by type* metric linked with the *crop yield by type* would enable estimates of the proportion of different crops impacted by flooding to enable calculations to be made on the agricultural losses from cropped land. For livestock the *stocking density* metric could be used to give some indication of potential losses, but given that stock can be moved if there is risk of flooding this is a less reliable metric than specific land use metrics. There are other metrics that could provide additional evidence for increased or decreased risk of flooding, such as those looking at land management factors that would impact on the rate of surface runoff e.g. *area of buffer strips, area with winter cover crop, area of functioning field drains* and *area/ frequency of moorland burning by habitat type* or *biodiversity* metrics that could provide similar information such as *area of habitat restored* and *area under relevant agri-environment scheme options*. Other metrics such as *soil type, soil erosion risk and soil organic matter* could provide additional information on areas at increased risk of flooding. For example where soils are more permeable infiltration rate following rainfall will be increased, reducing waterlogging and the volume of water likely to run off the surface and cause flooding, soils that are less permeable, or have a high clay content that are more at risk of compaction, conversely increase the risk of flooding[20].

Proportion of EA flood asset systems protecting agricultural land

This indicator would be supported by a combination of land cover metrics for *arable area* and *grassland area* with a metric identifying the area protected by *flood assets.*

Fertility of agricultural soils

Area of agricultural land covered by crops at high/low risk of soil erosion

The *crop area by type* metric will be the most relevant for identification of the area of land covered in crops associated with high or low risk of soil erosion, provided assumptions as to which crop types are at high or low risk of erosion are made. Additional supporting evidence could be provided by metrics on crop management practices that impact on the soil erosion risk e.g. *area under zero / min till/ conventional cultivation systems, area of buffer strips (along water courses / other)* and *area with winter cover crop*. These metrics could help to refine crop type data to management of that crop type that is high or low risk. *Soil type* will be relevant as soils with smaller particles (clay soils) are at lower risk of erosion than those with larger particle sizes (sandy soils)[21].

Area of agricultural land losing soil organic carbon, by grade

The two main metrics required for the support of this indicator are *land capability for agricultural grade* and *soil carbon organic matter content*. These would provide you with information on the grade of land and the soil carbon content of soils on that land. In order to capture whether the soil was losing soil organic carbon content a time series of the soil organic matter content metric would be required to measure trends over time. If time series data were not available consideration could

[20] Holman I, Hollis J, Bramley M & Thompson T (2003) The contribution of soil structural degradation to catchment flooding: a preliminary investigation of the 2000 floods in England and Wales. *Hydrology and Earth Systems Sciences* **7(5)**, pp 754-765. http://www.hydrol-earth-syst-sci.net/7/755/2003/hess-7-755-2003.pdf (accessed February 2016)

[21] Knox J, Rickson R, Weatherhead E, Hess T, Deeks L, Truckell, I, Keay C, Brewer T and Daccache A (2015) Research to develop the evidence base on soil erosion and water use in agriculture. *CCC Final technical report*. https://www.theccc.org.uk/wp-content/uploads/2015/06/Cranfield-University-for-the-ASC.pdf (accessed February 2016)

be given to metrics such as *area under zero / min tillage / conventional cultivation* combined with *crop area by crop type* to identify the areas that are at increased risk of soil carbon loss.

Area of agricultural land converted to development, by grade

The main metrics for this indicator are *land capability for agricultural grade* and *conversion to development* these would provide information on the quality and quantity of land converted. The *conversion to development* metric is not specifically covered in the review of datasets as it was classed as urban development and therefore considered out of scope, but it could be estimated from mapped time series data on land cover to track change from agricultural use to urban/ suburban development. Additional support could be provided by land cover/use data sets such as *arable area* and *grassland area* metrics to help identify what types of land were being taken for development.

Area of agricultural land under minimum/no tillage, by grade

The *proportion of UAA under zero/ min/ conventional tillage by crop type/ farm type/ region* metric should provide all the information needed to support this indicator, although the *land capability for agricultural grade* metric would provide the supporting information on the grade of land under each tillage type. However, additional supporting information from the *crop area by type* metric could be used to provide additional support to the tillage metric.

Area of agricultural land covered by soil conservation measures

Soil conservation is linked to the ability of the soil to store carbon and its fertility and therefore its ability to produce good quality crops, grass or forestry with minimal requirements for inputs[22]. Metrics such as the land and farm management practice metrics in relation to *mineral and organic fertiliser use* and *application* as well as *area under zero/ min / conventional tillage systems, area with winter cover crop* and *stocking density* could all be combined to provide evidence of practices that conserve soil. These metrics would need to be combined with the land cover /use metrics for *arable, crop area by type* and *grassland* to enabling spatial mapping of the trends. The *soil erosion risk* metric could be over laid over these practices and land use to identify whether the measures implemented are in the right locations to minimise the loss of soil.

Pests and diseases

Pests, pathogens and weeds

The main metric that is of relevance is the *incidence and prevalence of pests and diseases* metric. However, this metric is not expected to be able to provide details on all relevant pest, pathogen and weed species as only key pest and pathogen species are monitored each year, with little monitoring of weed incidence. Therefore, it is anticipated that multiple metrics will be required to provide additional support to this indicator. The most relevant and directly related metric would be the *pesticide usage per ha by crop type* metric, as an increase in incidence of a pest, pathogen or weed species can result in increased applications of pesticides for their control. *Crop yield by type, grassland yield by type* and *woodland yield by type* would also be relevant as any changes in these could provide evidence of pest, pathogen or weed incidence, although additional supporting evidence on why yield had been impacted would be needed.

In order to map these impacts spatially, metrics relating to land cover / use for *arable area, grassland area* and *woodland area* would be required.

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[22] Lal R, Delgado J, Goffman P, Millar N, Dell C & Rotz A (2011) Management to mitigate and adapt to climate change. *Journal of soil and water conservation*. Vol**66(4), pp 276-285** doi: 10.2489/jswc.66.4.276

Invasive non-native species

The main metric to provide evidence for the invasive non-native species indicator is the *invasive species population and distribution estimates* metric. This could be used alone, although there are a number of additional metrics, similar to those for incidence of pests, pathogens and weeds that could be used to provide additional supporting evidence, with specific evidence also available from some of the biodiversity metrics such as *indicator species population and distribution estimates*, metrics for *habitat condition* and *area of habitat restored*. These may include some aspects indirectly linked to non-native species, e.g. habitat restoration may involve the removal of non-native species.

Climate suitability of tree species

Area of woodland affected by wild fires

The most relevant metric for this indicator is the *area of woodland affected by wildfires* metric, which could be used as a standalone metric. However, additional evidence to support spatial mapping could be obtained through using a combination of land cover metrics on *woodland area* and *area of priority habitats* to show where the woodland areas are, combined with a *climate* metric to identify areas that are likely to suffer climatic conditions that will increase the risk of wildfire.

Area of woodland being sustainably managed

The main metric relevant to this indicator would be a direct *area of woodland certified as being sustainably managed* metric, which could be used as a standalone metric. Additional evidence on the location of this woodland would come from the metrics *woodland area* and *area of woodland in active management*.

Proportion of timber trees planted in areas that are likely to be suitable in 2050

The two main metrics of relevance to this indicator are the *woodland area, area of woodland in active management* and *climate* metrics. The climate metric will provide data on whether or not climatic conditions in a location are going to be suitable for timber production in the future, whilst the *woodland area* and *area of woodland in active management* metrics will identify where those areas are.

Proportion of woodland in active management

This indicator could be represented by a single metric of *area of woodland in active management*. Spatial mapping would be supported through the use of the *woodland area* metric.

Diversity of tree species

There is no single metric that can provide all the evidence for diversity of tree species. The most relevant metric would be *condition of designated sites* and *crown condition of key tree species* which will provide information on the quality of woodland habitat. Additional evidence could be provided by metrics on *indicator species population and distribution estimates*, *woodland area* and *area of priority habitats.*

Ecological condition of farmed countryside

Greater detail on the environmental quality indicators is covered in the Environmental Quality Indications section.

Area of agricultural area in targeted agri-environment schemes (HLS) or non-targeted agri-environment schemes (ELS), ELS options identified as priority for climate change

The metric *area of land under relevant agri-environment scheme options* would potentially be able to be used as a standalone metric for measuring both targeted and non-targeted agri-environmental schemes, as well as identifying the area under those options identified as a priority for climate change.

Number of farmland bird, butterfly, bat or pollinator species in decline

For each of these groups of wildlife, the key metric to provide evidence of decline would be the relevant *indicator species population and distribution.* Additional support for spatial mapping would come from the metrics *arable and horticulture area* and *improved grassland area.*

Fragmentation of habitats due to agriculture

The key metric for this indicator would be *habitat connectivity / fragmentation* which could potentially be used as a standalone metric. All of the *land cover / use* metrics would be relevant to this indicator, with the balance and distribution of the agricultural land uses and the more natural land cover types being important for understanding the level of fragmentation. Additional evidence for fragmentation due to agriculture would come from biodiversity metrics such as *indicator species population and distributio*n, *area of habitat restored* and *area of land under relevant agri-environment scheme options.* The indicator species and habitat condition metrics would provide information on the 'health' of the habitat, with the assumption that those habitats that are less fragmented would have higher levels of indicator species and have better condition scores. The habitat restoration and certain agri-environment scheme options both provide information on actions that are being taken that could potentially reduce fragmentation. There are other farming practice metrics that could provide some evidence to support either increased or decreases in habitat fragmentation such as *area of buffer strips, area under organic farming, area with winter cover crop* and *area/ frequency of moorland burnt by habitat type.*

Appendix 4: Environmental quality indicators of land use

Indicators of ecological condition

The UK Biodiversity Indicators 2015 report[23] contains indicators that relate to habitat condition (Table 10). These indicators are of several general types, and include the area under land management schemes such as agri-environment schemes or forestry certified as being sustainably managed, indicators of pollution such as critical load exceedances, indicator species such as farmland birds or terrestrial invasive species, and the condition of designated sites. Indicators with the longest time series are the total extent of protected areas on land (with a baseline date of 1950), and pressure from invasive terrestrial species (with a baseline of 1960). In contrast, status (condition) of habitats of European importance has only been reported since 2007, and area of land in entry-level agri-environment schemes since 2005.

Table 10. Indicators of habitat condition from the UK Biodiversity Indicators report.

Indicator	**Land type**	**Earliest date**	**Data rigour**	**Trend rigour**	**Overall rigour**
Area of land in higher-level or targeted AES	A, S	1992	M	H	M
Area of land in entry-level type AES	A	2005	M	H	M
Area of forestry land certified as sustainably managed	F	2001	H	H	H
Area of sensitive UK habitats exceeding critical loads for acidification	S, F	1996	M	M	M
Area of sensitive UK habitats exceeding critical loads for eutrophication	S, F	1996	M	M	M
Pressure from terrestrial invasive species	S, F	1960	L	M	L
Total extent of protected areas on land	S, F	1950	H	H	H
Condition of Areas/Sites of Special Scientific Interest	S	2005	M	M	M
Habitat connectivity	A, S, F	-	-	-	-
Status of UK habitats of European importance	S	2007	H	M	M
Farmland birds	A	1970	H	H	H
Woodland birds	F, S	1970	H	H	H
Wetland birds	S	1975	H	H	H
Butterflies: semi-natural habitat specialists	S, F	1976	H	H	H
Butterflies: species of the wider countryside	A, S	1976	H	H	H
Plants of the wider countryside	A, S	-	-	-	-
Mammals of the wider countryside: bats	A, S, F	1999	H	H	H
Pollinators	A, S, F	1980	-	-	-
Surface water status	A, S, F	2009	H	M	M

A = agriculture, F = Forestry, S = semi-natural; H = high, M = medium, L = low.

Confidence levels in trends and assessments have been reported by JNCC for indicators in the 2015 report[24]. Confidence levels are based on the methods used to collect data for the indicators and the statistical methods applied to assess temporal trends. Many indicators have been rated as 'high', particularly those derived from bird, butterfly and bat species data, but also some of the indicators relating to the area of land under management schemes. At the opposite end of the scale, pressure from terrestrial invasive species is rated as 'low', while two potential indicators are still under

[2323] Defra (2016) UK Biodiversity Indicators 2015. http://jncc.defra.gov.uk/pdf/UKBI_2015_v3a.pdf

[24] JNCC (2016) UK Biodiversity Indicators 2015. Confidence in trends and assessments. http://jncc.defra.gov.uk/pdf/UKBI2015_ConfidenceStatements_Final.pdf

development (habitat connectivity and plants of the wider countryside) and a third has not been assessed (pollinators).

A range of indicators of condition has also been identified for individual terrestrial Broad Habitats (Table 11). Indicators derived from Countryside Survey (CS)[25] data are available for all the terrestrial habitats reviewed, with the exception of montane habitats for which there are insufficient CS data. The CS indicators that are otherwise applicable universally are plant species richness, bird and butterfly foodplants and a range of plant functional indices based on Ellenberg values and plant strategies. The condition of designated sites using the JNCC's Common Standards Monitoring (CSM)[26] methodologies is also available as an indicator for most Broad Habitats. Attributes used in the CSM methodology to determine habitat condition include habitat extent, plant species composition and vegetation structure. In addition, there are CSM metrics specific to particular Broad Habitats, for example regeneration potential in broadleaved, mixed & yew woodland and coniferous woodland. Indices of species populations are also derived for some habitats. For example, farmland birds and farmland butterflies are relevant to the arable and horticultural, improved grassland and boundary & linear features Broad Habitats at national level. Finally, there is a small number of indicators that have been developed for specific purposes and are applicable to particular habitats. Examples include crown condition of key tree species (applicable to both broadleaved, mixed & yew woodland and coniferous woodland) and burning regimes on blanket bog.

Soil quality indicators

Soil biological indicators

The SQUID (phase 1) project[27] identified 21 'candidate' indicators, but stressed that further work was required in order to validate these, including sensitivity analysis, development of robust methodologies, protocols and quality control. SQUID phase 2 (SP0534), explored a subset of methods to assess their ability to distinguish between land-uses/management factors, and potential for national scale monitoring. It concluded that no one measure provided enough sensitivity and proposed a minimum data set of:

- Phospholipid fatty acid analysis (PFLA) to profile soil microbial community structure
- Terminal restriction fragment length polymorphism (TRFLP) to characterise soil bacterial, fungal and archaeal communities
- Multiple substrate induced respiration (MSIR) to profile soil respiration responses
- Dry extraction of soils (Tullgren funnels) to characterize microarthropods
- Microplate fluorometric assay to profile potential enzyme activities

[25] Carey, P.D., Wallis, S., Chamberlain, P.M., Cooper, A., Emmett, B.A., Maskell, L.C., McCann, T., Murphy, J., Norton, L.R., Reynolds, B., Scott, W.A., Simpson, I.C., Smart, S.M. & Ullyett, J.M. (2008) Countryside Survey: UK Results from 2007. NERC/ Centre for Ecology & Hydrology, 105pp. (CEH Project Number: C03259).
[26] http://jncc.defra.gov.uk/page-2199
[27] Ritz, K., Black, H. I. J., Campbell, C. D., Harris, J. A. & Wood, C. 2009. Selecting biological indicators for monitoring soils: a framework for balancing scientific and technical opinion to assist policy development. *Ecological Indicators*, 9, 1212-1221.

