CCC Land Use Modelling Project

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Table of Contents

List of Tables

List of Figures

Executive Summary

Purpose of project in Phase 1

Land excluding built-up areas (which includes agricultural land, woodlands and semi-natural habitats) is an important and finite resource. It provides a wide range of sometimes competing goods and services such as food, water, wildlife habitats, carbon storage, flood attenuation and green spaces for recreational activities. How this land is used in the future will have a significant influence on reducing GHGs emissions and preparing for the impacts of climate change. Therefore, the way that this land is managed and used is highly relevant to the advice and analysis of the Committee on Climate Change (CCC) on reducing GHGs (mitigation) and preparing for climate change (adaptation).

This report presents the findings of Phase 1 of the "Land Use Modelling project" funded by the CCC. The work aims to identify and quantify the potential impacts of plausible future land use pathways in a way that allows the pathways to:

- Maximise reductions in emissions and increase sequestration in the UK agriculture and LULUCF sectors, consistent with reaching net negative emissions in the second half of the century.
- Take account of the need to prepare for the impacts of climate change and characterise the resilience of a particular scenario to the effects of climate warming projections under a 2°C and 4°C world.
- Take account of other land uses that provide economic, environmental and social benefits to the UK.
- Take account of other constraints on land use, e.g. changes in climate and bio-physical properties of land over time.

There is a recognition that to take these factors into consideration within a modelling approach there is a need for an integrated, cross-sectoral modelling framework. The ClimSAVE/IMPRESSIONS Integrated Assessment Platform 2 (IAP2), developed at the European scale, is an integrated model that can be customised with user-generated scenarios to explore, in tandem, socio-economic and climatic impacts on land use and associated adaptation indicators. By linking the IAP2's land use with the Marginal Abatement Cost Curve (MACC) model used to underpin the UK's Fifth Carbon Budget, a linked-system also has the potential to assess mitigation-related impacts.

Phase 1 of the Land Use project aims to assess the extent to which the proposed IAP2-MACC linked system has the potential to model plausible "what if" scenarios of the future to provide insights that can be used to underpin the CCC's guidance.

Scenarios constructed

Within Phase 1 two scenarios were selected to demonstrate the potential of the IAP2-MACC modelling and the outputs it could produce:

1. A **mitigation *scenario*** based on the CCC's fifth carbon budget central abatement scenario in agriculture and forestry

2. A hypothetical adaptation ***scenario***, with an objective of maximising biodiversity levels under climate change.[1]

These two scenarios were modelled under two different climates in 2050: one equating to 1.5°C average European warming (the IPCC's RCP 2.6) and one equating to around 2.0°C (the IPCC's RCP4.5). Combining these with the socio-economic scenarios led to four combined climate and socio-economic scenarios in total. For comparison and validation three baseline scenarios were also run: one for contemporary baseline using contemporary socio-economic settings and two future baseline scenarios using contemporary socio-economic settings and the two 2050s RCP climates. The future baselines enable changes that result from shifting climate to be distinguished from those that result from changing socio-economics.

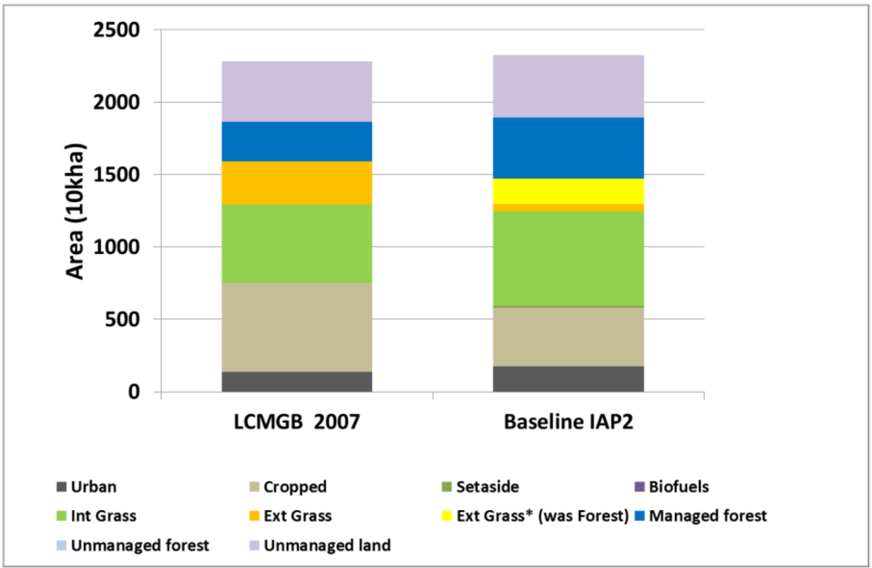
How well does the IAP2 approximate contemporary land use?

To assess the IAP2's projection of baseline land use for 2010 the model's output was compared with Land Cover Map of Great Britain 2007 (LCMGB).

The IAP2 model projects believable spatial patterns in urban land, agriculture and forestry. There are some gaps in the arable distribution in Scotland, but these are corrected for in a scheduled update.

In terms of total area covered, the split between intensive agricultural land (arable/intensive grassland) and extensive grassland/forestry was similar. However, forest cover and intensive grassland were over-estimated (+60% and +20% relative to LCMGB) and extensive grassland and arable land were under-estimated (-30% and -20% relative to LCMGB).

A post-processing module was developed to correct the forest cover to make it closer to reduce its overestimation and increase the representation of extensive grassland.



[1] It should be stressed again that this adaptation scenario was chosen not because it is a likely representation of the future, but solely to test how the model operates when prioritising resilience in one sector (i.e. the model could easily be varied to prioritise agricultural production, water availability or something else).

Figure ES1: Overview of land use differences between LCMGB and IAP2

What are the reasons for these differences?

The IAP2 is a model designed to explore far-future scenarios (2050s and 2080s) under which climatic and socio-economic changes may lead to marginal lands becoming more profitable and profitable lands less so. As such, the modelling needs to be based on core biophysical principles such as soil and climate, which provide the key constraints on land use potential. It then needs to decide, within the areas that are capable of delivering needed commodities, which areas get prioritised over others given the socio-cultural settings of the future world. The IAP2 model uses the *potential profitability* of different land uses as the means to determining allocation. In doing so it takes into consideration the demand for commodities determined as a factor of socio-economic inputs (e.g. population, diet preference); supply as constrained by soil and climate-related conditions (e.g. yield, water availability, relative profitability of other sectors), and socio-economic changes (e.g. changes in technology, irrigation etc.). The resultant maps from the IAP2 model are therefore profit-optimised maps of potential land use.

These maps differ from the LCMGB as, in reality, land use is not driven solely by profitability, but by a number of factors that include a range of socio-political and economic factors (e.g. tradition, inertia, subsidy, policy constraint etc.). Furthermore, the difference is exacerbated by the optimisation of profit at a European scale. The resulting 30% decrease in cropland and 20% increase in intensive grassland reflects the fact that the IAP2 has optimised demand by producing cropland elsewhere in Europe and prioritising intensive grassland in the UK. Similarly, the 60% increase in forests relative to baseline reflects the fact that many areas of the UK are modelled to be more profitable than the extensive grassland given the UK's soils and climate.

It is possible to post-process the outputs to better fit them to known conditions (e.g. to correct the over-estimation of forest to extensive grassland, or to ensure targets for forest planting are met). The corrections reflect the fact that land use is a continuum, and that the thresholds used to separate classes to best fit at the European scale may not be as applicable for a single country. Doing so assumes that the commodities no longer produced in the UK could possibly be produced elsewhere in Europe. In extreme scenarios (e.g. high-end climate or considerable population change) analysis at the European scale would be needed to ensure that this assumption is internally consistent with the model (i.e. to ensure that the pressures on the rest of Europe aren't so great that there is not sufficient flexibility within the system).

It is important to understand the IAP2's projection of the world at baseline to be able to interpret its projections of the future and to identify steps that are needed to better customise it to the UK in Phase 2. However, it is important to remember the real strength of the IAP2 is in its ability to explore the implications of the future land management pathways driven by a wide range of "what if" scenarios. As such, the model doesn't have to be able to perfectly reproduce current day land use patterns – its purpose is to provide scenarios of the future that consider cross-sectoral interactions and socio-economic and biophysical constraints to "sense check" guidance developed in the absence of these considerations.

Summary

- Believable patterns in land use are produced by the IAP2 model
- There are notable under-estimations in some classes and over-estimations in others
- It is possible to post-process to correct land use to better reflect baseline conditions
- Any corrections need to be assessed at the European scale to ensure internal consistency is preserved, particularly in extreme scenarios

- The purpose isn't perfect replication of current land use but to sense check guidance in a way that takes cross-sectoral interactions and socio-economic and biophysical constraints into consideration.

IAP2 Scenarios

The IAP2 model was used to generate predicted future land use for each of the scenarios. Socio-economic and environmental scenario settings were customised individually within the IAP2 model to match the 5th CB and adaptation scenarios. The settings that could be changed included:

- EU population change. (% from current)
- Water savings due to behavioural change (% change from current)
- Change in dietary preferences for beef and lamb (% change from current)
- Change in dietary preferences for chicken and pork (% change from current)
- Household externalities (Preferences for lived environment: 1 = Urban; 5=Country)
- Compact vs sprawled development (Low = Sprawl; Medium or High = Compact)
- Desire to live by coast (Low – High)
- Change in agricultural mechanisation (change in the amount of labour saving mechanisation) % from current
- Water savings due to technological change (% from current)
- Change in agricultural yields (% change of current)
- Change in irrigation efficiency. Percentage increase in water efficiency relative to current (2010).
- Increase in arable land used for biofuel production (% change from 2010)
- Food imports(% change from 2010)
- GDP as % changes relative to current.
- Change in energy price (oil; % of 2010)
- Land allocated to set-aside/buffer strips/beetle banks etc.
- Post processing: Targeting of "set-aside" for woodland (UK)
- Reductions in diffuse pollution by reduced crop fertiliser/pesticide inputs (1= no change; >1 reflects a decrease in crop inputs)
- Planting of climatically appropriate trees (in Atlantic region)
- Protected Area Increase
- Protected Area target land use (Target Forest, Grassland or "Other" unmanaged land uses – or "even split")
- Process for new areas: prioritise buffering existing areas or target connectivity by prioritising areas without existing PA.
- Afforestation target (UK only, 10kHa)
- Keep Extensive Grassland where present at LCMGB Baseline over Forest (% of possible correction) (UK only)

There are a number of additional settings that can be changed within the MACC to modify on-farm management for mitigation within the scenarios. These were not changed between scenarios for Phase 1 but could be altered in Phase 2.

Model outputs were generated in Excel format across a grid of 18 km^2 cells covering the UK. These results were imported into ArcGIS to calculate regional and national land use coverage. The areas of land covered by different land uses related to livestock and crops were post-processed to match the format required by the MACC. These areas were then substituted into the MACC input data spreadsheets (replacing original estimates of crop areas and livestock numbers projected from the FAPRI-UK study results). The MACC model was run for all four scenarios, to calculate the GHG emissions that could be expected with the corresponding land use change in each scenario. The

MACC also generated abatement and cost estimates for individual mitigation measures that could be implemented to reduce emissions from livestock and soil.

Using the combination of the IAP2 land use outputs and the MACC emissions calculations, we were able to estimate the changes in agricultural emissions that may occur under each of the modelled scenarios.

Emissions were estimated in terms of annual total greenhouse gas (GHG) as kilograms of carbon dioxide equivalent (kg.CO_2e y^{-1}). Emissions from livestock were further split into those from animals' enteric systems, and those from managed manure (e.g. slurry). Emissions from soil (crops) were estimated as kg.CO_2e y^{-1}, representing N_2O lost from soil. We also estimated the potential abatement that could be achieved, if individual mitigation measures were applied. The majority of measures applied were also assessed as part of modelling undertaken by SRUC and Ricardo-AEA in 2015 when the current MACC was developed.

The model did not estimate soil carbon losses; these could be approximated in Phase 2 from the areas of each land use type plus the best available UK information on current relationship between land management and soil carbon loss.

The 5th Carbon Budget scenario

Table ES1 shows the combined measures possible to represent the 5th CB within the linked system. The process involved both ensuring that socio-economic factors driving the IAP2 were consistent with that put forward by the 5th CB and using the same MACC settings for mitigation options that were used to underpin the 5th CB report.

Table ES1: Integration of 5th Carbon Budget mitigation measures and IAP2 land use changes in the Phase 1 modelling process. Those in green are implemented in the IAP2 prior to the application of the MACC.

5th Carbon Budget Central Scenario[2] ALULUCF Conditions/Features	Corresponding element of the IAP2/MACC modelling approach	Notes
Crops and soil management: • Precision farming for crops • Manure planning and application • Grass clover crops • Controlled-release fertilisers • GM crops with enhanced nitrogen use efficiency • Triticale • Loosening compacted soils	***Mitigation Measures in the MACC:*** • MM1: Improving synthetic N use • MM2: Improving organic N planning • MM3: Low emission manure spreading • MM4: Shifting autumn manure application to spring • MM5: Catch and cover	Triticale was considered a novel crop that could be introduced as part of measure MM10