Table 11. Indicators of ecological condition for terrestrial Broad Habitats.

Broad habitat	Indicator	Baseline	Frequency	Notes
Broadleaved, mixed and yew woodland	Woodland certified as sustainably managed	2001	Annual	Audited against UK Woodland Assurance Standard
	Condition of designated sites	2005	6-7 years	5-yearly reporting; UK, E, NI, S
	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Woodland birds	1970	Annual	Data from Breeding Bird Survey
	Woodland butterflies	1990	Annual	England only
	Crown condition of key tree species	1984	Annual until 2004	GB
	Tree pests and pathogens	?	Continuous	GB
Coniferous woodland	Woodland certified as sustainably managed	2001	Annual	Audited against UK Woodland Assurance Standard
	Condition of designated sites	2005	6-7 years	Designated native coniferous only; 5-yearly reporting
	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Woodland birds	1970		Data from Breeding Bird Survey
	Crown condition of key tree species	1984	Annual until 2004	GB
	Tree pests and pathogens	?	Continuous	GB
Boundary and linear features	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Structural condition of hedgerows	1984	6 - 9 yearly	GB, E, S, W
	Structural condition of walls	1998	6 - 9 yearly	GB, E, S, W
	Farmland birds	1970	Annual	Data from Breeding Bird Survey
	Farmland butterflies	1990	Annual	E only
Arable and horticultural	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Farmland birds	1970	Annual	Data from Breeding Bird Survey

Broad habitat	Indicator	Baseline	Frequency	Notes
	Farmland butterflies	1990	Annual	E only
Improved grassland	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Farmland birds	1970	Annual	Data from Breeding Bird Survey
	Farmland butterflies	1990	Annual	E only
Neutral grassland	Condition of designated sites	2005	6-7 years	5-yearly reporting; UK, E, NI, S
	Condition of non-statutory semi-natural grasslands	2005	infrequent	E only
	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Breeding birds: grassland specialists	1970	Annual	Data from Breeding Bird Survey but specific grassland index not published
	Butterflies: grassland specialists	1976	Annual	Data from Butterfly Monitoring Scheme but specific grassland index not published [CHECK THIS]
Calcareous grassland	Condition of designated sites	2005	6-7 years	5-yearly reporting; UK, E, NI, S
	Condition of non-statutory semi-natural grasslands	2005	infrequent	E (lowland) only
	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Breeding birds: grassland specialists	1970	Annual	Data from Breeding Bird Survey but specific grassland index not published
Acid grassland	Condition of designated sites	2005	6-7 years	5-yearly reporting; E, S (lowland); E (upland)
	Condition of non-statutory semi-natural grasslands	2005	infrequent	E (lowland) only
	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Breeding birds: grassland specialists	1970	Annual	Data from Breeding Bird Survey but specific grassland index not published
Bracken	Plant species richness; plant functional types	1978	6 - 9 yearly	GB, E, S, W
Dwarf shrub heath	Condition of designated sites	2005	6-7 years	5-yearly reporting; UK, E, NI, S

Broad habitat	Indicator	Baseline	Frequency	Notes
	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Burning regimes on dwarf shrub heath	1970s	c. 30 years	E only
Fen, marsh and swamp	Condition of designated sites	2005	6-7 years	5-yearly reporting; UK, E, NI, S
	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
Bogs	Condition of designated sites	2005	6-7 years	5-yearly reporting; UK, E, NI, S
	Plant species richness; bird & butterfly foodplants; plant functional types	1978	6 - 9 yearly	GB, E, S, W
	Burning regimes on blanket bog	1970s	c. 30 years	E only
Montane habitats	Condition of designated sites	2005	6-7 years	5-yearly reporting; UK, E, NI, S
Supralittoral sediment	Sediment supply	-	-	No national data source identified
Littoral sediment	Sediment supply	-	-	No national data source identified

These have been linked to various ecosystem services, but can only really distinguish between different types of habitat or land use, not effects of management. Moreover, they are not routinely sampled as part of any national monitoring scheme, except for microarthropods which were included in the Countryside Surveys of 1998 and 2007. The 2007 survey also included measurement of nematodes, TRFLP (bacteria, fungi and archaea) and PLFAs on a subset of samples[28].

Soil chemical indicators

EA SC030265[29] identified 5 chemical indicators and 1 physical indicator for soil function of environmental interaction and habitat support:

- Soil organic carbon
- Total nitrogen (C:N ratio)
- Olsen P
- pH
- Total metals (Zn, Cu, Pb, Cd, Ni)
- Bulk density (physical property)

Nominal trigger values were proposed and then road-tested in subsequent projects[30]. Trigger values could be established for Olsen P, pH, metals, C:N (and bulk density), but not for SOC (note also work by Loveland[31] and Verhejen *et al*.[32] on critical levels of organic matter). All these properties are routinely measured in national monitoring schemes, or are part of national datasets (one-off surveys) e.g. Countryside Survey, National Soils Inventory, National Soils Inventory for Scotland, Environmental Change Network and Woodland Biosoil.

Soil physical indicators

In addition to bulk density identified by Merrington *et al* (2006), SP1611[33] identified the following properties:

- Bulk density/packing density
- Soil water retention characteristics
- Rate of erosion
- Aggregate stability
- Depth of soil

[28] Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Peres, G. & Rutgers, M. 2012. Soil Biodiversity, Biological Indicators and Soil Ecosystem Services-An Overview of European Approaches. *Current Opinion in Environmental Sustainability*, 4, 529-538.

[29] Merrington, G., et al. 2006. *The Development and Use of Soil Quality Indicators for Assessing the Role of Soil in Environmental Interactions*. Environment Agency Science Report SC030265, 241pp

[30] Nicholson, F. A., Boucard, T., Chambers, B. J., Merrington, G. (2008) Road Testing of 'Trigger Values' for Assessing Site Specific Soil Quality. Phase 1 – Metals. Environment Agency Science Report – SC050054SR1. 70pp; Bhogal, A., Boucard, T., Chambers, B. J., Nicholson, F. A., Parkinson, R. 2008. Road Testing of 'Trigger Values' for Assessing Site Specific Soil Quality. Phase 2 – Other Soil Quality Indicators. Environment Agency Science Report – SC050054SR2. 60pp

[31] Loveland, P. & Webb, J. 2003. Is There A Critical Level Of Organic Matter In The Agricultural Soils Of Temperate Regions: A Review. *Soil & Tillage Research*, 70, 1-18.

[32] Verheijen, F. G. A., Bellamy, P. H., Kibblewhite, M. G. & Gaunt, J. L. 2005. Organic carbon ranges in arable soils of England and Wales. *Soil Use and Management* 21 2-9.

[33] Rickson, R.J., Deeks, L.K., Corstanje, R., Newell-Price, P., Kibblewhite, M.G., Chambers, B., Bellamy, P., Holman, I., James, I.T., Jones, R., Kechavarsi, C., Mouazen, A.M., Ritz, K., Waine, T. (2013) Indicators of soil quality – physical properties. Final Report to Defra for project SP1611.

- Sealing
- Visual soil evaluation (semi-quantitative)

Only bulk density and depth have been measured in national surveys. Pedotransfer functions can be used to derive soil water retention characteristics and packing density, based on measures of clay content, organic carbon and bulk density.

Drivers of change in ecological condition

The NEA provides a comprehensive review of the direct and indirect drivers affecting ecosystems and the services provided by different habitats. Habitat change (conversion from one Broad Habitat to another as well as deterioration in habitat condition), pollution and nutrient enrichment and exploitation of resources have had the greatest effect on terrestrial habitats. Invasive species have also affected habitats, although to a lesser extent in most cases. Climate change has also affected some montane, upland and coastal habitats but this is predicted to increase and to affect all habitats in the future. Delivery of ecosystem services is affected by the same set of drivers, although effects are more variable within and among the services, and invasive species are considered to be less of threat. Climate change is not currently considered to be a major driver affecting ecosystem services but is likely to become so in the future.

Birds are among the best studied indicators of habitat condition and the drivers of declines in both farmland and woodland birds are now well understood. Long-term farmland bird declines have been associated with use of agrochemicals, intensification of grassland management, reduction in crop diversity (particularly spring sown crops), deterioration of field margin habitats and increased drainage, with consequent reduction in landscape diversity. Climate change might also be affecting some species, particularly in areas outside the UK used by migratory species.

In forestry and semi-natural woodland, bird declines have been driven by changes in vegetation structure, itself a consequence of reductions in woodland management, a shift in age classes to older stands, high levels of browsing by deer and, in some cases, nest predation by grey squirrels (an invasive species) (e.g. Amar et al., 2006)[34].

A similar set of drivers in both woodland and farmland is also thought to be responsible for declines in butterflies that have specialist habitat requirements[35]. Less specialised species with wider distribution are also in decline but the drivers responsible not well understood. A few species have increased distribution in the UK in response to climate change, but increasing severe weather events predicted under climate change scenarios are likely to have detrimental effects on butterflies.

Drivers of change in soils

Soil is the foundation of all terrestrial ecosystems and provides multiple ecosystem service benefits; the most prominent of these being the provision of food and fibre, climate regulation and carbon storage, the regulation of water flow and quality and the support of both above and below ground biodiversity. Different soils deliver some ecosystem services more effectively than others, with lowland mineral soils under arable and grassland management important for food production, while deep peats in upland areas support semi-natural habitats and are arguably more important for

[34] E.g. Amar, A., Hewson, C.M., Smith, K.W., Fuller, R.J., Lindsell, J.A., Conway, G., Butler, S. & MacDonald, M.A. (2006) What's happening to our woodland birds? Long-term changes in the populations of woodland birds. BTO Research Report No. 169. RSPB Research Report No. 19.

[35] Butterfly Conservation (2015) The State of the UK's Butterflies 2015. http://butterfly-conservation.org/files/soukb-2015.pdf

carbon storage and climate regulation. However, there are a number of drivers which affect the ability of soils to deliver these services, notably: compaction, erosion, loss of organic matter, land-use change, loss of biodiversity, climate change and surface sealing (loss to development).

Compaction of soils due to machinery trafficking or livestock trampling, particularly when soils are wet, can cause a significant deterioration in soil structure, reducing the number and connectivity of soil pores and increasing bulk density. This has a direct impact on a number of key soil physical and biological processes, notably water infiltration, gaseous exchange, root access and soil faunal activity, with implications for crop productivity, water quality, flood management and biodiversity. Increases in runoff and erosion from compacted fields result in higher nutrient and sediment loads in water courses, while reduced infiltration rates increase the risk of flooding. Nitrous oxide emissions may also increase. Compaction affects farm operations by reducing opportunities for access and increasing the risk of further soil degradation associated with mechanical cultivations and livestock trampling[36]. Recent research has indicated that approximately 10-15% of grassland soils in England and Wales were in poor structural condition and 50-60% were in moderate condition[37]; notably the poor soil conditions were not restricted to improved grasslands; semi-improved grassland soils were also affected.

Accelerated soil erosion, by water, wind, cultivation or livestock, can have serious implications not only for the provision of food and fibre (due to a loss of productive topsoils), but also impacts on water flow and quality (due to increased sediment loads and nutrient enrichment) as well as carbon storage (due to removal of C-rich topsoils). In lowland areas, light arable soils are often at the greatest risk of erosion, whilst in uplands, thin soils and deep peats are the most sensitive soil types[38].

Loss of soil organic matter (SOM) has significant implications for soil natural capital and the delivery of key ecosystem services. Organic matter provides a food source and habitat for the soil biological community, drives the cycling of nutrients within soils and is a central component of soil aggregation and the maintenance of structure and water relations[39]. It is therefore key to the maintenance of soil quality and health; it is also an important carbon store. SOM can be lost from the soil system via microbial respiration during decomposition or via water or wind erosion. Although these are natural processes, they can be accelerated by human intervention e.g. tillage or removal of vegetative cover. Land use change, particularly the removal of permanent vegetative cover (e.g. deforestation or ploughing grasslands for arable cultivation) can have a major impact on SOM levels.

It is not yet clear how soils are responding to a changing climate, with much debate over whether measured declines in UK soil carbon concentrations over the last few decades are a result of climate change or other factors such as changes in land management[40]. However, given the predicted increases in temperature and changes in the seasonality and magnitude of rainfall events, changes to soils and the services they provide are highly likely, particularly if land-use patterns also change[41].

[36] Batey, T. (2009). Soil compaction and soil management – a review. *Soil Use Man.* **25**, 335-345.
[37] Newell-Price, J. P. et al. (2013). Visual Soil Evaluation in Relation to Measured Soil Physical Properties in a Survey of Grassland Soil Compaction in England and Wales. *Soil & Till. Res.* **127**, 65-73.
[38] Evans, R. (1990) Soils at risk of accelerated erosion in England and Wales. *Soil Use Man.* **6**, 125-131.
[39] Tisdall, J.M. & Oades, J.M. (1982). Organic matter and water-stable aggregates in soils. *J. Soil Sci.* **33** (2), 141-163.
[40] Barraclough, D. *et al*. (2015). Is there an impact of climate change on soil carbon contents in England and Wales? *Eur. J. Soil Sci*. **66,** 463-475.
[41] E.g. Mullan, D. 2013. Soil Erosion under the Impacts of Future Climate Change: Assessing the Statistical Significance of Future Changes and the Potential On-Site and Off-Site Problems. *Catena*, **109**, 234-246.

This includes potential changes in soil carbon storage and greenhouse gas (GHG) emissions, soil stability, biodiversity and erosion, flooding and water regulation.

Development, whether it be due to housing, or commercial/industrial (including mineral extraction), inevitably leads to some degree of soil sealing/removal and hence the permanent loss of soil and associated functions. Besides the loss of productivity and habitat, the other major impact of development is on the role of soils in regulating the flow of water, with reduced infiltration and higher run-off increasing the pressure on un-sealed soils to receive water, resulting in greater flood risk (Defra project SP0541: The Application of Remote sensing to Identify and Measure Changes in the area of Soil Prevented from Carrying Out Functions by Sealing). Poor construction practices during development can also lead to further soil degradation due to compaction and pollution.

Synergies and trade-offs between ecosystem services

The NEA considers synergies and trade-offs between ecosystem services under different management regimes and land uses. At a general level, if land is exploited primarily for provisioning services, there will tend to be a trade-off with regulating and cultural services. For example, intensively managed arable land is patently the most important land use for providing food crops but this is often at the expense of biodiversity, water quality and soil quality. Conversely, land use that is important for providing cultural services is often also valuable for regulating services. An obvious example of this would be semi-natural woodland, which has positive benefits for biodiversity and landscape quality, while also contributing to climate regulation, carbon storage and water quality. However, there are exceptions to these general patterns. A notable example is forestry as a land use, which has a provisioning service as its primary output (timber) but, depending on the intensity of management, can also be important for providing regulating services such as climate regulation and water quality, and cultural services such as recreation. Maintenance of upland habitats using grazing livestock can be beneficial to biodiversity but also produces methane that is detrimental to climate regulation. There are also more specific cases where synergies among ecosystem services can be actively promoted by change in land use. Examples cited in the NEA include managed coastal realignment, catchment management to alleviate flood risk, and provision of habitat for pollinators with consequent benefits also for biodiversity.

The NEA provides an assessment of the ecosystem services provided by different types of land (above Broad Habitat level), and their relative importance. This illustrates where there are synergies and trade-offs among different ecosystem services. In fact, at this level most land types provide a wide range of ecosystem services, albeit with varying degrees of importance, and the only obvious trade-offs would be where provisioning services were exploited at the expense of cultural and regulating services. Variation among the results from the UK countries will be due in part to real differences in the prevailing environment and land use intensity, but might also be a consequence of the subjectivity involved in making these appraisals. For example, enclosed farmland is judged to be of high or medium importance for wild species diversity in England and Scotland, but medium or low importance in Wales and Northern Ireland.

Appendix 5: Review of literature land use scenarios

Special Report on Emissions Scenarios (SRES)

The IPCC developed a set of scenarios for its Special Report on Emissions Scenarios (SRES). The main purpose of this was to predict future GHG emissions, but the scenarios developed are also used to make predictions for land use and land use change. The report acknowledges the broad drivers as having economic, technical, environmental, and social dimensions, and that all of these interact in a highly complex manner. In order to simplify matters and develop broad scenarios or 'storylines', two key categories of driver are brought to the fore which reflect whether societal preferences are more aligned towards a global or regional/local outlook ("globalisation"), and whether economic or environmental objectives are more highly valued ("sustainability"). Four different storylines (A1, A2, B1 and B2) are then developed which occupy each a quadrant on an imaginary chart where globalisation and sustainability are orthogonal axes. Additional complexity is added by considering different types of technological change in the energy system that could apply to the A1 storyline, and by using different modelling approaches to develop a range of individual scenarios for each storyline. Demographics, economic output, and broader technological change in each scenario are a function of the overarching societal values. Population growth decelerates at a greater rate in the more globalised storylines. GDP growth is higher where society values it as a driver, but also where society is more global. Technological change and progress is also more encouraged in the globalised storylines.

Estimated land use metrics are given for major land use types: cropland (for food), grassland, energy/biomass, forests, and others. The A1 storyline, where society values economic output and becomes more globalised and harmonised, assume that decisions on land use are driven primarily by economic forces. As such land rental and agricultural prices become the dominant factor in land use. Higher incomes generate more demand for meat and energy, with a resultant increase in grassland, biomass crops, and a reduction in forest. However, higher incomes also generate a greater demand for environmental goods and crop productivity improves, so the pressure to increase cropland and reduce forest decreases over longer time horizons. The A2 storyline, which reflects a desire for higher economic output, but on a more localised scale, follows a similar pattern to A1 but the changes are less dramatic. The B1 storyline sees local environmental issues given a higher priority with less desire for wealth, but a global outlook is retained. Agricultural productivity, renewable energy and environmental goods are driving forces and there is decrease in food cropland, grassland, but an increase in biomass cropping and forest. The B2 storyline also ascribes higher value to environmental matters, but there is less global cooperation and the focus is more local or regional. Agricultural productivity growth is slower, so there is initially a higher demand for cropland at the expense of forest, though eventually there is a net gain in all land use types apart from urban and degraded land.

Foresight Futures 2020

A set of scenarios was developed in 2002 for the UK Government by researchers at the University of Sussex, as part of the *Foresight* project. There are four scenarios in all reflecting a similar two-axis chart to the SRES scenarios but the orthogonal axes are social values and systems of governance respectively. Social values could vary between being more individualistic or more community-led, whilst governance could be more autonomous (where power is retained at national level) to where is more interdependent (where power is more devolved to higher or lower levels). In the "World

Markets" scenario, people aspire to greater personal wealth and mobility whilst government plays a minimal role. "National Enterprise" also reflects a desire for greater personal independence and wealth, but within a strong national-cultural identity, leading to a greater role for national government but less so local and EU. "Global Responsibility" reflects a trend towards more community values and a sound environment, but that this is achieved through increasing international cooperation. "Local Stewardship" has a similar social emphasis but seeks to achieve this through devolved power to the local level. In many respects the scenarios are similar to the A1, A2, B1, and B2 respectively and this is acknowledged in the report.

World Markets saw a trend away from manufacturing and agriculture towards services and is associated with high economic growth (in GDP terms). As an industry, agriculture becomes more concentrated, industrialised and global in scale as EU subsidies are cut back. This also encourages innovation with GM and organic approaches becoming increasingly distinguished. High mobility and wealth creates demand for housing and transport infrastructure, some of which is at the expense of greenfield land, especially in the South East. Energy markets remain dominated by fossil fuels, and renewable energy is not widely adopted. *National Enterprise* saw a more modest growth in services and development pressures, and a more moderate level of growth. Agriculture would remain strongly subsidised and reliant on conventional practices, whilst energy would focus on provision of the least-cost and most secure resource. *Global Responsibility* envisioned a growth in the service industry, but with greater emphasis on work with low environmental impact or greater social value hence a more moderate growth path. Development pressure focussed on investments to improve the quality of existing urban centres and infrastructure. The CAP would be reformed to encourage higher biodiversity and lower environmental impact, with substantial land released to nature conservation or organic production. Meat consumption also reduces. *Local Stewardship* involves a de-scaling of economic activity so growth is lower, and although services are still the dominant portion of the economy the focus moves towards satisfying more basic needs and less towards high income and international work. Development is highly constrained, with the exception for investment in local renewable energy, resource efficiency, and public transport schemes. Agricultural subsidies continue, output and land use increases with the objective of meeting local demand, mainly for organic and low input farming.

The scenario analysis made no explicit prediction for land use, but it is still useful for understanding the relationships between and relative strengths of the "indirect" drivers identified in Task 4. The social values is comparable to the "cultural/behavioural" driver, whilst governance aligns to "socio-political". Again, like the SRES storylines the development places social values at the top of the hierarchy and the other drivers (demography, economics and technology) are a function of these.

Academic work influenced by SRES and Foresight

Rounsevell et al (2005) develop the SRES storylines into a range of agricultural land use scenarios for the EU-15, Norway and Switzerland. The use a model where land area required for cropland or grassland is based on a simple supply/demand equilibrium, where change in land use reflects the product of change in demand and change in supply. The factors determining change in demand are population, consumer preferences, market liberalisation, and EU enlargement. Meanwhile supply changes reflects changes in productivity and extent of oversupply. Productivity itself is a function of changes in technology/management and changes in climate (temperature, precipitation, and CO_2 concentration). Values for each change parameter were derived from models, proxies, or assumptions. Declines in cropland and grassland for 2020, 2050, and 2080 show a similar pattern to the previous analysis with the greatest losses predicted for the A1 and A2 scenarios, in some cases by more than 50%. The spatial distribution of the land use change was also estimated with greater losses of agricultural land to 2080 for the A1 scenario in southern Europe, though the UK would see its biggest loss under the A2 scenario.

This work is taken further to incorporate other land uses, including urban, forestry, biofuels, and protected areas (Rounsevell et al, 2006). The analysis draws on the global work done for SRES and suggests that: urban areas show little change in all four scenarios; forest increases significantly in the B1 and B2 scenarios but modestly in A1 and A2 (at the expense of agricultural land), whilst biofuel land use increases materially in all scenarios. The model does not allocated a particular land use for much of the agricultural land made available in A1 and A2. It is unlikely the land would be actually abandoned as it likely that policy measures would intervene to prevent this.

Morris et al (2005) refine the broader Foresight work into four explicit agricultural scenarios for England and Wales with five underlying drivers: agricultural and rural policy, food markets and prices, environmental policy, farmer attitudes/motivation, and agricultural production and farming systems. Narratives were generated for each scenario to reflect how the each underlying driver would change under the societal and governance pressures associated with that scenario. For example, under agricultural policy each scenario implies a different outcome for the CAP where it is abandoned, strengthened, or reformed as described in the Foresight work above.

Experts then considered how a set of underlying factors would change under each of the scenarios including: free trade influence, value of farm subsidies, consumer food prices, farm size, yields, farm diversification, proportion of conservationist farmers, biodiversity, environmentally regulated land area, extent of use of environmental fiscal instruments, and adoption rates for voluntary measures. Arbitrary scores were assigned related to a “business as usual” baseline to provide an indicator for each factor, from which estimates for actual metrics such as crop yield, animal yield, input/output prices, and water use could be inferred. Land use for agriculture was also modelled relative to current use: declines were greatest in the World Markets scenario mainly due to the improved yields enabling land to be released for other uses. The scenario analysis also predicts the spatial distribution of land use change with greater losses expected in the Midlands and North East England than elsewhere. In order to understand the effects of technical change in crop production, four additional scenarios were developed where integrated management, alternative machinery, reduced tillage, and genetically modified crops each play a leading role in farming systems.

Climate change itself was not considered as a driver in the Morris et al analysis, but this was explored in a subsequent study (Audsley et al, 2008). Here, the UKCIP scenarios (which have different temperature and precipitation predictions) were combined with the Foresight scenarios to explore ten different scenarios which were intended to capture a range of possible future socioeconomic and climate outcomes for two different study areas (East Anglia and North West England). The model makes predictions for crop areas and the range of outcomes is too extensive to explain here.

Rounsevell & Reay (2009) review the relationship between land use and climate change, and draw on some other studies done in the context of developing scenarios for future land use that have not been mentioned above. They note that scenario analysis is generally based on assumptions, rather than verified facts and that data can often be of poor quality, leading to significant variation in the range of land use estimates from similar scenarios. They also note that many of the drivers which contribute to the models are poorly understood, in particular technological change and policy reform. Rounsevell et al (2006) raise similar caveats about the subjectivity of scenario interpretation and the high reliance on assumptions to underpin model development. The authors also note models themselves are typically spatially constrained (e.g. UK/Europe) so cannot take into account variables outside this area (e.g. demand from Asia). Equally the models are typically static and calibration assumes only that historic relationships will still hold into the future.

Land Use Futures

The Land Use Futures research also developed scenarios to help understand how drivers of UK land use would interact. The researchers used a mixture of systems analysis, existing literature, and expert workshops, to develop three scenarios. Like the previous work, different ends of a spectrum of three societal values were considered, in this case: the extent of adaptation to climate change, the degree of societal resistance to change, and the extent to which population and economic growth is more concentrated or dispersed. Only three scenarios were actually developed. "Leading the Way" imagines a scenario where the society adapts to environment change and institutional response is strong, but the population and economic activity is dispersed. In "Valued Service", the population and economic activity is more concentrated but resistance to societal and institutional change is low. Whilst in "Competition Rules", society is generally resistant to change and struggles in particular to adapt to environmental change.

Leading the Way sees the national government playing a strong role, and investments in agricultural technology allow for a sustainable intensification where agricultural productivity doubles but land use decreases by a third. There are corresponding increases in forest and renewable energy-related land cover. Population growth is aligned to where land is most productive with corresponding demand for land and water. *Valued Service* also sees a strong societal and institutional response to environmental change, but the approach is devolved to more local level and relies more on collaborative processes than central edicts. *Competition Rules* sees a slower institutional and societal response, with little investment in environmental goods, and continuing challenges of food, energy, and resource security. Explicit land use estimates for each scenario are not developed. Instead the report imagines a future narrative for each scenario, imagining broad political, societal and economic developments which occur up to 2050.

UK NEA

The UK NEA used a structured approach to developing its own scenarios (storylines) which involved a survey and a review of previous work on scenario analysis, in particular the SRES, Foresight, and Land Use Futures material mentioned above, as well as work done for the natural environment and water resources by Natural England and the Environment Agency respectively. However, the approach differs from that used in previous studies. Instead, a morphological analysis was used to develop a matrix of drivers and trends in drivers where the drivers (direct and indirect) were columns and the trends in are rows. Each cell was populated with knowledge about the relationship between driver and trend. Scenarios were constructed by moving horizontally across the matrix and linking cells in each column that had some commonality or coherence.

In total, six scenarios were generated which allow a broader set of future worlds to be explored than the previous two by two sets. Three of the scenarios (World Markets, National Security, and Local Stewardship) are quite similar in name and nature to the previous Foresight scenarios. There is a 'global responsibility' element to two of the scenarios (Green and Pleasant Land and Nature@Work) but they differ in that the former take more or a preservationist attitude to environmental conservation, valuing cultural and biodiversity aspects, whilst the latter takes a more utilitarian approach, seeking to balance provision of multiple ecosystem services. The final scenario (Go with the Flow) reflects an extrapolation of current trends.

A Bayesian belief network was used to estimate future changes in land cover, where each unit of land cover modelled in the NEA in 2010 could transition to any other in 2060 with a certain probability, assigned based on the assumptions applicable to each scenario and other contextual variables endemic to the land parcel itself (such as altitude and climate). The narrative for each scenario provides detail as to the likely outcomes for land cover, though the detail of what probabilities were assigned and the rationale behind is not made explicit.

CISL (2014)

The CISL analysis aims to project the UK's additional land use demand based on likely built environment, bioenergy, food security, wildlife protection, woodland cover, and water management drivers to 2030. On the supply side, the extent to which additional land can be released from agricultural production is also assessed within the context of technological and management drivers leading to higher yields in crops and livestock, reductions in food waste, and changes in eating habits. Unlike previous work, the analysis does not seek to develop overarching broad 'storylines' but instead looks at each driver independently and estimates a 'high' and 'low' land use change scenario associated with it. The high and low scenarios are referenced from a range of other sources including DEFRA reports, ONS population projections, DECC emissions pathways, the NEA Nature@Work scenario, WRAP reports on food waste, as well as academic literature on crop and livestock yields.

The variation between low and high scenarios when all are combined is quite significant, with approximately 2 million hectares required if all the low demand scenarios are met, and over 7 million hectares if all the high demand scenarios are met. The results do not indicate the probability of these two 'extreme' scenarios, nor whether there is a coherent storyline that joins all of these. If the NEA process were replicated, then a morphological analysis could be used to develop storylines from this initial analysis. In the supply side, the gap is smaller with around 1.3 million hectares released in the low scenarios and 5 million in the high. However this difference does not reflect interaction and redundancy between initiatives. Again, a morphological analysis could be performed to develop storylines.