[2] From CCC 2015 'Sectoral scenarios for the Fifth Carbon Budget', technical report prepared November 2015, UK Committee on Climate Change, available online at https://www.theccc.org.uk/publication/sectoral-scenarios-for-the-fifth-carbon-budget-technical-report/

	crops • MM6: Controlled release fertilisers • MM7: Plant varieties with improved N-use efficiency • MM8: Legumes in rotations • MM9: Legume-grass mixtures • MM10: Precision farming for crops • MM11: Loosening compacted soils and preventing soil compaction ***Changed land use in IAP2:*** • Reduced diffuse source pollution (for 5th CB scenarios compared to Adaptation), by reducing crop inputs of fertilisers and pesticides • Agricultural yields set at 10% higher than current levels, for 5th CB scenarios	
Livestock health measures: • Improvements to cattle health • Improvements to sheep health	***Mitigation Measures in the MACC:*** • MM16: Improving cattle health • MM17: Improving sheep health ***Changed land use in IAP2:*** Slider settings	Not included in Phase 1 modelling
Livestock diets: • Improved nutrition • Probiotics • Nitrate additives	***Mitigation Measures in the MACC:*** • MM12: Improving ruminant nutrition • MM13: Probiotics as feed additive • MM14: Nitrate as feed additive • MM15: Dietary lipids for ruminants	No direct changes to livestock diets in IAP2; however feed demand would be influenced by changes in human dietary preferences.
Livestock breeding: Use of balanced breeding goals	***Mitigation Measures in the MACC:*** • MM18: Selection for balanced breeding goals	Not included in Phase 1 modelling
Waste and manure management: • Anaerobic digestion • Slurry acidification	***Mitigation Measures in the MACC:*** • MM19: Slurry acidification • MM20: Anaerobic digestion: cattle slurry with maize silage • MM21: Anaerobic digestion: pig/poultry manure with maize silage • MM22: Anaerobic digestion:	Not included in Phase 1 modelling No direct mitigation for emissions from waste and manure in IAP2

	maize silage only	
Fuel efficiency: Improved housing, drying, glazing, irrigation etc.	***Mitigation Measures in the MACC:*** • MM24: Behavioural change in fuel efficiency of mobile machinery ***Changed land use in IAP2:*** • Labour saving mechanisation in agriculture was set 10% higher than current levels, for the 5th CB scenarios	
Baseline: Measures already being taken up or promoted through the GHG Action Plan	***Mitigation Measures in the MACC:*** • MM23: Afforestation on agricultural land ***Changed land use in IAP2:*** • Used UK target of 3,706 kHa afforestation for the 5th CB scenarios • "Setaside" slider used to mimic agri-environment use of arable land	Not included in Phase 1 MACC modelling, but some post-processing of IAP2 results covers mitigation: e.g. carbon sequestration from trees and targeting of set-aside woodland set at 50% for 5th carbon budget scenarios.

How well does the IAP recreate the 5th Carbon Budget Scenario?

Use of the 5th CB scenario demonstrates the potential for the IAP2 model to be applied to meet a scenario with pre-defined targets. This is quite different from the "explorative mode" within which the model is designed to be used, and required additional post-processing to ensure that timber planting targets were met. IAP2 land use and stocking densities calculated from a combination of IAP2 baseline land cover and DEFRA June Statistics livestock numbers and cropping production outputs were also linked to the MACC inputs. The purpose was to demonstrate that this linkage was possible; a priority for Phase 2 will be determining with relevant stakeholders the most appropriate values to use (for example, stocking densities) so that the results have end user buy in.

($MtCO_2e$)	Published 5th CB	IAP2 modelled 5th CB RCP2.6	IAP2 modelled 5th CB RCP4.5	Adaptation Scenario RCP 2.6	Adaptation Scenario RCP4.5
Mitigation measure		NB without interactions between measures (for Phase 2)			
Crop and soil management	2.7	4.0	4.1	-5.2*	-5.0*
Livestock measures	1.9	2.6	3.4	1.2	2.2
Waste and manure management	0.4				
Fuel efficiency	0.9	0.9	0.9	0.9	0.9
Baseline uptake (GHG action plan)	2.6	2.6	2.6	2.6	2.6
Total	8.5	10.1	11.03	-0.6	0.7
Residual UK emissions	46.5	44.9	44.0	55.6	54.3

Table ES2 Overview of abatement within the linked IAP-MACC Note: *MM8 legumes in rotation skews these results in the adaptation scenario

Using the current settings, the outputs produced for the 5th CB were in the right orders of magnitude, and responded to overall changes in land use (Table ES2). The analysis, as it is currently run, does not include the interactions between different abatement measures. In the published 5th CB only measures which were cost-effective were included and interactions were taken into account. Once interactions are assessed in Phase 2 it will be possible to identify which of the current measures should be included, but as they are they show the method has the potential to produce plausible results.

The modelling already raises some considerations. For example, to reach the afforestation target, it was necessary to increase the extent of forestry in the 5th CB scenario via post-processing, suggesting that forests are not the most profitable use of land in this scenario. Also, the different climates (RCP 2.6 and RCP 4.5) have different optimal land use patterns, and different amounts of total abatement possible.

Whilst accepting that land use is not driven by profitability in reality, the modelling does pose the important question: in this future world where the most profitable opportunities for the UK's soil and climate are in crops and pasture to what extent do current priorities hold? Further analysis would be needed to understand within the European context the extent to which the UK's food provisioning is needed to meet European food demand – but under very extreme scenarios it may be that there is a choice between timber, ensuring food supply and offsetting European environmental impacts elsewhere by increasing food imports. It is these kinds of issue that the IAP2 is designed to explore by running and re-running scenarios making modifications to identify what options are possible within the constraints of climate and the socio-political context.

The adaptation scenario

In order to test the IAP's assumptions and output metrics, a hypothetical adaptation scenario was chosen, focussing on maximising the land use and management options to benefit biodiversity. To achieve this, IAP2 input sliders were adjusted to attempt to maximise the amount of available habitat for different species:

- >25% decrease in food production, and water exploitation
- >10% decrease in availability of potential carbon stock
- >25% increase in irrigation, timber production, and landscape experience (active management of non-productive land)
- 20% increase in imports to lower the land used for agriculture within the UK

How well does the IAP2 approximate a potential adaptation scenario targeted at minimising impacts on biodiversity?

The adaptation scenario was purely a hypothetical scenario designed to showcase how the model allocates land use, what metrics it provides, and how different priorities might affect land use allocation.

The adaptation scenario demonstrated that it is possible to use the IAP2 model to explore scenarios that show significant land use change. It also highlights trade-offs; for example any loss of agricultural land that results from future land use change to maximise habitat space for non-farmland species will result in loss of habitat for species adapted to those habitats. As such, whilst the forest species in the adaptation scenario gain space, even under RCP4.5 climate change, arable species suffer. It should also be noted, that by increasing imports the scenario is focussing on reducing land use change within Europe, but will be offsetting the impacts on biodiversity elsewhere. In a Phase 2, multiple adaptation scenarios could be explored to assess what options lead to minimising the trade-offs between agriculture, biodiversity and other adaptation indices within a range of socio-climatic constraints.

As much of the species-to-habitat modelling is done through post-processing in Phase 2 there is scope to better customise the conditions under which species are considered vulnerable to loss of habitat (e.g. thresholds can be adjusted, and species can be associated with other habitats beyond their preferred habitat).

The take home message is that the scenario led to very different land use change to that of the 5th CB scenarios and very different again from the land use change which may result from climatic change on its own (the IAP2 baseline scenario).