Appendix 6: References used for rapid review of land use modelling

Review publications

Agarwal, C., Green, G. L., Grove, M., Evans, T. & Schweik, C. (2002) A review and assessment of land-use change models: Dynamics of space, time, and human choice. UFS Technical Report NE-297. Burlington, VT:U.S. Department of Agriculture Forest Service, Northeastern Forest Research Station.

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Appendix 7: Review of the Shortlisted Models

This document contains focussed descriptions of the shortlisted models that aim to provide information on each model to allow CCC to assess its usefulness for predicting future land use. As land use is the core input to a number of impact models, the review was restricted solely to models that were primarily focussed on spatial allocation of land.

For each model, the following are provided:

- The most common or most recent name of the model
  [Other names by which the model is known]
- A description of how the model works and produces predictions of land use
- The spatial and temporal scales at which the model operates and the spatial resolution at which outputs are produced or the model input data is required.
- A description of the drivers covered within the model
- A description of the inputs required by the model and the outputs produced
- A review of the strengths and main assumptions (weaknesses) of the model
- The key references related to the model

In the descriptions of the models, only an overview of the drivers, inputs and impacts assessed by the models is provided. A list of the drivers, inputs and impacts assessed by each model (including names of external or linked models used for inputs or impact assessments) is provided in Appendix 8.

Framework for the Evaluation and Assessment of Regional Land Use Scenarios (FEARLUS)

[FEARLUS-W, FEARLUS-SPOMM]

Core purpose of the model

FEARLUS was developed to allow application of agent-based models to land use decision and has been used to assess decision relating to protection of water quality.

How the model calculates land use

FEARLUS uses agent-based simulation to predict land use. It is set up as a modelling framework for development of models using the SWARM modelling system for agent-based models, so that users can develop their own version of the model for land use, to account for the drivers of relevance to the system being modelled by the user.

The model consists of a set of land managers (representing households) who manage a set of land parcels, with each parcel having a set of biophysical properties. Climatic and economic factors are both represented as external conditions that can change over time, but act to influence the decision.

The land manager selects the land use for each parcel based on the economic return and a profit aspiration level (if the profit is above the aspiration level then no land use change takes place). Land use change is then chosen on a "case" basis where the land manager can choose what land use to change to based either on what their neighbours are doing, previous experience or the farmer can choose to experiment where no other information is available.

The value of the production from the land parcel is then calculated to give each land manager an account. Managers with accounts below zero sell their worst-performing parcels one by one until reaching or exceeding zero. A random buyer is chosen from the neighbours of the owner of the parcel, who have sufficient profit to buy the land parcel.

In FEARLUS-W, an additional step in the decision making allows the land managers to select land use based on social approval as well as economic return, where social approval allows constraints to be placed on selections e.g. highly polluting land uses. FEARLUS-SPOMM added the ability for a government agent to apply rewards or fines to land managers based on their actions.

Spatial & Temporal Scales

FEARLUS does not have a fixed spatial scale as it takes its spatial scale from the input data. Also, FEARLUS does not need to use a grid-based system and can cope with polygons representing actual fields.

Drivers (Full list provided in Appendix 8)

FEARLUS includes user-defined agronomic and economic drivers as part of the algorithm for determining the economic return for a land use on a parcel of land. Cropping constraints are included via the biophysical constraints assigned to a land parcel. However, cropping rotations are not explicitly represented within the model. The behaviour of the farmers is determined by their selection algorithm and so behavioural drivers can be included here, although at present the only behavioural constraint is the requirement for an aspirational profit threshold to be achieved so that the agents are satisficing rather than profit maximising. Policy drivers are represented via the external conditions allowing fines or penalties to be applied to unacceptable land uses and rewards to acceptable land uses. In addition, social acceptability is included through the use of a social approval ranking that allows the neighbours of a land parcel to score the acceptability of the land use on that parcel.

Climate change drivers such as sea level, temperature and rainfall changes can be incorporated through the external conditions that affect the price and profit achieved from a land parcel.

Inputs (Full list provided in Appendix 8) & Outputs

The FEARLUS inputs are dependent upon user needs according to the biophysical, climatic and economic factors that the user has defined as being most important for determining the profit achieved for a given land use on a given land parcel. However, core input data will include land cover, soil type, yields, economic information, climate (temperature and rainfall).

The output of FEARLUS is a set of land use predictions at a polygon/land parcel level.

Strengths and Assumptions

A strength of FEARLUS is that it is able to model decisions at an individual farm level and has an approach to allow decisions to include factors other than economics. FEARLUS is one of the few models that does not assume that farmers are profit maximising, instead it assumes that they are satisficing (i.e. as long as they achieve their aspirational level of profit they will not change land use). A weakness with this is that potentially the land use on a parcel will not change even though it should due to cropping constraints or other factors.

Another strength of FEARLUS is that it is integrated with the SWARM agent modelling system and the user is able to develop their own representation of the FEARLUS model within the SWARM system, accounting for the factors and drivers of most interest to the user. FEARLUS has a lot of novel approaches, some of which are in their infancy in terms of being used to model land use.

An advantage of being a framework that can be configured to address the needs of the user is that it can be specifically tailored to the question of interest. However, this does mean that time and through have to be put into developing the most appropriate representation for the system within the modelling framework. FEARLUS is also is downloadable, but would require a person with programming expertise to develop the model.

With the social approval component of FEARLUS, it is assumed that social approval is driven by neighbours and a "general public" agent. The inclusion of a social approval component to influence the decision making is a strength of this model, but the utility of this will be dependent upon the weighting given to the neighbours versus the general public when accounting for social approval in choosing a land use.

FEARLUS does not have many inherent assumptions as most of the assumptions will be made by the user when determining the factors to be included in determining profit and also in the methods used to determine the external factors that are included as time variable inputs.

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Mathematical Programming-based Multi Agent Systems (MP-MAS)

[MAS-CA]

Core purpose of the model

MP-MAS was developed to replicate human decision making in agriculture and has been applied to case studies of land use change in Thailand, Chile and Ghana.

How the model calculates land use

MP-MAS is an agent-based model: it predicts land-use changes driven by constrained profit-maximisation at the level of individual agents (land managers) with imperfect knowledge of crop yields and prices.

Land and resources are allocated unequally to the agent population based on farmer survey data, creating a heterogeneous agent population. Surveys are not generally comprehensive – they cannot cover every single land manager – and individual-level data may be provided in an aggregated format for confidentiality reasons, so there is some uncertainty when using survey data about what the 'real' distribution of land and resources amongst the population is. A repeated sampling ('Monte Carlo') process generates many different possible combinations of agent-land allocations, all statistically consistent with the farmer survey data. MP-MAS is run repeatedly using each of these possible combinations of agent-land allocations (the sampling process means that there is stronger representation of the most probable combinations). The model therefore predicts the land-use change that is most likely, and also the potential range of outcomes around this average (accounting for the uncertainty in land-agent allocation only – there are other sources of uncertainty).

Changes in market prices are determined by pre-set scenarios defined by the user at the beginning of the model run (an economic model could be used to provide these projections). Crop yields vary with water availability and soil quality, determined by rainfall (from pre-set scenarios defined by the user at the beginning of the model run) and agent land management decisions. Agent expectations of prices and crop yields are updated each year, formed from a mixture of the previous years' conditions and partial foresight of future conditions.

The decision process for land use and management at the agent level is based on an optimisation of the combination of farm activities (area of different crops grown, number of livestock kept, labour inputs and timing, investment in technology, whether to buy or sell land/water rights) that the farm manager expects will maximise the net income from their land. Each activity requires land, cash and labour input costs, and has an expected return which is based on the land manager's expectations of both crop yields on a specific parcel of land and of future market prices for the crop/livestock at the time that the product is sold. The decision-making is therefore influenced by macro-economics and by local (biophysical, socio-economic and policy) constraints.

The model is run iteratively. At the end of each model run, the actual crop yields and market prices are used to calculate each land manager's actual net income, and the land manager's resources and expectations are updated. The land manager then makes the next year's land-use decisions. In this way, MP-MAS models land-use change as a gradual process driven by decisions taken at the level of individuals.

Spatial & Temporal Scales

The model is most frequently operated at a 100m pixel scale, but can be applied at different scales depending on the resolution of input data and the size of the landscape/region being modelled. All applications to date have been at a sub-national scale.

The model operates in annual time steps (but takes account of seasonal/monthly constraints in labour and water availability), and has been used to project land-use up to 25 years into the future.

Drivers (Full list provided in Appendix 8)

MP-MAS incorporates most of the main categories of driver (agronomic, socio-economic, policy and behavioural), but does not currently represent cropping constraints directly. However, there is feedback of the land management impacts on soil quality and water availability to the crop yields achievable on land, which influences agents' decisions. The structure of the model could also allow for cropping constraints to be added through a conversion costs matrix.

Annual rainfall is an input to MP-MAS, being used to calculate water availability as an input to some of the crop yield models that can be used as part of MP-MAS. The model is therefore capable of capturing some effects of changing rainfall, but it currently simulates rainfall events based on historical rainfall patterns. The pattern of rainfall events is likely to change as a result of global warming. Temperature is an input to some of the crop yield models can be used as part of MP-MAS. Sea level rise is not currently included in the model.

Inputs (Full list provided in Appendix 8) & Outputs

MP-MAS requires a number of inputs, some of which are best taken from farm survey data, some can be provided by another model and some are currently provided by expert opinion.

Market prices for each year that the model is to run are required as a model input. An economic model could be used to provide this. The agent decisions modelled by MP-MAS determine the supply of agricultural products, but there is currently no feedback mechanism in MP-MAS to update market prices based on the balance of supply and demand.

The crop yield models require weather data, which could be taken from meteorological data on the current climate, or on projections of climate change. Data on soil type and quality is also required. Data on the farmer population in the region to be modelled (e.g. the range of farm sizes and cash resources), demography, average required inputs for livestock, average livestock outputs is also required to initialise the model and can be provided by survey data.

A number of model inputs, such as the costs and benefits of new technologies, the impacts of policies and a parameter controlling the extent to which agents in the model are able to predict the future, are set based on expert opinion.

MP-MAS generates data on land use and management over time, with spatially explicit outputs of land use, food production and impacts on soil quality and water availability. As MP-MAS models a land manager/farmer population, it produces data that can be used to measure the well-being of that population, with indicators including the range of farm net incomes and labour hours required. It also provides estimates of the uncertainty in model outcomes.

Strengths and Assumptions

MP-MAS has a number of innovative features which contribute to the functionality of the model. The model uses a heterogeneous agent population, created through a Monte Carlo sampling process to ensure consistency with survey data. The sampling process is used to give an estimate of uncertainty in model outcomes. The representation of heterogeneity in the land manager population and the measure of uncertainty are both quite rare features in land use change models.

MP-MAS assumes that agent decisions are driven by constrained profit-maximisation, but accounts for the fact that decisions aiming for profit-maximisation are not taken with perfect knowledge of the future, which again is a rare feature in land use change models based on profit-maximising algorithms. The model also includes representation of social networks. Agents have the ability to trade land and water rights, and a technology diffusion model represents a frequency dependent uptake of technology within social networks, where the technology is initially available as an activity only to the early innovators in the population, and becomes available for uptake by land managers in lower innovation segments once sufficient early innovators have adopted the technology. The combination of the representation of the social aspects of technology uptake with the requirement that the technology fits into land managers' cost-benefit analysis and cash constraints is also an unusual and innovative feature.

MP-MAS has a flexible framework: each farm activity is represented by an equation that encompasses its costs and outputs/benefits, so additional crops and technologies can be added so long as the user is able to provide information on their costs and outputs. The adaptability of the MP-MAS framework is demonstrated by the range of regions and questions to which it has been applied – from prediction of how agricultural production will adapt to climate change in the German

Swabian Alps, to the impact of policy and new crop types in Uganda. However, the model must be adapted and provided with appropriate input data for each new application.

A number of assumptions do need to be made when setting up the model – for example, the extent to which agents in the model are able to predict the future, and the costs and benefits of any new technologies. Other assumptions will be introduced depending on which crop yield model is chosen, what economic model is used for projections of market prices, and the interpretation of any survey data used to set up the model.

Key References

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Schreinemachers and Berger (2011) An agent-based simulation model of human-environment interactions in agricultural systems. Environmental Modelling & Software 26: 845-859.

Troost (2014) MPMAS Central Swabian Jura Model Documentation: Model Version 3.1. Documentation Version 1.1

Valbuena et al (2010)

Core purpose of the model

This model was developed to simulate individual farmer decision making in terms of selection of farm practices and has been applied to a case study in the Netherlands

How the model calculates land use

Farms are classified into a typology based on farm type, size and resources, and the farm/land manager's behavioural/business strategy.

This typology is used to define the probability of a particular farmer making a range of decisions about land use/management – for example, the probability that a farmer will choose to buy land or sell land, diversify into tourism or not, or participate in an agri-environment scheme or not.

The probability of an agent taking a decision is defined by an agent's 'ability' and 'willingness' to make that decision – for example, an 'expansionist' has high willingness to buy land, but their ability may be limited by the size of their cash reserves. If they do have ample cash, they will have a high probability of choosing to buy land, but there must be land available to buy (due to another agent choosing to sell it) or the decision to buy land will never be open to the expansionist.

The model is iterative and previous decisions restrict the options available to agents in the next year, and the probabilities of their decisions in the next year. For example, an agent who buys land has a reduced probability of buying land in the following year. If an agent chose to remove the hedgerows on their land in the previous year, they cannot choose to maintain the hedgerows in the following year.

Drivers such as policy and agronomic factors are represented by their effect on the probability of each type of agent making particular decisions.

Spatial & Temporal Scales

The model operates at a 1ha pixel scale, and has been used to project land-use up to 15 years into the future, with an annual time step. It has been designed to operate at a sub-national scale, but, given the simplified representation of the agent population provided by the typology, it may be possible to adapt it to a national scale.

Drivers (Full list provided in Appendix 8)

The drivers included in the typology can be adapted depending on the scenario/questions to be addressed. Behavioural drivers are captured in the agent typology. The other drivers (agronomic, economic, policy and cropping constraints) can be represented by their effect on the probability of each type of agent making a decision – for example, proximity to the seaside may increase the probability of land managers deciding to diversify into tourism, and the size of the effect on the decision probability may vary between agent types. The limitation to the number of drivers that can be added is that there may not be sufficient data to determine the effect of each driver on decision-making probabilities.

Inputs (Full list provided in Appendix 8) & Outputs

Inputs required to build the agent typology and determine decision probabilities include survey data on the distribution of farm types and sizes, and survey or interview data on land manager attitudes/business strategies (this must be linked with the land managers' associated farm type and farm size).

The model also requires an initial land cover map and other information about the physical environment which could affect land managers' 'ability' to make particular decisions – for example, soil maps can be used to determine whether each land manager has the option of growing a particular crop.

The model output will always include an annual land-use map, but the typology and other outputs can be adapted depending on the scenario/questions to be addressed. Outputs from applications of the model to date have included land ownership patterns, the location/quantity of natural landscape features, and the proportion of farms that derive some of their income from diversification into other income streams such as tourism. The land use categories represented in applications of the model to date were very broad (urban, semi-natural, water bodies and agricultural land) but these could be expanded given sufficient data.

Strengths and Assumptions

The strategy of using an agent typology allows for a simplified representation of land manager heterogeneity, and the structure of the agent population is defined based on survey data.

The model also captures the feedback effects between social and environmental outcomes and policies that attempt to prevent undesirable outcomes. The model uses policy thresholds: if an undesirable outcome becomes sufficiently widespread, a policy is introduced to regulate the spread of the undesirable outcome or to promote a more desirable outcome. The policy then changes the probability of agents making decisions that result in the desirable or undesirable outcome. For example, if a sufficient proportion of hedgerows in the landscape are removed, a policy may be introduced providing financial incentives to maintain hedgerows, increasing the probability that agents will choose to maintain hedgerows.

The use of the typology assumes that new farm types and business strategies will not emerge. The decision probabilities used in the model were partially drawn from experimental/survey data, but were partially based on expert opinion due to limitations with data availability (in particular, expert opinion was required to estimate the response of decision-making to future changes and new policies). Drivers not captured in the model may also affect agent decision-making – if these change, the probabilities used in the model may no longer be representative.

Key References

Valbuena et al (2008) A method to define a typology for agent-based analysis in regional land-use research. Agriculture, Ecosystems and Environment 128: 27-36

Valbuena et al (2010) An agent-based approach to model land-use change at a regional scale. Landscape Ecology 25: 185-199.

Valbuena et al (2010) Effects of farmers' decisions on the landscape structure of a Dutch rural region: An agent-based approach. Landscape and Urban Planning 97: 98-110.

The European Forest and Agricultural Sector Optimization Model (EUFASOM)

Core purpose of the model

EUFASOM was developed to investigate the competition between land for forestry, food and non-food agriculture within the context of meeting renewable energy targets.

How the model calculates land use

EUFASOM calculates the distribution of land use that will achieve the constrained 'market equilibrium' between supply and demand for agricultural and forestry products.

If prices for a product are high, demand for it may fall, as consumers may be able to meet the same needs by purchasing a cheaper product instead. As demand for the cheaper product rises, it will change the balance of supply and demand for that product. To restore the balance, the supply of the product may increase, the price of the product may increase, or a combination of the two may occur.

If prices for a product are low, consumers do not have to pay as much to meet their needs and so have a larger economic surplus, but producers receive less for their product and so have a smaller economic surplus. If prices for a product are high, producers receive more for their product and have a larger economic surplus, while consumers have to pay more to meet their needs and so have a smaller economic surplus.

The constrained market equilibrium is the balance between supply and demand that, meeting the constraints specified in the model/scenario, maximises the overall sum of producers' and consumers' economic surplus, when totalled over all agricultural and forestry products represented in the model.

The balance between demand and price is represented in EUFASOM by truncated demand curves – demand reduces as prices increase, and vice versa, but these are truncated so that neither demand nor price can be infinite. The balance between supply and cost is represented by supply curves – each unit of a product incurs costs, for example expenditure on seed and fertiliser, and labour and land requirements. There are upper limits on the availability of some of these input requirements, such as labour and land, and EUFASOM restricts the supply curve so that supply cannot exceed the limits set by these constraints. EUFASOM can also represent alternative land management strategies/technologies for producing each product, each strategy having its own supply curve representing costs and outputs.

EUFASOM also takes into account subsidies, any costs imposed by policy such as emissions taxes, the cost of converting land from one use to another and the cost of transportation for the imports and exports of the area being modelled (EUFASOM currently operates at a national scale).

The overall economic surplus is calculated as the area under all the product demand curves plus subsidies, less transportation costs, land use conversion costs, other costs and the area under all the product supply curves. EUFASOM calculates the land use share of cropping and forestry that optimises the overall economic surplus. Future costs and benefits for perennial crops and forestry are included in this calculation, but at a discounted rate. The solution must comply with the constraints on the supply curves and a model limit on the extent of land use change.

EUFASOM can also be optimised for alternative objectives, such as minimising greenhouse gas emissions or maximising natural habitat area, or a user-specified mixture of these.

Spatial & Temporal Scales

EUFASOM currently operates at a national scale resolution, producing predictions of land use up to 2050 at five year intervals. It has been designed to operate at a European scale. The results can be processed to obtain a higher spatial resolution, by using them as input to allocation models (the EUFASOM model developers suggest that its results are compatible with AROPAJ, a model developed in the French language that has similarities to CLUE).

While EUFASOM was developed with a European scale focus and therefore runs at national scale (optimising for the combinations of different products and other variables included in EUFASOM at a sub-national scale model across 36 countries would be extremely computationally expensive), many of the models that EUFASOM uses as input data do operate at a finer spatial scale and the model structure could potentially be used to produce outputs at a sub-national scale if run just for a single country.

Drivers (Full list provided in Appendix 8)

EUFASOM incorporates socio-economic, cropping and local decision/policy drivers and constraints directly. Agronomic factors such as soil type and climate are considered in the input models EPIC (crops) and OSKAR (forestry). Behavioural drivers are not considered.

EUFASOM does not currently represent sea level rise, but it uses projected land availability for agriculture/forestry in each five year period as an input (for example increased urbanisation may reduce land availability), so it should be possible to incorporate projections into the model. Climate is included as a driver in the EPIC crop model, and expected climate change effects are included in the OSKAR forestry model.

Inputs & Outputs (Full list provided in Appendix 8)

The model is data intensive. Precisely what data is required depends on what activities and policies are to be modelled.

EUFASOM optimises for 17 crop products, 8 forestry products, 5 bioenergy products and 10 livestock products, and considers 16 crops, 21 forest types, 6 types of livestock and 6 types of land management strategy as part of this. The input models EPIC and OSKAR, which model cropping and forestry and supply biomass yield data and environmental impact data to EUFASOM, require biophysical data such as soil type and climate.

EUFASOM itself requires data on the initial conditions of forests, cropping and ecological inventories (e.g. area, age cohort and species of forests), market data including current consumption, trade and price data, demographic projections, agricultural management costs and other data on policies. The user must also specify a discount rate (for perennial crops and forestry) and land use change limits.

Strengths and Assumptions

The main assumption made by EUFASOM is that the market is in competitive equilibrium. This assumption can be relaxed by optimising the model for alternative objectives, which gives the model additional flexibility. However, the model is probably not intended to be used for predictive purposes if being optimised for alternative objectives, but rather to scope technical (rather than economic) limits on policy goals such as emission reductions.

EUFASOM also assumes perfect foresight on the part of producers and does not take behavioural constraints such as risk aversion into account. It does include future discounting, but the level of future discounting and limits on the maximum amount of land use change are assumptions that must be specified by the user.

The main strength of the model is that it represents a large number of different crops, as well as including a detailed representation of forestry and perennial bioenergy crops, and different land management strategies, all of which are included in the optimisation function. Natural habitats such as wetlands can also be represented in the optimisation function (without a demand curve but with a subsidy). This detailed representation not only of agriculture but also of forestry and bioenergy crops goes beyond that found in many land use models.

Key References

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Schneider et al (2008) The European Forest and Agricultural Sector Optimization Model – EUFASOM. Paper prepared for annual conference of EAERE.

Land-Use-based Integrated Sustainability Assessment modelling platform (LUISA)

[LUMP]

Core purpose of the model

LUISA was developed to provide ex-ante evaluation of European and national policies that impact on land use. It has been applied to the whole of the European Union.

How the model calculates land use

Population (EUROPOP), economic (GEM-E3/ DG ECFIN), agricultural (CAPRI, see separate review for more details) and forestry models predict a minimum and maximum demand for each land-use type. The land uses for which the demand is modelled are: urban (residential and leisure facilities), industry, arable cropping (with separate classes for cereals, maize, root crops, energy crops and others), permanent cropping (including agro-forestry), pastureland and forests.

Land uses for which demand has increased replace land uses for which demand has decreased and unprotected 'passive' (non-demand-driven) land uses like scrubland, within the bounds of restrictions/constraints imposed by transition costs. Passive land uses included in the model are transitional woodland shrub, scrub (including natural grassland, moors and heathland), and abandoned urban, industrial and arable cropping areas. Some 'fixed' land uses are also included in the model: water bodies, wetlands, other nature, green urban areas and infrastructure such as road and rail networks. The area and location of fixed land use classes remains fixed throughout the model iterations, but they are important in providing inputs to impact models, for example for calculating access to nature-based recreation.

The overall suitability of each unit of land for each land-use is determined from data on current land-use, physical characteristics such as soil type and local policy restrictions. The allocation module (EUClueScanner100, part of the CLUE family of models - see separate review for more details) uses the overall suitability to assign the land-use demand to the most likely/most appropriate units of land, with urban land allocated first, followed by a bidding process between land uses. Passive land uses fill any remaining area that is not used by a fixed land use or a demand-driven land use.

Spatial & Temporal Scales

LUISA operates at a 100m pixel scale and produces annual predictions of land use up to 2050. It has been designed to operate at European, national or sub-national scale.

Drivers (Full list provided in Appendix 8)

LUISA incorporates most of the main categories of driver (agronomic, socio-economic, cropping constraints, local decision/policy contexts) directly. It does not include behavioural drivers such as social networks or risk aversion in land managers. Macro level policy drivers are included with the models that drive land-use demand and can be changed for different scenarios.

The effect of temperature and rainfall changes can be included as different scenarios within the CAPRI model that drives demand. Sea level rise is not currently included in the model, but could be added as a 'fixed' land use.

Inputs (Full list provided in Appendix 8) & Outputs

LUISA uses the following demand models as inputs to the allocation module:

- CAPRI for agricultural land demand, including food and bioenergy cropping and pastureland – see separate review of CAPRI for more details.
- Projected trends for forest areas based on an extrapolation from historical data (UNFCCC)
- Urban and industrial land-use demands – uses demographic projections (EUROPOP2010) and economic projections from the GEM-E3 model.

LUISA uses also biophysical factors and local policy restrictions as inputs to the allocation model:

- Soil and terrain – e.g. slope, elevation.
- Land accessibility
- Neighbourhood effects (proximity to different land uses as neighbours, and to population)
- Conversion matrix with transition costs

LUISA outputs predict land use at a 100m pixel scale, with annual predictions up to 2050. LUISA also includes an impact assessment module which quantifies indicators of a wide range of impacts, including indicators of food and bioenergy production, economic impacts (for example GDP and employment), housing, access to green space and amenities, transport, air quality, habitat quality, biodiversity, soil quality and water use.

Strengths and Assumptions

LUISA is a framework of well-established models, and benefits from the extensive development and testing-through-use that these models have undergone.

The framework captures land-use change drivers at multiple scales: the wider scale economic drivers that feed into the demand models, the national/regional response to policy and market demand,

and the local scale constraints that influence how a regional demand for land is distributed at a landscape scale.

LUISA actively models future urban, industrial and forestry land demands, and so captures competing demands rather than assuming that the amount of land available for agriculture will remain fixed.

The impact assessment module that is part of the LUISA framework quantifies indicators of a wide range of impacts, and documentation is available for each indicator included.

The model is based on the assumption of profit-maximising land managers who have perfect knowledge of the future and the properties of their land.

The weighting of different factors in determining the suitability for different crop types is based on historical data. Using these weights to predict future suitability assumes that there will not be a significant change in the relative importance of the different factors affecting suitability.

The allocation module does not feed back into any of the demand modules, so constraints from land suitability and conversion costs do not influence the balance of supply and demand, except to the extent that they are represented in the demand models (generally at a regional scale).

Key References

Lavalle *et al.* (2014) The Reference scenario in the LUISA platform – Updated configuration 2014: Towards a Common Baseline Scenario for EC Impact Assessment procedures. JRC Science and Policy Reports, JRC94069.

Lavalle *et al.* (2015) LUISA Dynamic Land Functions: Catalogue of Indicators – Release I: EU Reference Scenario 2013 LUISA Platform – Updated Configuration 2014. Luxembourg: Publications Office of the European Union, JRC99582.

IMAGE

Core purpose of the model

IMAGE was developed as a dynamic integrated assessment framework for the analysis of global change. Has been used to provide scenario studies for the Intergovernmental Panel on Climate Change, the United Nations Environment Program and Organisation for Economic Co-operation and Development.

How the model calculates land use

IMAGE is an integrated assessment framework based on a DPSIR approach. It is most suited to conducting large-scale (global) and long term (up to 2100) assessments of interactions between human development and the natural environment. It uses a large number of models to provide inputs to the land allocation model and drive land use allocation (covering economics, energy demand, food demand, timber demand and a climate model of atmospheric gases).

Future land use is calculated using either a regression-based suitability assessment (over 26 world regions) where land use change is not a focus of the assessment, or a more detailed model (derived from CLUE) known as CLUMondo. CLUMondo, a member of the CLUE family (described separately) includes data on landscape composition, heterogeneity and land use intensity and uses the concept of land systems (a combination of land cover, livestock density and agricultural intensity to provide 30 land system classes). Logistic regression between biophysical and socioeconomic indicators and land systems are used to determine spatially explicit suitability scores for each land use system. The suitability score is then combined with information on neighbourhood effects and rules on conversion resistance to predict changes in land use and the future land use pattern. A review of the IMAGE framework by its advisory board notes that the more detailed predictions from CLUMondo are not consistent with the regression approach and that the dynamics of CLUMondo are not yet trusted. Both models compute crop yields from potential yields and management intensities and then adjust agricultural area to ensure that production meets demand.

Within the IMAGE framework, there are a number of additional models that are linked to the CLUMondo outputs to provide assessment of impacts and responses to the land use predictions. The framework identifies socio-economic pathways and projects the implications for energy, land, water and other natural resources. Impacts in terms of emissions to air, water, soil, climatic change and depletion plus degradation of stocks are accounted for in future projections. The models operate on unique and identifiable grid cells to capture the influence of local conditions. Climate Policy is included through the use of the FAIR model to derive costs and losses for various activities. Air pollution and land use policies are integrated models that adjust demand and taxes or apply constraints to use of energy and land.

Spatial & Temporal Scales

Due to its emphasis on European and global scales, IMAGE produces output at a 10km by 10km spatial resolution. It produces annual land use allocations (share of land) which is fed into impact models and also back to the economic, climatic and energy demand models in order to modify the inputs to the land allocation for the next year.

Drivers (Full list provided in Appendix 8)

Due to its comprehensive suite of models, IMAGE includes the majority of significant economic, social and policy drivers that influence land use at global and European scale. In terms of agronomic drivers, it includes productivity, fertiliser user, manure use, crop yields as well as soil type, slope as major factors. Other agronomic factors can be included as part of the suitability scoring used within the CLUMondo land allocation model. For climate change drivers of land use, the IMAGE framework explicitly incorporates a model to predict temperature and precipitation changes based on outputs from the MAGICC climate model and a model that is able to predict coastal storm surges.