Caveats to consider

Some important limitations need to be considered when interpreting the findings of the Phase 1 modelling process. These include:

- The IAP2 model was developed at the European scale: it optimises for Europe and uses European-level values as inputs (e.g. European population increase, imports to Europe).
- The IAP2 is a highly complex system of several smaller models integrated for the purpose of exploring potential socio-economic and climate futures in tandem. The IAP2 model is managed by a network of modelling experts across Europe, and the internal infrastructure of the model is therefore not easily accessible or able to be manipulated without significant resource implications. This project is designed to see what can be done with the existing system as is.
- Post-processing is possible to better customise the IAP2 by assuming the land use changes modelled will be corrected for in other areas of Europe. However, under extreme scenarios it is important to check the European context to ensure that corrections remain internally consistent with the model.
- The MACC model was designed for the specific purpose of helping to identify an optimal scenario for the 5th Carbon Budget. It does not reflect the entire range of potential emissions from livestock and soils, as a more comprehensive inventory would.
- Costs estimated by the MACC are limited to those that would be expected up to 2030; costs to 2050 and beyond have not been calculated because the MACC does not currently have this capacity.

Areas for further research

The following steps should be considered in a Phase 2:

- Run a wide range of scenarios exploring trade-offs and synergies between different scenarios targeting both adaptation and mitigation
- Agree land use post-processing to apply with relevant end users (e.g. DEFRA, FC, EA etc.)
- Agree stocking densities / crop approximation approach with relevant parties (e.g. DEFRA, SRUC)
- Look into separating tree species into deciduous and conifer (e.g. based on UK-specific datasets)
- Explore the Greenhouse Gas Inventory to identify further areas of mitigation not necessarily covered by the existing MACC. This may suggest additional post-processing options for the following (for example):
    - Carbon sequestration in soils.
    - Afforestation (increasing woodland cover)
    - Agro-forestry (integration of trees and shrubs within arable and livestock systems)

    - Peatland restoration (re-wetting of degraded peatland)
    - Land management practices (impacts on the measures above)
- The MACC will need to be extended from 2030s to 2050 and 2080 in Phase 2 and we have identified steps that would need to be taken in Phase 2 to achieve this.

1 Background

1.1 Project goals for the Committee on Climate Change

The ways in which 'non-developed' land (including agricultural land, woodlands and semi-natural habitats outside of built-up areas) is managed and used in the future are highly relevant to the advice and analysis of the Committee on Climate Change (CCC) on reducing GHGs (mitigation) and preparing for climate change (adaptation). The CCC's aim for the current project is to test the capability of the ClimSAVE/IMPRESSIONS IAP2 integrated model to identify and quantify the impact of plausible future land use pathways that:

- Maximise reductions in emissions and increase sequestration in the UK agriculture and the land use, land use change and forestry (LULUCF) sectors, consistent with reaching net negative emissions in the second half of the century.
- Take account of the need to prepare for the impacts of climate change and characterise the resilience of a particular scenario to the effects of climate warming projections under a 2°C and 4°C world.
- Take account of other land uses that provide economic, environmental and social benefits to the UK.
- Take account of other constraints on land use, e.g. changes in climate and bio-physical properties of land over time.

1.2 Project objectives

This is a report for Phase One of the CCC land use project. The aim of this Phase is to provide proof of concept of modelling capability and resulting outputs in order to demonstrate that the linked system is capable of delivering the wide range of scenarios required within a Phase Two of the Project.

The specification for this work outlined that Phase One of the Project should achieve the following objectives:

i. Demonstrate the integration of the 5th carbon budget mitigation scenario into the modelling.
ii. Demonstrate how the model allocates land to maximise resilience for a particular sector under climate change (in this case, biodiversity).
iii. Provide sufficient relevant outputs to demonstrate the model's fitness for purpose for both assessing mitigation impacts and adaptation/resilience. These should include GHG emissions by gas and source, and resilience indicators that relate to the ASC's indicator framework.
iv. Provide assurance of modelling capability in order to explore further scenarios and a range of other outputs for the second phase.

The contents of this report will demonstrate that we have met these objectives, and are prepared to begin work on Phase Two of the Project pending CCC approval.

In completing Phase One we modelled the following scenarios selected by the CCC:

a) The 'Fifth Carbon Budget mitigation scenario', consistent with the type of abatement measures set out in the fifth carbon budget work. Outputs were produced for 2050.
b) A hypothetical adaptation scenario that maximises land use allocation and management for biodiversity, for the 2050 time period.

To meet the CCC's goals there is a need for scenario-based modelling that deals with the challenges for both adaptation and mitigation in a way that takes into consideration i) future climatic changes, ii) future socio-economic changes and iii) interactions between sectors within a limited and constrained land resource system.

This project proposes a solution that addresses this goal by combining scenario-driven, cross-sectoral integrated assessment modelling using the ClimSAVE/IMPRESSIONS IAP2 (see Section 2.1.1) with the Marginal Abatement Cost Curve (MACC) spreadsheet-based model developed by SRUC and used to support the CCC's 5th Carbon Budget (CCC, 2015). The integrated assessment modelling takes into consideration interactions between six sectors (agriculture, forestry, water use, urban growth, flooding and biodiversity) to produce optimised, modelled land use for a range of combined climate and socio-economic scenarios. The modelled land use outputs can characterise land use in terms of its resilience to future climate change scenarios. It can also be used to derive livestock numbers and arable crop coverage, and this data is fed into the MACC to work out the potential emissions reductions that result from the changing land use.

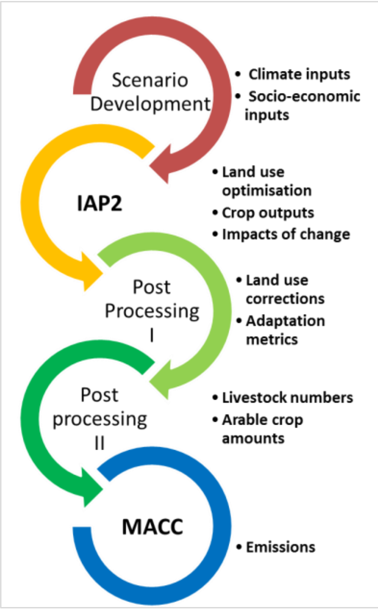


Figure 1 Conceptual framework for the linked system

Figure 1 provides an overview of the proposed linked system developed within this project, of which the sections in bold (the IAP2 and the MACC) existed prior to the project commencing. The focus of this project has been on developing the links between the two to produce a single linked system to assess the impacts of environmental change on emissions from the land use sectors, and the synergies and trade-offs with land use choices to maximise adaptation for different sectors including, for example, ecosystem service provision.

The following section (1.3) provides an overview of the five-step process followed, and the report is then structured to follow each step of the process (section 2 through 6). Sections 2 through5 detail methodological steps required to construct the linked system and Section 6 presents the outputs of the project. Section 7 discusses next steps, and Section 8 concludes by tying achievements back to the project specification.