Inputs (Full list provided in Appendix 8) & Outputs

Due to the large suite of models included in IMAGE, a large number of inputs are required that cover energy data and statistics, agricultural statistics, emission factors, climate data (daily) and the location of dams and reservoirs. A large number of map inputs are also required to define the baseline land cover, the river network, soil types, area of land irrigated and protected areas.

As well as predicting land use, IMAGE also has a suite of impact models that can output: energy use, conversion and supply, agricultural production, emissions to air and surface waters, carbon stocks, greenhouse gases and air pollutants (including radiative forcing), changes in temperature and precipitation, sea level rise, water use, biodiversity loss, human development, water stress and flood risks.

Strengths and Assumptions

The major strength of the IMAGE framework is that it includes a large number of drivers through its linkage to a suite of models to provide inputs to the land use prediction component. A second significant strength of IMAGE is that it incorporates feedbacks between land-use, the impacts of the predicted land use and drivers to provide an integration of land and energy systems. In addition to the impact and response assessment models directly developed by the IMAGE team, IMAGE outputs can also be linked to a suite of supported additional models or external models for analysis of impacts beyond those covered within the IMAGE framework itself.

A weakness of the linkage of so many models is that there are multiple assumptions within each of the component models. For land use prediction, the model providing the economic inputs (MAGNET) requires several ad hoc assumptions to allocate prices to inputs and many elasticities are kept constant over time. In addition, deforestation is only driven by net expansion of agriculture rather than by other factors. Finally, although the model includes feedback to the models providing the inputs, there is only limited feedback of land use allocation model to the economic model (MAGNET) since the suitability of land only feeds back to agricultural production as regional averages.

The spatial scale at which IMAGE works is fine for the global and sub-global scales at which it is designed to operate, but would be unsuitable for a model at a national scale. As the land allocation model is part of the CLUE family of models then it has the capacity to work at a higher resolution (up to 100m by 100m) but the main issue would be having sufficient input data at those scales to use the IMAGE framework.

Key References

Stehfest *et al.* (2014) Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, The Hague: PBL Netherlands Environmental Assessment Agency.

Verburg *et al*. (2012) The representation of landscapes in global scale assessments of environmental change. Landscape Ecology 28, 1067-1080.

The Integrated Model (TIM)

Core purpose of the model

TIM was developed to identify optimal ways for implementation of multi-objective policy changes. Has been used to assess the scenarios in the National Ecosystem Assessment

How the model calculates land use

The Integrated Model (TIM) is a spatially explicit structural econometric model of agricultural land use and production with the inclusion of a limited number of impact assessment models.

For land allocation, TIM uses a farm profit function that accounts for the fact that not all land uses will be available to all farms to derive land use allocation, input applications, crop yields and livestock numbers. The relative influence of different biophysical and economic factors are determined by fitting the equations describing land share to historical data to estimate the parameters for each of the factors included in the equations. Once this has been done, predictions can be made under conditions where any one of the factors varies (e.g. increased temperature or rainfall).

For estimation of parameters and the prediction of land allocation, land is split into ten different categories. Of these, the allocation of the nine main categories of land use is estimated directly and the allocation of the remaining land category(representing marginal land uses) are not estimated directly, but as the difference between the total available agricultural area and the allocated area for the main land uses that are directly modelled. Profit maximisation per unit of land is used to determine the optimal land use shares for each land use type.

In the equations describing land share, TIM uses national scale input prices (e.g. fertiliser) but output prices are converted to a regional scale using the agricultural output regional price statistics from the UK Farm Business Survey. The crop and livestock prices incorporate subsidies and levies.

Spatial & Temporal Scales

TIM operates on a 2km by 2km grid scale and produces annual predictions of land use. It has been designed to operate at a national or sub-national scale.

Drivers (Full list provided in Appendix 8)

TIM incorporates most of the main categories of driver (Agronomic, Socio-Economic, Cropping constraints, local decision/policy contexts directly. It does not include drivers of farmer behaviour. Macro level policy drivers are included through the use of scenarios by determining the impact of the scenarios for the input and output prices used to calculate land allocation.

The effect of temperature and rainfall changes can be directly incorporated into the model through scenarios as both of these factors are used in the system of equations determining land use shares. Sea level rise is not directly incorporated in the model, but as the model has the ability to include protected areas, then it should be possible to incorporate land area lost to sea level rise within each 2km by 2km square as an area for which the share of land is fixed.

Inputs (Full list provided in Appendix 8) & Outputs

TIM uses both biophysical and economic factors as inputs to the model:

- Land area in different categories
- Average annual rainfall, temperature, degree days, evapotranspiration
- Elevation, land slope
- Costs and prices of inputs (e.g. fertiliser, oil) and outputs (crops, livestock)
- Demographic data
- Designated areas (e.g. Nitrate Vulnerable Zones, Environmentally Sensitive Areas)

The biophysical factors are derived from climatic and topographic data. As it is the precision of the June Agricultural Census data that determines the spatial resolution of the model, then it should be possible to run this model at higher spatial resolution where appropriate land use data is available.

The main output from TIM is a gridded assessment of land share with predictions of crop yields and livestock numbers, which can then be used to produce maps of land use or to drive other models of lands use. Within TIM, additional impact models are included for the assessment of greenhouse gas emissions (Cool Farm Tool), water quality, carbon storage, recreation and biodiversity. For several of these impact models, the use of a monetised market value or a monetised social value allows the model to predict land use that is optimised according to the market value or social value of the impacts (as has been done for forestry). Impacts that cannot be monetised (e.g. water quality) can be assessed but are currently unable to be used to determine an optimal land use strategy.

Strengths and Assumptions

TIM provides a coherent and unifying structural model that links land use decision, livestock numbers and crop yields, costs and profit. It provides a flexible approach that can be implemented on both aggregated data (national/regional) and at farm level. A significant strength of this model is that it is currently being actively developed by CSERGE, potentially allowing it to be adapted to meet the needs of CCC. The model has also been used for assessment of national scenarios as part of the National Ecosystem Assessment.

The model derives parameters for the drivers of land use allocation through regression analysis of historical data. Predicted land use is then determined by modification of the input data to allow comparison against the baseline predictions from the business as usual scenario. This means that the model assumes that the factors driving current land use will be the same in the future and that caution needs to be exercised when using scenarios that have values for driving factors that are outside the currently observed range of values.

TIM assumes that land managers are profit maximising and risk neutral, a limitation that is recognised by the model developers, as farmers can be significantly risk averse. The model is aimed at predicting the long term equilibrium situation and impacts, which means that it does not include feedbacks between the impacts and the land use. It can predict the optimal outcome for the land use, but does not provide any information about the pathway from current land use to the optimal land use.

TIM considers only land uses where the farm gross margin can be estimated. It does not include land tenure and does not account for introduction of new crops, technologies or farming practices.

In terms of the climatic component of the model, TIM does not consider extreme events only temperature and precipitation changes.

Key References

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CLIMSAVE

[SFARMOD, Silsoe Whole Farm Model, REGIS, IMPRESSION]

Core purpose of the model

CLIMSAVE was developed as an exploratory tool for the complex issues surrounding impacts, adaptation and vulnerability to climate change. Applied to Europe and Scotland.

How the model calculates land use

CLIMSAVE is an interactive web-based modelling framework that uses a suite of meta-models based around a set of core scenarios to drive the SFARMOD land allocation model (based on the Silsoe Whole Farm Model) and associated impact assessment models. SFARMOD uses linear programming based on economics and cropping constraints to determine the percentage of cropping by soil type and the profit associated with the cropping. The model uses three main types of information:

- Data from a farm database containing crop prices, yields, variable costs, labour and machinery costs and timeliness penalties (reflecting timing of sowing and harvesting on yield), labour and machinery requirements and workable hours to determine the profit achieved
- Soil, climate and crop yields from a crop yield model (ROIMPEL)
- Future economic data for the scenario

The optimum cropping percentage for each soil and climate type cell is then calculated and a profit threshold is the used to assign farms as intensive or extensive.

This output can then be compared with the baseline land use and the profit thresholds adjusted so that the predictions from the land allocation model and the baseline land use match. This allows a calibration of the land allocation model to account for the effects of disease pressure and adjust yields to modern levels.

When running scenarios, the first step is to remove any additional urban land from the allocable land and then the non-urban soils are allocated a land use based on profit and the percentage change in land use calculated.

Within CLIMSAVE, a meta-model based on the full SFARMOD has been produced by running SFARMOD for a large number of input scenarios and then producing a regression model for each crop that describes the percentage of agricultural area under a given crop based on a selected set of input parameters. This regression provides a rapid approximation of the full model. Within CLIMSAVE, the land allocation predicted by the SFARMOD meta-model is then used in a set of output models to assess impacts (e.g. biodiversity, water use).

Spatial & Temporal Scales

CLIMSAVE operates on 10 and 5 degree squares at a global/European level. It has been used at a national scale for Scotland on the 5 degree scale, which is approximately equivalent to a 5km by 5km resolution.

All predictions are for fixed time periods, either the baseline, 2020s or the 2050s.

Drivers (Full list provided in Appendix 8)

CLIMSAVE includes a large number of drivers and constraints both directly and as assumptions within the set of scenarios included within the framework. SFARMOD itself directly includes both economic (costs and prices), agronomic (soil, crop yield, climate) and social (labour) drivers as well as cropping constraints (sowing times, harvesting times, livestock density). The interactive nature of the CLIMSAVE framework means that the user is able to modify, within set ranges, the drivers used within the land allocation model and the scenarios to investigate the impacts on land use and the vulnerability/adaptability of areas to climate change. It should be noted that the vulnerability and adaptability assessments are indicative only and cannot be used for detailed assessment.

Inputs (Full list provided in Appendix 8) & Outputs

SFARMOD requires information on soil, climate, land cover, administrative boundaries, yield, crop price, variable costs, labour & machinery costs, timeliness penalties, labour & machinery requirements and workable hours in order to generate the land use. Additional information will also be needed for the suite of models that are used to assess impacts of changes in land use within the CLIMSAVE framework.

Strengths and Assumptions

The CLIMSAVE framework has a number of key strengths. The first being that it is interactive and incorporates multiple impacts along with a large number of key drivers. However, the use of meta-models means that the scenarios that CLIMSAVE can currently examine are limited to those developed for the web-based tool. However, the underlying models could be used directly with a set of scenarios to examine areas and driver changes not currently included within the web-based tool.

For the land allocation model, SFARMOD, the key strengths of this land allocation model is that it includes yields, derived from a crop yield model and cropping constraints within the linear programming system as well as multiple economic drivers. SFARMOD assumes that land use decisions are made on the basis of profit maximisation but within a set of constraints based on soil & climate and the assumption that the profit maximisation is done with imperfect knowledge. It does currently assume a limited number of land uses, but there could be scope for extending this to a wider range if suitable data was available. There is a hierarchy of land use assumed in assigning land use with intensive land at the top level, then extensive land, followed by forestry and then abandoned land at the bottom. This will inherently impose some restrictions on how land is allocated, but the hierarchy could be modified or changed to reflect different constraints or scenarios.

Key References

Audsley *et al*. (2006) What can scenario modelling tell us about future European scale agricultural land use, and what not? Environmental Science & Policy 9, 148-162.

Defra (2005) Development of a metamodel tool for regional integrated climate change management. Final report for Defra project CC0362.

Holman *et al*. (2005) A regional, multi-sectoral and integrated assessment of the impacts of climate and socio-economic change in the UK: Part II Results. Climatic Change 71, 43-73.

Holman *et al*. (2016). Cross-sectoral impacts of climate and socio-economic change in Scotland - implications for adaptation policy. Regional Environmental Change 16, 97-109

Harrison *et al*. (2015). Assessing cross-sectoral climate change impacts, vulnerability and adaptation: an introduction to the CLIMSAVE project. Climatic Change 128(3-4): 153-167 -1324-3

Various paper and reports at http://www.climsave.eu/climsave/outputs.html

Common Agricultural Policy Regionalised Impact analysis (CAPRI) [CAPRI-Spat]

Core purpose of the model

CAPRI was developed to assess the impact of the Common Agricultural Policy at European, national and sub-national scale.

How the model calculates land use

CAPRI is driven by a global market module that calculates product prices based on demographics, international trade policies and the balance of supply and demand. These prices feed into a regional supply module, which calculates the constrained profit-maximising land use at a NUTS-2 regional level and the resulting supply of each modelled product. The supply is then input back into the global market module, which updates demand and product prices. The new prices then feed back into the regional supply module. The model is run iteratively, updating supply, demand and prices on an annual basis.

The regional supply module uses a set of non-linear equations to represent the different drivers and constraints. For each crop/livestock product, these equations include product prices from the global market module, but at a regional level also include the level of inputs (e.g. fertiliser, pharmaceutical inputs for livestock) required to achieve different levels of crop/livestock yields, labour and capital availability and constraints imposed by policy quotas. For each region, the model uses these equations to calculate the balance of land use, cropping and livestock that will maximise producers' profit within the constraints of the region.

CAPRI-Spat disaggregates the predicted land use output from NUTS2-level projections to the level of 'homogenous response units' ('HSMU'), which are clusters of 1km grid cells with similar soil, slope and land cover falling within the same administrative boundaries. HSMUs vary in size depending on how heterogeneous the landscape is, and can be as small as 1 km^2, or almost as large as 10,000 km^2. Local regression equations between current land cover data (LUCAS and CORINE) and characteristics of the HMSU such as soil type and rainfall are used to predict the likely/expected share of each crop in that HSMU. These predicted proportions are then used to distribute the NUTS 2-level projections from the supply module between HSMUs, to achieve the crop share that is most consistent with the predicted proportions.

Spatial & Temporal Scales

CAPRI operates at a NUTS2 (sub-national) spatial scale, but in CAPRI-Spat the results can be disaggregated to the level of 'homogeneous response units', which vary in size from 1km^2 to almost 10,000km^2. Alternatively, the results can used as input to another allocation model such as CLUE to obtain results at a finer resolution. The model operates in annual time steps to 2050.

Drivers (Full list provided in Appendix 8)

CAPRI incorporates many of the main categories of driver (agronomic, socio-economic (including global policy impacts) and local decision/policy contexts) directly. It does not include behavioural drivers such as social networks or risk aversion in land managers, except for a specific adjustment taking account of risk aversion in sugar beet production, and does not appear to include cropping constraints such as rotation (regional yield response curves based on historical trends will however capture some of the benefits and effects of crop rotation).

Sea level rise does not appear to be included in the model at present, but regional land availability is a model input, so projections of sea level rise could be included by restricting regional land availability.

Regional yield response curves (the relationship between inputs and achieved yield) are calculated from data on historical trends. Scenario modelling of climate change effects has been carried out with the CAPRI model (Witzke et al, 2014), by modifying the crop yields and input requirements in the supply module. The effect of global productivity shocks from changes in productivity in non-European countries was represented in the market module, affecting global product supply and therefore prices.

Inputs & Outputs (Full list provided in Appendix 8)

CAPRI uses input data from EUROSTAT, FAOSTAT, OECD, FDN, GTAP, UNSTATS, the models GLOBIOM, AGLINK and PRIMES and trade policies from the WTO. The input data covers many different classes of drivers, including data about global markets, demographic projections, regional requirements and yield per hectare of crop/ per livestock unit, regional land availability for agriculture, regional labour and capital availability, current land cover, soil type, drainage, presence of stones, slope, elevation, rainfall and temperature in the growing season and the regional impact of policies and agricultural subsidies.

CAPRI outputs land use area shares at a NUTS2 sub-national scale; CAPRI-Spat outputs land use maps at the scale of 'homogeneous response units'. CAPRI also produces predictions of food and biofuel production, product prices, fertiliser and manure use, livestock numbers, farming intensity (crop and livestock density), crop diversity, greenhouse gas emissions and a High Nature Value Farmland indicator. These outputs can also be processed to predict other impacts.

Strengths and Assumptions

CAPRI is a well-established, widely used model that has benefited from many years of ongoing development and funding. Its results are used by European policy makers. It is based on long-term harmonised datasets, and significant resources have been dedicated to building a 'complete and consistent' database to meet model input requirements.

CAPRI represents both global and regional market effects, and has a very detailed representation of policy impacts. It includes both global policies, such as global trading rules, as well as policies that have a direct effect on local production such as CAP subsidies and sugar beet quotas. It also has a detailed representation of the cropping and livestock sectors.

CAPRI operates on the assumption of constrained profit maximisation at a regional scale. The model does account for the profit maximisation is constrained by the fact that land managers have imperfect knowledge of future yields. In the baseline scenario, yield response curves are based on historical trends.

The model is controlled by a network of researchers (currently centred in Bonn), and use of the model would require collaboration with or entry into this network.

Key References

Britz et al (2014) CAPRI model documentation 2014.

Witzke et al (2014) CAPRI Long-term Climate Change Scenario Analysis: The AgMIP Approach. JRC Technical Reports, JRC85872.

Conversion of Land Use and its Effects (CLUE)

[CLUE, CLUE-CR, CLUE-S, CLUMondo, EUCLUEScanner100, Dyna-CLUE]

Core purpose of the model

CLUE was developed to simulate land use change using empirically quantified relations between land use and its driving factors. It has been applied to a wide range of case studies and is the land allocation model underpinning the LUISA and IMAGE frameworks.

How the model calculates land use

CLUE is a land allocation only model that translates an input that determines the demand for different land uses into an allocation of the land uses and the changes at different locations. The demand can be driven by scenarios or models that incorporate a wide range of drivers.

Allocation of land is based on conversion elasticities and transition sequences that define what changes can occur. The elasticities are used to ensure that radical land changes are less likely to take place and the transition sequences are used to place time constraints on the conversion of land (e.g. arable land can only be cultivated for a maximum of 3 years in a row to prevent soil deterioration before its use has to be changed).

A preference or suitability score is determined based on a set of factors (determinants of land use change e.g. soil type, accessibility, population pressure, etc.) defined by the user of the model. The contribution of the different factors to the suitability score is determined by an approach selected by the user, but in most instances where CLUE has been used it has usually been determined through an analysis of historical land use data. However, there is the potential for the contribution of the different factors to the suitability score to be determined by expert opinion or through the use of biophysical mapping and models of crop growth.

The suitability score is used in conjunction with the conversion elasticities and data on the competitive advantage of different land use types to determine the probability that a land use occupies a location. Initially, the most suitable land use is assigned to each location. This is the followed by an iterative procedure of comparison of supply with demand and adjustment of over supply or undersupply until a balance between supply and demand occurs.

The CLUE land allocation model is a central component to a number of the integrated frameworks such as LUISA and IMAGE (described separately).

Spatial & Temporal Scales

CLUE operates on a 1km by 1km grid, but the version used by the European Joint Research Centre (EUCLUEScanner100) operates on a 100m by 100m resolution. CLUE predicts annual land use and the prediction from one year is used as the base land allocation for the next year. There is also potential for the predicted land allocation to be fed back into models determining the land demand (such as GTAP and LEITAP) as has been done in the IMAGE framework (described separately).

CLUE has been used at both European and national scales.

Drivers (Full list provided in Appendix 8)

As a pure land allocation model, CLUE does not directly or explicitly account for any socio-economic, climate change or policy drivers as these would form part of the demand scenario or model that is used to provide the land use demand input to the model.

Agronomic drivers and cropping constraints are included through the use of the suitability scores and are generally user-defined. Where CLUE is being used as part of an integrated framework, then climate, topography, soil types, slope, accessibility, human population, pest pressure and disease pressure have all been included within the factors accounted for by the suitability score. Cropping constraints are directly included through the use of the conversion elasticities and transition sequences for land use which define how the land is able to change and over what time scales.

Behavioural drivers of land use decision are not explicitly represented within CLUE.

Inputs (Full list provided in Appendix 8) & Outputs

The primary inputs to CLUE are gridded data on land demand, an initial land use map, data on conversion elasticities, transition sequences and the data required for the factors included in the suitability scoring (e.g. soil maps, climate data). In addition, maps of protected areas can be used to restrict the area of land that can be included within the allocation procedure.

The output that CLUE produces is the share of land uses for each grid cell based on the outcomes of the allocation module.

Strengths and Assumptions

The approach used by CLUE is very flexible as the methods used to define suitability, transition sequences and conversion elasticities are not pre-defined but determined as part of the process of building the model for a specific region or area by the model users. It also has the ability to be linked with multiple external models to provide the demand inputs and assess impacts of predicted land use outputs (as done in IMAGE and LUISA).

CLUE itself does not have many inherent assumptions as most of the assumptions will be made by the user when determining the methods used to create the suitability, transition sequences and conversion elasticities. However it does assume a top-down approach to assigning land use, in that the most suitable land uses are always assigned first and then adjusted according to demand and supply. This approach effectively replicates top-down land use planning and assumes that land will always be used for the best possible application and would not necessarily allow for less profitable land uses to be assigned to grid cells as part of crop rotations or for ecological reasons. However, it should be possible to relax this assumption through the use of spatial restrictions on land use, which form part of the model inputs (e.g. setting a restriction that a percentage of the land in a grid cell must be fallow).

Key References

Britz *et al*. (2011) Modelling of land cover and agricultural change in Europe: Combining the CLUE and CAPRI-Spat approaches. Agriculture, Ecosystems and Environment 142, 40-50.

Sun *et al*. (2012) Scenarios of changes in the spatial pattern of land use in China. Procedia Environmental Sciences 13, 590-597.

Veldkamp & Fresco (1996) CLUE: a conceptual model to study the Conversion of Land Use and its Effects. Ecological Modelling 85, 253-270.

Veldkamp & Fresco (1996) CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecological Modelling 91, 231-248.

Verburg *et al*. (1999) A spatial explicit allocation procedure for modelling the patterns of land use change based upon actual land use. Ecological Modelling 116, 45-61.

PCRaster Land Use Change (PLUC)

Core purpose of the model

PLUC was developed to assess future developments in land availability for bioenergy crops. It has been applied to case studies in Mozambique and Brazil.

How the model calculates land use

PLUC is a pure land allocation model that allocates land use based on demand data using a set of weighted suitability factors that represent key constraints (biophysical, political, ecological or economic) and the influence of neighbouring cells within a defined neighbourhood (to reflect the fact that it may be advantageous to farmers if their neighbours grow a similar crop).

Land uses, defined in broad categories, are allocated using a fixed order, defined by the user according to the area of interest, but usually based on the economic importance and labour requirements of the land use. For an application in Mozambique, the order was: forest, cropland, mosaic cropland-pasture, mosaic cropland-grassland and pasture. The first land use in the sequence is allocated to the most suitable places until demand is met by the supply (where supply is a function of area, productivity (yield) and management level). Once demand is met, then allocation moves to the next land use in the sequence and this process continues until all land uses are allocated to meet demand. This process occurs in each grid cell so that the dominant land use within the cell is determined. PLUC can also include land conversion elasticities as part of the suitability factors, to constrain cropping changes, as was done when the model was used in Ukraine.

Spatial & Temporal Scales

PLUC uses a 1km by 1km grid as it spatial scale and predicts land use on an annual basis. A feedback loop is incorporated by using the land use prediction from one year as the base map for the next year.
PLUC has been used to predict land use a national scale in developing countries and Europe.

Drivers (Full list provided in Appendix 8)

As a pure land allocation model, PLUC does not directly or explicitly account for any socio-economic, climate change or policy drivers as these would form part of the demand scenario or model that is used to provide the land use demand input to the model.

Agronomic drivers, cropping constraints and socio-economic drivers are included through the use of the suitability scores and are generally user-defined. In the countries where PLUC has been used to date (Brazil, Mozambique and Ukraine) climate, soil type, yield, transport links, land rental prices, unemployment, have all been included within the factors accounted for by the suitability score.

Behavioural drivers of land use decision are not explicitly represented within PLUC.

Inputs (Full list provided in Appendix 8) & Outputs

The key inputs for PLUC are time series of demand and productivity development, dynamic land use classes, suitability factors per land use class, the initial land use map that designates the initial configuration of these land use classes and several maps of suitability factors (e.g. population density and distance to road).

The output is a map of the land use within each of these classes, with a dominant land use for each 1km square on the map.

Strengths and Assumptions

PLUC is very flexible as models are not pre-defined but determined as part of the process of building the model for a specific region or area by the model user. PLUC has the potential to link with multiple external models to provide the demand inputs and assess impacts of predicted land use outputs. For example, PLUC was linked with an economic model MAGNET (based on GTAP & LEITAP) to provide the demand inputs when the model was run for a Brazilian case study to examine the impact of increasing biofuel production.

PLUC itself does not have many inherent assumptions as most of the assumptions will be made by the user when determining the methods used to create the suitability of areas for particular land uses. As in other land allocation models, such as CLUE (described separately), the location characteristics defining the suitability for land use can be based on a regression approach using historical data. However, if data for determining suitability is not available, the suitability factors can be derived from proxies based on expert opinion.

The main assumption in PLUC is a fixed order of assignment of land use classes based on the economic importance and labour requirements. This represents a bottom-up approach to land allocation, representing the choices made by farmers (hence a crude incorporation of behavioural drivers) and is most appropriate for countries where land use is not heavily influenced by high level top-down planning decisions but at a more local level.

Key References

Hilst et al. (2012) Spatiotemporal land use modelling to assess land availability for energy crops – illustrated for Mozambique. Global Change Biology Bioenergy 4, 859-874.

Hilst et al. (2014) Integrated spatiotemporal analysis bioenergy production potential agricultural land use, and related GHG balances in Ukraine. Biofuels, Bioproducts and Biorefining 8, 391-411.

Verstegen et al. (2015) What can and can't we say about indirect land-use change in Brazil using an integrated economic – land-use change model? Global Change Biology Bioenergy doi/10.1111/gcbb.12270

Verstegen et al. (2016) Detecting systemic change in a land use system by Bayesian data assimilation. Environmental Modelling & Software 75, 424-438.

Appendix 8: List of inputs, outputs, drivers & impact assessments for shortlisted models

This document provides additional information to support the review of the shortlisted models provided in Chapter 5 and Appendix 7.

For each model we provide a list of the input data used to run the model and the drivers that are included either in the land allocation model itself or the models used to provide input data for the land allocation model.

The main output from the land allocation components is a spatial pattern of land use (either as a share of a defined area or as a dominant land use per unit area). Where this land allocation output has been used to assess impacts, then we provide a list of the impacts assessed and, where appropriate, the name of the model used to make the assessment.

Note that for some models, where implementations of the model are produced for specific instances, the input data and drivers may be dependent upon the model implementation, its aims and the geographical area to which the model was applied. Where there are multiple version of the model we have provided the input data and drivers that are common to all implementations of the model, as we consider these to be the core data inputs and drivers used by the model.

Framework for the Evaluation and Assessment of Regional Land Use Scenarios (FEARLUS)

Inputs

These are dependent upon the drivers required by the user for the system of interest. In the published uses of the model, the common inputs are:

- Land cover map (polygon or raster based)
- Biophysical data (soil type, evapotranspiration, etc.)
- Crop yields
- Economic information (crop prices, labour costs, machinery costs, etc.)
- Climate/weather data (temperature, precipitation)

Drivers / Influencing factors

- *Agronomic & cropping constraints*
  The drivers included are dependent upon the needs specified by the user, but can include:
    - Crop yield
    - Soil type
    - Temperature
    - Precipitation
- *Economic*
    - Costs
    - Prices
- *Behavioural*
  FEARLUS assumes land managers are satisficing rather than profit maximising.
- *Decision constraints*
    - Protected areas
    - Imitation of neighbour behaviour
    - Social approval
    - Rewards or fines used to represent policy factors

- *Non-agricultural land uses*
  These are not explicitly defined, but can be included through non-managed land uses or by including agents to manage non-agricultural land.

Impact Assessment

- Water quality (FEARLUS-W)
- Biodiversity (FEARLUS-SPOMM).

Mathematical Programming-based Multi Agent Systems (MP-MAS)

Inputs

- Farmer population survey data (to define agent types)
- Market price projections
- Land cover/land use maps
- Biophysical and crop data (dependent upon user requirements/needs)

Drivers

- *Agronomic & cropping constraints*
  - Soil (erosion, nutrients and water availability) as inputs to crop yield models
  - Climate/weather (temperature, rainfall, evapotranspiration) as inputs to crop yield models
  - Livestock (Pasture area, feed and outputs per head)
  - Temperature
  - Precipitation
- *Economic*
  - Market costs and prices
  - Labour supply
  - Farm managers' cash reserves
- *Behavioural*
  - Farmer innovation strategy
  - Age
  - Management strategy
- *Decision constraints*
  - Financial rewards or penalties to represent policies
  - Market costs & prices scenarios
- *Non-agricultural land uses*
  Not included in the model directly

Impacts Assessed

- Soil quality
- Water availability
- Peak water flows
- Speed of technology diffusion through land manager population
- Average farm profits
- Food production
- Land ownership patterns

Valbuena *et al.* (2010)

Inputs

- Land cover/ land use maps
- Land manager attitudes (survey data)
- Farm typology
- Factors influencing land manager decisions (determined by user requirements) (e.g. soil type, temperature, precipitation, distance to transport, policy rewards/fines, etc.)