1.3 Overview of the project methodology

A five-step process (Figure 2) was used to develop and demonstrate the capability of the linked system and produce the required outputs for the two scenarios set out by the CCC.

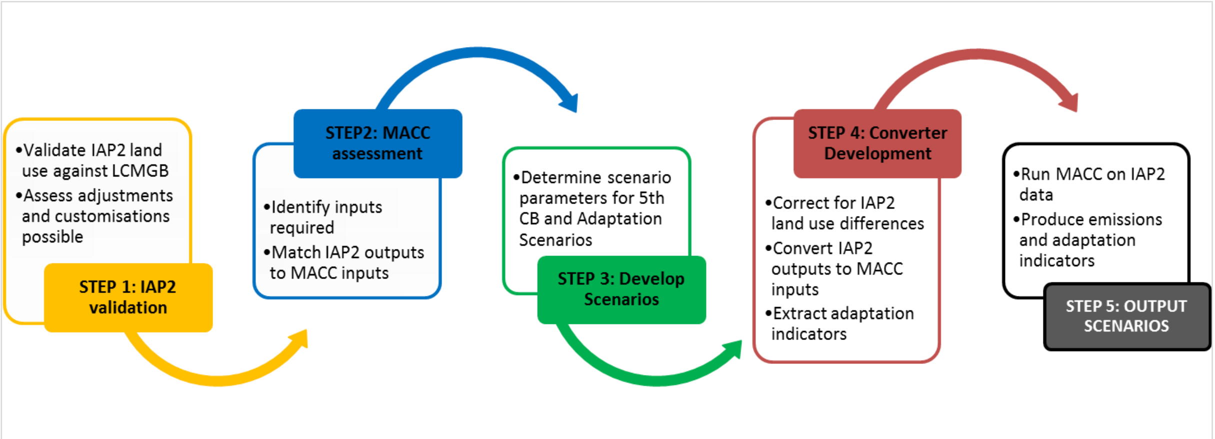


Figure 2 Project approach

Step 1: Assessment of IAP2 land use for the UK. The IAP2 is a model designed and customised at a European scale and it has not been specifically validated in the UK. Also, this is the first time it has been applied with a focus on an individual country. As such, a thorough validation process against UK specific land use datasets (Land Cover Map of Great Britain (LCMGB), 2007) was applied to identify its ability to reproduce land use under baseline conditions.

Step 2: The MACC is designed to run with agricultural inputs from economic projections of livestock and cropping data. It was necessary to identify what inputs were required and how the outputs from the IAP2 could be converted into inputs that the MACC could use.

Step 3: To model the two scenarios put forward by the CCC it was necessary to develop a suite of scenario input parameters for the IAP2, and the “converter” that matched the underlying assumptions of the two scenarios.

Step 4: A new MS Excel-based model, “the converter”, was developed within this project with three main purposes: i) to convert outputs from the IAP2 into inputs that could be used by the MACC; ii) to post-process IAP2 outputs into adaptation-related indices and iii) to post-process IAP2 outputs to allow UK-specific land transformations to allow better customisation of UK land use.

Step 5: With all prior steps complete the full model chain from scenario → IAP2 → Converter → MACC could be run producing fully quantified scenarios of land use change and its impacts on emissions and adaptation indicators. There is no feedback loop between the MACC and the IAP2. These results are presented in Section 6.

2 Step 1: Assessment and validation of the IAP2 modelled land use for the UK

2.1 Introduction to the IAP2

2.1.1 What is the IAP2?

The “Second ClimSAVE/IMPRESSIONS Integrated Assessment Platform” (IAP2) is an integrated modelling system designed to explore the cross-sectoral impacts of combined climate and socio-economic change, the vulnerabilities that result and the potential to adapt to these changes to reduce the impacts.

The IAP2 platform combines ten established models (Table 1) for different components of the land/environment system and is specifically designed for the exploration of different future scenarios of land use change related to changes in climate and socio-economic drivers. It includes interconnected modules related to: agriculture, forestry, water availability and demand, flooding, land use, biodiversity and urban growth (Figure 3). It enables the exploration of a wide range of future climate scenarios based on the internationally recognised IPCC AR5 representative concentration pathways (RCP’s 2.6, 4.5 and 8.5; https://www.ipcc.ch/report/ar5/) as projected by multiple climate models (at least 3 Global-Regional climate model combinations for each pathway) for each of three time periods (2020s, 2050s and 2080s). These climate change scenarios can be mapped onto specific magnitudes of global warming such as 1.5^{o}C, 2^{o}C and 4^{o}C. Furthermore it allows for the exploration of a wide range of socio-economic changes including major drivers of land use change related to population, GDP, technological innovations, behavioural change and policy targets. By default, socio-economic drivers are represented in a set of scenarios of plausible future developments based on the IPCC-related Shared Socio-economic Pathways (SSPs) which have been downscaled from the global to the European scales. However these can be further customised, and/or new independent scenarios can be implemented. A wide range of land use, sectoral and ecosystem service outputs are produced by the modelling platform which enable the assessment of trade-offs and synergies, climate resilience and vulnerability under multiple interacting drivers.

The ClimSAVE Integrated Assessment Platform is an *integrated* modelling framework. The individual models within it are all independently validated and published within the peer reviewed literature (Table 1). The models are hard-linked so that flows of information are directly passed across a modelling chain. The integration of the models within the European IAP2 has been extensively tested through an iterative development process spanning six years, involving stakeholder feedback (Gramberger et al. 2015), sensitivity analysis (Kebede et al. 2015) and uncertainty assessment (Dunford et al. 2015; Brown et al. 2015). Application of the integrated framework has been extensively published in a number of journals including Nature Climate Change (Harrison et al., 2016) and a Special Issue of 18 papers in Climatic Change.

The modelling framework (Figure 2) allows the RCP-based climate scenario input data to be combined with different socio-economic scenario input data, in addition to the baseline conditions, to explore the sensitivity of land use and ecosystem services to different driver assumptions. Furthermore, the user interface to the integrated model is highly flexible, encompassing multiple sliders representing different drivers which allow individually customised scenario settings to be developed to match specific requirements.

The purpose of the CLIMSAVE IAP2 is not to predict what the future land use will be in a given future but to explore the implications of a large number of factors driving land use change in a way that takes into consideration interactions *between* sectors. It is designed to focus on

"what if" style questions and can provide a means to sense test visions of the future driven by sectoral policies and models focussed on individual sectors.

Unlike other models, the IAP2's integrated nature enables it to highlight constraints that result from both changes in climate and socio-economic scenarios, but also indirect constraints that are the implications of changes in one sector (i.e. changes in water use limiting irrigation; food security pressures on the forestry sector or flood-related pressures on the agricultural system etc.). The IAP2 is state-of-the-art with respect to cross-sectoral modelling in Europe and is the best-available integrated assessment model that covers the UK. The integrated modelling approach taken is the result of over 10 years of development through a number of UK and European projects (REGIS, REGIS2, CLIMSAVE and IMPRESSIONS). The IAP2 platform is technologically complex and the 10 models combined are coded as independent DLLs which pass inputs and outputs between each other. To enable fast model run times (from 20 seconds to 1 minute depending on the complexity of the scenario) each DLL is a simplified "meta-model" that summarises or mimics the outputs of larger, more complex, models. Redesigning the IAP2 internally is a significant task which would require the specific involvement of the key international modelling teams responsible for the individual components of the model and a modification of the core code which joins the individual modules. Similarly, developing a specific UK version of the IAP2 would also be a significant task, requiring the development and customisation of the existing models to a finer resolution appropriate to the UK and the collection and processing of UK-specific datasets. **As such, the focus of this research is to identify what insights related to potential future trajectories for UK land use can be attained by focussing on outputs for the UK, within the IAP2's existing modelling capacity to provide projections for Europe.**

Within Phase 1 of this project the IAP2 is used to reproduce the CCC's 5th Carbon Budget (5th CB), and a hypothetical adaptation scenario that maximises land use benefit for biodiversity, and to quantify the land use, mitigation and adaptation impacts that result from the scenarios under two different climates. In Phase 2 the model will be used to explore a wider range of combined climate and socio-economic scenarios.

Sector	**Model**	**Example outputs**	**References**
Urban	Regional Urban Growth (RUG)	Percent Artificial surfaces	Reginster & Rounsevell (2006)
Agriculture	ROIMPEL	Average yield (irrigated and rainfed) Irrigation needed (mm)	Audsley et al., (2015) Audsley et al., (2008)
Forestry	GOTILWA	Potential wood yield Potential net ecosystem exchange	Audsley et al., (2015) Morales et al., (2005)
Rural Land Allocation	SFARMOD	Percent intensive/ extensive/ very extensive/ forest / unmanaged land Crop area Irrigation usage Land use diversity (multi-functionality) Land use naturalness (intensity) Land use change (difference from before)	Audsley et al., (2015) Holman et al., (2005) Annets & Audsley (2002)
Water exploitation	WaterGAP3	Water availability Median annual Q5 discharge Total water use Water exploitation index (available/use)	Wimmer et al., (2015) Doll et al., (2003)
Coastal and Inland Flooding	REGIS & DIVA	People flooded Damages due to flooding	Mokrech et al., (2015) Mokrech et al., (2008) Vafeidis et al., (2008)
Pests	CLIMEX	Number of generations (of pest)	Dubrovsky et al., (2015) Sutherst et al., (2001)
Biodiversity	SPECIES	Potential climate suitability for	Harrison et al (2008)

(Species)		species Potential climate/habitat suitability for species Land with soil and climate appropriate for heath/bog	
Biodiversity (Ecosystems)	LPJ-GUESS	Net primary productivity Biomass	Salaba et al., (2015) Sitch et al., (2003)

Table 1 Models that make up the ClimSAVE/IMPRESSIONS Integrated Assessment Platform 2

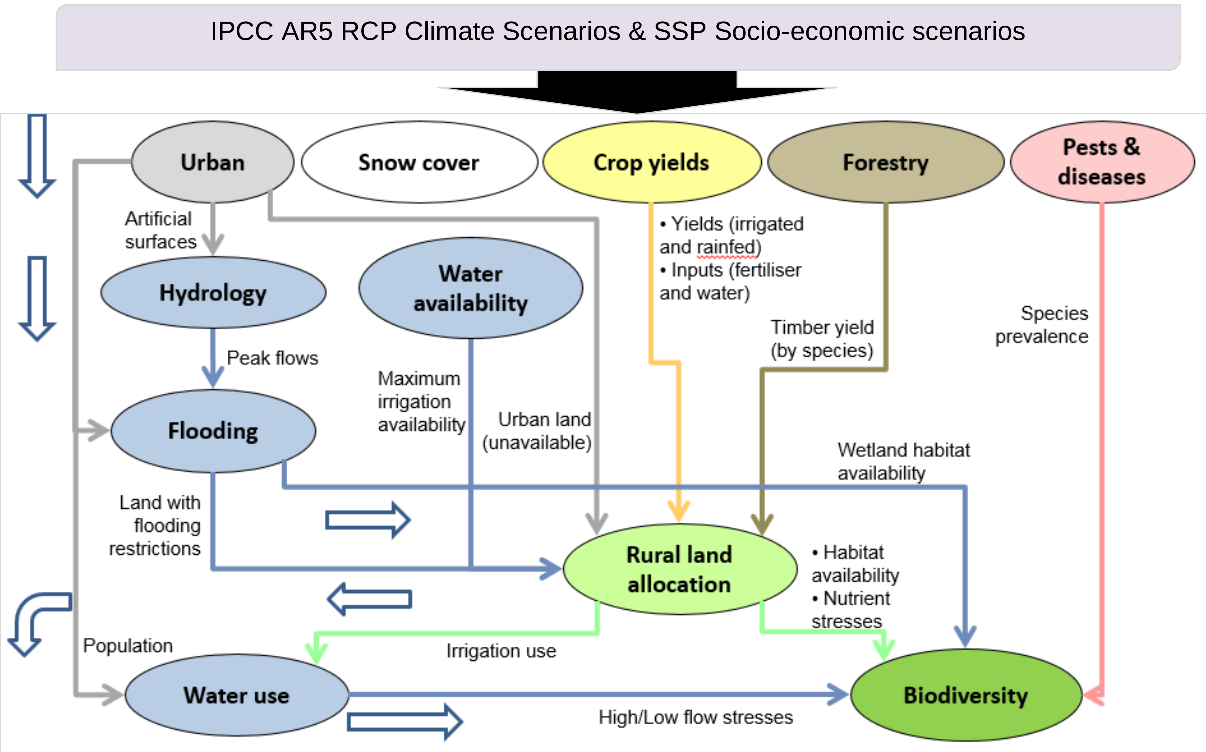


Figure 3 Overview of the ClimSAVE/IMPRESSIONS IAP2 integrated modelling framework.

2.1.2 How does the IAP2 allocate land?

The platform is designed to examine how land use changes over long timescales over which the suitability of land for the current uses of land (such as agriculture and forestry) will change. Over these timescales some areas of land not currently used for a given land use may become more suitable, whilst some areas that are currently suitable may become less so. As such, **to model land use into the future land allocation needs to be based on the underlying properties of the land, soil and climate and not their current land use or the historic suitability of the land for different uses such as agriculture**. In addition, socio-economic and technological change may mean that more or less land is needed so that land which is currently marginal may become cropped or vice-versa. In addition, both environmental pressures and political changes will mean that priorities for land use reflected in current policy may not be as appropriate 30 or 50 years in the future. To address this, the IAP2 models the relative profitability of land for each grid cell within *each scenario*. Profitability is driven by both the *demand* for different commodities (itself driven by factors such as population change and dietary preference) as well as social and environmental factors that influence the potential for *supply* (themselves driven by both direct and indirect social and environmental variables such as climate and technological change). (*For more detail on how supply and demand are balanced to allocate land use within the model see Appendix A)*.