Drivers

- *Agronomic & cropping constraints*
    - Soil type
    - Field size
    - Density of linear landscape elements
- *Economic*
    - Farm type (profitability)
- *Behavioural*
    - Farm Type (farmer age)
- *Decision constraints*
    - IPCC economic & policy scenarios (agri-environment)
- *Non-agricultural land uses*
    - Urban
    - Water bodies
    - Protected areas

Impact Assessment

- Landscape ownership patterns
- Density of semi-natural areas
- Density of linear landscape elements

The European Forest and Agricultural Sector Optimization Model (EUFASOM)

Inputs

- EUROSTAT data (tourism, economics, agriculture, irrigation)
- FAO data (water withdrawals, livestock density
- Biophysical data (soil type, slope, temperature, rainfall, management regimes, yields, etc.) to drive EPIC crop model and OSKAR/G4M forestry models
- Initial land allocation map
- Projected energy consumption (POLES model)
- Within framework EC4MACS, uses CAPRI agricultural projections

Drivers

- *Agronomic & cropping constraints*
    - Soil type & characteristics
    - Climate/weather
    - Crop management regimes (e.g. fertiliser use, manure use)
    - Altitude
    - Slope

    - Yield
- *Economic*
    - Production costs
    - Product prices
- *Behavioural*
  Not included
- *Decision constraints*
    - Policy subsidies and costs
    - Emission control (via economic adjustments)
- *Non-agricultural land uses*
    - Forestry
    - Bioenergy crops

Impact Assessment

- Air quality (human health and ecosystem impacts)
- Greenhouse gas emissions
- Food, bioenergy and forestry production

Land-Use-based Integrated Sustainability Assessment modelling platform (LUISA)

Inputs

- CORINE land cover map
- Forest fires database
- University of Maryland forest layer
- Soil characteristics (European Soils Database)
- Land demand projections based on GDP for urban, UNFCC for forestry and CAPRI for agriculture
- Population projections (EUROPOP2010)
- Economic projections from GEM-E3 & DG ECFIN models
- Climate data (JRC-Ispra)
- AirBase database of air quality (for regression models predicting air quality)
- Leaf Area Index
- European Soil Sealing Map

Drivers

- *Agronomic & cropping constraints*
    - Soil characteristics
    - Climate/weather
    - Crop management regimes (e.g. fertiliser use, manure use)
    - Altitude
    - Slope
    - Yield
    - Cropping conversion constraints
- *Economic*
    - Industrial and urban demand
    - Agricultural demand
    - Economic factors included in CAPRI (see separate description)

- *Behavioural*
  Not included
- *Decision constraints*
  - Renewable Energy Directive
  - Common Agricultural Policy subsidies and cross compliance
  - 2020 Biodiversity strategy
  - TEN-T Transport network
- *Non-agricultural land uses*
  - Urban
  - Industrial
  - Forestry
  - Bioenergy crops
  - Protected areas

Impact Assessment

- Food production
- Biomass production
- Water use
- Urban flood risk
- Soil erosion (USLE/RUSLE equation)
- Soil carbon stocks (IPCC methodology (Tier 1))
- Greenhouse gas emissions (IPCC Methodology (Tier 1))
- Air quality (Regression models)
- Access to nature-based recreation
- Gross Domestic Product (GEM-E3)
- Population and urban/industry density
- Transport network efficiency
- Green infrastructure
- Habitat quality & landscape fragmentation (Species distribution models)

IMAGE

Inputs

- IEA energy data
- National energy statistics
- GTAP 8 database
- FAO Forest Resource Assessment data
- HYDE land use map (1970-2005)
- Protected area maps
- Accessibility maps
- Irrigated area maps
- FAO irrigation projections
- FAOSTAT for crops and livestock
- EDGAR database of emission factors
- FAO harmonised world soil map
- Digital river network DDM30
- Location of dams and reservoirs

- Radiative forcing coefficients (IPCC)
- Biome and eco-regions
- Regional land cover maps (for GLOBIO)
- Nitrogen critical load (for GLOBIO)
- Species area relationships (for GLOBIO)
- Coastal storm surges (for GLOFRIS)
- Daily Climate data - EU-watch database (for GLOFRIS)
- HydroSHEDS elevation model (for GLOFRIS)
- Terrain slope
- Soil profiles (S-world)

Drivers

- *Agronomic & cropping constraints*
    - Soil characteristics
    - Climate/weather
    - Crop management regimes (e.g. fertiliser use, manure use)
    - Altitude
    - Slope
    - Yield
    - Fertiliser and manure usage efficiency
    - Irrigation and irrigation efficiency
    - Livestock productivity and feed conversion ratios
- *Economic*
    - Population size
    - Urban population fraction
    - Household consumption (expenditure)
    - Capital supply
    - Labour supply
    - GDP per capita
    - GINI coefficient (income distribution)
    - Energy intensity
    - Technology uptake
    - Lifestyle (balance between economic activities and energy demand)
    - Energy resources
    - Energy prices
    - Electricity production
    - Urban area
    - Carbon storage price
    - Costs and losses due to mitigation, adaptation, etc. (from FAIR model)
- *Behavioural*

  Not included
- *Decision constraints*
    - National climate and energy policies
    - Trade restrictions
    - Agricultural trade policy
    - Taxes
    - Air pollution policy
    - Biofuel policy

    - Climate targets
    - Technological change
    - Livestock production mix (intensive versus extensive)
    - Non-price preferences determining market shares
- *Non-agricultural land uses*
    - Urban
    - Industrial
    - Forestry
    - Bioenergy crops
    - Protected areas

Impact Assessment

- Energy use conversion and supply (TIMER)
- Agricultural production (MAGNET)
- Land cover & land use (CLUMondo)
- Nutrient cycles in natural and agricultural systems
- Emissions to air and surface waters (IPCC methodology)
- Carbon stocks in biomass pools, soils, atmosphere and oceans (LPJmL & MAGICC 6.0)
- Atmospheric emissions of greenhouse gases and air pollutants (MAGICC 6.0)
- Concentration of greenhouse gases in the atmosphere and radiative forcing (MAGICC 6.0)
- Changes in temperature and precipitation
- Sea level rise
- Water use for irrigation (LPJmL)
- Biodiversity loss (GLOBIO)
- Human development (GISMO)
- Water stress (Empirical regression with GDP, urbanisation rate and population density)
- Flood risks (GLOFRIS)

The Integrated Model (TIM)

Inputs

- June Agricultural Census (EDINA version at 2km x 2km)
- LANDIS (average annual rainfall, machinery working days, mean potential evapotranspiration, median duration of field capacity, total degree days in the growing season (April to September))
- OS Digital Terrain Model (mean elevation, land slopes higher than 6 degrees)
- Economic information - costs and prices (Defra statistics & British Petroleum Statistical Review of World Energy)
- Protected area Maps

Drivers

- *Agronomic & cropping constraints*
    - Rainfall
    - Evapotranspiration
    - Field capacity during growing season
    - Degree days in growing season
    - Land Slope
- *Economic*
    - Crop prices

    - Livestock prices
    - Fertiliser prices
    - Oil price
    - Milk price
- *Behavioural*

  Not included
- *Decision constraints*
    - Nitrate Vulnerable Zones
    - Protected areas
    - Climate change (via scenarios of temperature or rainfall change)
    - Government policy (via economic change scenarios)
- *Non-agricultural land uses*
    - Forestry
    - All other non-agricultural land uses considered en masse as other land use

Impact Assessment

- Agricultural food production
- Greenhouse gas emissions (Cool Farm Tool)
- Water quality
- Carbon storage
- Open-access recreation
- Urban greenspace amenity
- Biodiversity.

CLIMSAVE

Inputs

- Soil characteristics (texture, water regime, stoniness)
- Climate data (temperature, rainfall)
- Land cover at 1km square resolution
- Administrative boundaries
- Crop yields
- Crop prices
- Variable costs of agricultural production
- Labour & machinery cost
- Timeliness penalties (for agricultural production base don sowing and harvesting dates),
- Labour & machinery requirements
- Workable hours.

Drivers

- *Agronomic & cropping constraints*
    - Soil properties (texture, water regime, stoniness)
    - Rainfall
    - Temperature
    - Crop yields (from regression models)
    - Livestock density
    - Sowing dates
    - Harvesting dates
    - Latitude

- Irrigation
- *Economic*
  - Crop prices
  - Labour & machinery prices
  - Fertiliser prices
  - Gross margins
  - Irrigation costs
  - Labour requirements & workable hours
- *Behavioural*
  Not included
- *Decision constraints*
  - Policy scenarios used to set economic costs and prices
- *Non-agricultural land uses*
  - Forestry (via forestry model)
  - Flooded land

Impact Assessment

- Timber production and ecosystem services (metaGOTILWA, metaLPJ-GUESS)
- Crop production (metaSFARMOD)
- Water availability (WGMM)
- Flooding & flood protection (CFFlood)
- Biodiversity (SPECIES, metaLPJ-GUESS)
- Recreation (SnowCover)

Common Agricultural Policy Regionalised Impact Model (CAPRI)

Inputs

- EUROSTAT agricultural statistics (crop production, herd size, land use, slaughter, imports & exports) and agricultural economics data
- FAOSTAT agricultural statistics (crop production, herd size, land use, slaughter, imports & exports) & trade balances
- Biofuel production and consumption data (PRIMES model, European Biodiesel Board, ePURE)
- EUROSTAT Energy prices, demand and consumption
- Fertiliser Use statistics
- Labour information (Farm Accounting Data Network)
- EUROSTAT Farm Structure Survey (Farmer Age)
- Trade tariff rates and quotas (OECD AGLINK model)
- Gross Domestic Product and expenditure data (UNSTATS database)
- Medium term outlooks for quantity and price developments (AGLINK – COSIMO model)
- Long run projections of market balances in world regions (GLOBIOM model)

Drivers

- *Agronomic & cropping constraints*
  - Soil properties (texture, water regime, stoniness)
  - Rainfall
  - Temperature
  - Crop yields

- Livestock density
- Slope
- Altitude

- *Economic*
    - Crop prices
    - Labour & machinery prices
    - Fertiliser prices
    - Irrigation costs
    - Labour availability
    - Capital availability
- *Behavioural*

  Not included
- *Decision constraints*
    - Common Agricultural Policy subsidies
    - Single Payment Scheme subsidies
    - Trade policies (via market prices for commodities)
- *Non-agricultural land uses*

  Not actively modelled

Impact Assessment

- Greenhouse gas emissions from agriculture (linkage to DNDC)
- Agricultural fertiliser usage
- Farming intensity including livestock and crop density
- High Nature Value Farmland indicator
- Crop diversity.

Conversion of Land Use and its Effects (CLUE)

Inputs

- Spatial policy restriction maps (e.g. nature reserves)
- Land use transition matrix (possibility of conversion, how long land use should remain the same before can be converted again, maximum time it can remain the same)
- Land use transition sequences
- Initial land cover map
- Demand for commodities (from external models e.g. LEITAP/GTAP)
- Soil maps

Drivers

- *Agronomic & cropping constraints*
    - Soil properties (texture, water regime, stoniness)
    - Rainfall
    - Temperature
    - Pests
    - Diseases
    - Slope
    - Other user defined factors according to geographical area of interest
- *Economic*
    - Scenarios defining suitability factors and transition sequences

- *Behavioural*
  Not included
- *Decision constraints*
    - Scenarios defining suitability factors and transition sequences
- *Non-agricultural land uses*
    - Urban
    - Forestry

Impact Assessment

No impacts are assessed using CLUE.

PLUC

Inputs

- Time series of demand (LEITAP, GTAP, MAGNET models)
- Protected Areas
- Suitability factors (Land use, land rental prices, population density, sloping land, Livestock numbers/density, temperature, rainfall, soil, yield information)

Drivers

- *Agronomic & cropping constraints*
    - Soil properties (texture, water regime, stoniness)
    - Rainfall
    - Temperature
    - Slope
    - Other user defined factors according to geographical area of interest
- *Economic*
    - Scenarios defining suitability factors
- *Behavioural*
  Not included
- *Decision constraints*
    - Scenarios defining suitability factors
- *Non-agricultural land uses*
  User defines land use types within model set-up so any non-agricultural land use can theoretically be included

Impact Assessment

- Greenhouse gases (IPCC methodology)
- Soil Carbon (IPCC methodology)

Appendix 9: CCC UK land-use workshop agenda and delegates

Title: What future uses of UK land could help reach net zero emissions in the agriculture and LULUCF sectors post-2050, while ensuring resilience to the impacts of climate change?

Venue: Grantham Institute, Imperial College, London

Date: 26 April 2016

Agenda:

10.30-10.45	**Introduction**	• Welcome and purpose for the day • Roundtable introductions	Chair (Graham Wynne, CCC)
10-45-11.15	**Context for the land-use project**	• Why land use is important for CCC adaptation and mitigation. • Overview of current and projected GHG emissions from UK land (Agriculture & LULUCF) • Overview of CCC's advice on Agriculture/LULUCF and bioenergy in Fifth Carbon Budget • Consideration of projected impacts of climate change on UK land-use	CCC
11.15-11.20	**Scenarios & pathways**	• Introduction to potential pathways for reaching net zero emissions from agriculture & LULUCF	CCC
11.20-12.00 12.00- 12.30	**Break out session one**	• Identifying potential pathways to net zero emissions • Feedback from groups	Joe Morris
12.30 13.15	**Lunch**		
13.15-13.30	**Modelling requirements**	• Brief introduction to model approaches , and key modelling requirements	Dave Skirvin (ADAS)
13.30-14.00 14.00-14.15	**Break-out session two**	• What are the key determinants for modelling selected net zero emission pathways? • Feedback from groups	Dave Skirvin (ADAS)
14.15-14.30	**Round up and close**	• Round up of workshop • Next steps	Chair

Workshop delegates:

Delegate	Organisation
Jo House	Bristol University
Andrew Balmford	Cambridge University
Peter Coleman	DECC
Mandar Trivedi	DECC
Julian Harlow	Defra
Calum Brown	Edinburgh University
Eric Audsley	Ex-Cranfield
Ian Bateman	Exeter University
Amy Binner	Exeter University
Mike Render	Forestry Commission
Clare Oxborrow	Friends of the Earth
Chris Gordon-Smith	Friends of the Earth
David Mottershead	IEEP
Jeremy Woods	Imperial College
Mark Kibblewhite	Inst. Of Agricultural Engineers
Tim Benton	Leeds University
John Kay	National Trust
Mike Moorcroft	Natural England
Jonathan Scurlock	NFU
Olly Watts	RSPB
Lucy Bjork	RSPB
Sally Thomas	Scottish Government
Peter Melchett	Soil Association

Organisers and facilitators:

Name	Organisation
Graham Wynne	CCC
Corinne Le Quere	CCC
Adrian Gault	CCC
Ewa Kmietowicz	CCC
David Style	CCC
Indra Thillainathan	CCC
Dave Thompson	CCC
Joe Morris	CCC Expert Champion (Cranfield)
John Elliott	ADAS UK Ltd
Dave Skirvin	ADAS UK Ltd
Charles Ffoulkes	ADAS UK Ltd