The majority of existing studies that look at the impacts of climate change on land use consider relatively rigid sets of pre-defined scenarios, usually four (Hossel et al, 1996; Rounsevell et al., 2003;

Holman et al; 2005; Audsley et al., 2006; Schroter et al., 2012). The CLIMSAVE IAP2, however, is designed to be flexible enough to allow the user to develop their own scenarios. This makes it a particularly powerful tool for exploring multiple "what if" style scenarios. Under these scenarios it is more important that the interactions between sectors map credible challenges for adaptation and mitigation that arise under different constraints than that the exact values are calculated.

The IAP2 covers the EU28 plus Norway and Switzerland and land use is allocated across this area through an iterative process within the rural land use model within the IAP2. It considers a wide range of factors (detailed above and in Figure 3 and described, by land use class, below) to meet demand across the European continent. The IAP2 works on a 10' x 10' grid, this is a spherical projection and grid cells are not the same size (those over Norway are larger than those over Spain for example). Over the UK grid cells are approximately 18km x 18 km.

Urban areas are considered to be unavailable for agricultural or forestry use. In addition flooded areas limit agricultural options: an area of land subject to a 1 in 10 year flood is considered inappropriate for arable agriculture and an area subject to 1 in 1 year floods is not considered suitable for any agriculture (Mokrech et al., 2006). Including flood impacts on agriculture within an integrated system provides a mechanism to explore the implications of climatic shifts in flooding and the impacts this may have on other sectors by exacerbating challenges with regard to meeting food demand given the loss of flooded land.

Each grid cell includes a number of soil clusters that are considered independently when determining profitability (allowing a grid cell to have multiple different optimum land uses for the different soil elements within a cell). If a given combination of climate and soil is profitable enough (> €350/ha) it is allocated to either intensive grassland (if the grass profit is higher) or arable (if the crop profit is higher). If profitability is > €150/ha it is defined as either forest or extensive grassland depending on whether timber or grass profit is higher. Where the profit is less than €150 the land is either allocated to unmanaged forest, if Net Primary Productivity is positive and greater than the grass yield, or otherwise to extensive grass when it is allocated to "very extensive grass". If grass yield is very low the land is classified as "unmanaged" land (Audsley et al., 2014).

When determining arable profitability the IAP2 calculates the yields (t/ha) for a number of crops including winter and spring wheat, winter and spring barley, potatoes, sugar beet, winter and spring oilseed rape, maize, forage maize, cotton, sunflower and soya as well as yields for grass, permanent grass and extensive grass. At the grid cell level crops are allocated with reference to their profitability derived from their yield in a given scenario, all crops are modelled and the most profitable for a given soil within the scenario are used. The impact of irrigation is considered within the profitability calculation and modelled by iterating with increasing levels of irrigation (taking into consideration the scenario setting for irrigation efficiency). The most profitable level of irrigation is used (Audsley et al., 2015).

Demand for each commodity type (e.g. cereals, carbohydrates, protein, oil, cotton, milk, meat and timber) is calculated as proportional to the population but modified by dietary preference and imports from outside of Europe (which offsets demand to locations outside of Europe, reducing it within). Reduced preference for red (ruminant) meat (cows/sheep) reduces grazed meat demand, but increases demand for other foods. Reduced preference for white (non-ruminant,) meat (pork/chicken) reduces the need for livestock feed and increases the food crops required.

The model then determines if there is an under- or over-supply of each commodity and repeatedly iterates increasing or decreasing prices for crops and timber until demand is met. Irrigation is treated in a similar way with the cost of irrigation increasing if there is insufficient water available in the scenario. The scenario will continue to iterate until water use is less than available water. Commodity (food and timber) demand and water availability must both be met for the iteration to end. Under extreme scenarios it is possible that demand is not met (within a set number of iterations) in which case the model reports back the proportion of each commodity demand that is met (this doesn't occur within the modelling presented below). Figure 3b provides an overview of the land allocation process and responses to FAQ on the approach are addressed in Appendix A.

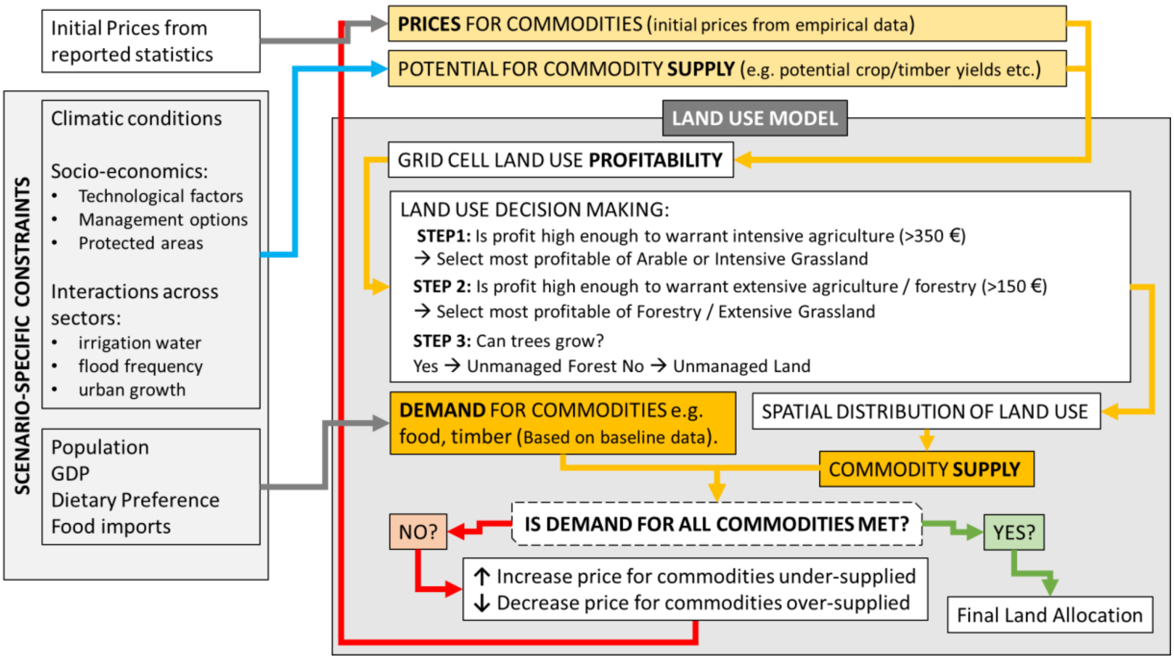


Figure 3b: overview of the land use allocation within the IAP2.

The factors influencing the distribution of land use:

When the final iteration is complete, each grid cell has information on the proportion of the cell in which the land cover is allocated according to seven major classes. These classes (in bold below), and their main drivers, are detailed below. A solid understanding of the logic behind the IAP2's classification of land use is important to interpret what it is and isn't modelling when interpreting the results.

Arable land: land where growing crops is the most profitable use of the land. The definition of this class will have taken into account: changes in demand resulting from population change within Europe, or food imports into Europe from the rest of the world; agricultural technology; anthropogenic changes in yields (e.g. from agronomy, intensification or extensification of farming practices); dietary preferences for meat within Europe (both in terms of increased vegetarianism, and increased feed and fodder crops from changes in meat consumption); availability and cost-effectiveness of irrigation, inundation from flooding (which can take land out of agricultural production); urban growth as well as direct climate impacts on yields (e.g. improving/worsening climate) and soil type. The IAP2 does not include exports of food from Europe to the rest of the world, and does not make assumptions about demand or dietary choices outside of those listed above.

Intensive grassland: land with high-quality grass that supports dairy and beef livestock and **extensive grassland** seen as poorer-quality grassland for sheep grazing. These will take into consideration similar socio-economic, demand-related drivers to arable land as well as soil and climate factors that influence grass yield. Lower yields will lead to the classification of land as extensive grassland except in areas where the timber yield of the same area of land would lead to forestry being a more profitable land use.

Managed forestry: is defined within the IAP2 modelling in areas where profitability is between 350€/ha and 150€/ha and forest is more profitable than grassland. It reflects areas that the IAP2 considers to be necessary to meet timber demand at the European scale. The species of tree is not specified in the IAP2 outputs, however the species of tree will be considered internally within the model when determining yield. As such, the managed forest class reflects *timber producing forest* – and could be either conifer or broadleaf. By default the tree species modelled are those which are climatically suitable at baseline; however, it is possible to model the impacts of adaptation by planting climatically appropriate trees. Forest productivity is influenced by climatic changes as well as changing levels of CO_2. **Unmanaged forestry**, is influenced by the same drivers, but is defined as is land on which crops, livestock and timber are not profitable (<150€/ha) yet forest Net Primary Productivity (NPP) is greater than grass yield. Again, it is impossible to determine species from the outputs but it will have been considered internally within the model: unmanaged forest can also be considered to be either conifer or broadleaf.

Unmanaged land: areas where soils and climate mean that it is not sufficiently profitable to manage the land for agricultural purposes and trees are unable to grow. This would include lands with poor soils, where forest and grass yields are both very low. "Unmanaged" land is shorthand for "non-forest, non-urban land not managed for agricultural production", the land may be "managed" for landscape or environmental reasons, but is not being managed for food or timber and is not projected to be suitably productive for forests to establish naturally (low NPP). The "Unmanaged land" class includes a number of land cover types such as heath, moorland, marshes, wetlands, very poor grasslands and bare rock etc..

Urban: cities and human habitations, these grow with population, with new areas being targeted according to preferences (such as for compact/sprawling development, rural/urban surroundings and proximity to the coast) which are defined within the socio-economic scenarios.

Semi-natural habitats

Semi-natural habitats are not explicitly allocated within the IAP2's approach to land use which focuses on meeting food and timber demand. However, locations where semi-natural habitats would be more/less appropriate can be inferred from the land use distribution. Semi-natural habitats would not be expected to be found in locations where 100% of the land area is allocated to intensive land uses (intensive grassland, arable, urban, managed forestry) and would be more likely to be found on the extensive and unmanaged land classes. Protected Areas included within the model prevent intensification of land use and such maintain extensive and unmanaged land in the face of the pressures of the food system. Furthermore, the set-aside slider determines the proportion of arable land that is "set aside" for nature. This means that in a scenario where 6% of land is set aside 6% of land designated as "arable" is not used for food production and instead can be considered to be managed to maintain or re-produce semi-natural habitats (e.g. buffer strips, beetle banks, on-farm woodlands etc.).

Baseline

"Baseline" is used to describe a scenario that reflects present day reference conditions. Within the IAP2 the baseline scenario uses climate data from 1961-1990. This is the standard climate baseline used by UKCP09. For socio-economic data a baseline year of 2010 was used. To match this, 2010 was also used as a reference year within the MACC analysis.

2.1.3 Considerations when interpreting the IAP2

The model projects future conditions based on profitability. It is important to remember that the model is designed to explore far future scenarios where current policy and historical legacy cannot be assumed to be the driving force of land use, and where climatic and socio-economic change will enable and constrain the use of land in ways that it has not previously. The underlying assumption of the model is that land will be distributed in the most profitable way possible. Both supply and demand are considered, and profitability is considered within the context of the ability of different areas within the EU28 to meet the level of demand. This raises a number of considerations. **In reality, modern**

land use is not "optimised for profit" and other socio-political considerations (tradition, inertia, legislation, policy, subsidy etc.) also contribute to how land is distributed. As these are all factors that can change significantly into the future the modelling needs to be based on assumptions that are driven by biophysical constraints based on soils and climate, modified by socio-economic changes in technology and preference rather than existing patterns of land use.

There are values included in real decision making that go beyond commodity profits that are not currently included within the IAP2. For example, **ecosystem service benefits are not considered when determining land use profitability within the IAP2** (beyond meeting food and timber provisioning needs). As such additional revenues from recreation or damages avoided through flood prevention or water regulation don't influence the land use pattern. It should be noted, however, that i) at a very broad level it is possible to infer the potential of different scenarios to provide some of these values from the land use distribution; ii) that the "set-aside" sliders can be used to force the IAP2 to take areas of arable land out of productive use to represent agro-environment schemes preserved for their ES benefits rather than profit iii) biofuels from crops can be modelled in a similar way with a slider in the IAP2 which takes agricultural land away from providing food and feed to providing biofuels.

European Scale: The IAP2 runs at a European scale. This means that input settings are considered to apply evenly across Europe. For example if there is a 10% increase in population, or GDP this is seen to apply at the scale of the EU28 + Norway and Switzerland. Similarly if there is an increase in behavioural or technological change this applies equally to all member states. It also means that the land use optimisation to meet food and timber demand also happens at a European scale.

In the context of this project where the focus is on the UK this highlights a number of important considerations:

> i) There is an inbuilt assumption within the modelling that EU countries would balance their food and timber production to prioritise the most profitable land uses in a given location within the EU. This includes an assumption that food/timber produced in one area can be transported to meet a demand in another.
>
> ii) Even though the 5th CB and adaptation scenarios are being developed with the UK in mind, the input parameters used need to be developed and will apply to the EU level. This may need some conversion (e.g. a 24% increase in UK population is consistent with a total EU population increase of just 6.4% - see Section 4).
>
> iii) Drivers set at the European scale affect all countries evenly when in reality there will be significant variations in the ability and inclination to uptake measures. This limitation is driven by the considerable complexity required to customise driver inputs and independently model the cross-sectoral interactions *within and between* 28 individual countries. It is a priority for future research, but would likely take considerable time and resource to implement, test and validate. However, the IAP2, as it is, is currently state-of-the-art with respect to European integrated modelling and the assumption is sufficient for the purposes of exploring "what if" scenarios to highlight the broad implications of alternative land use strategies under a range of climate and socio-economic scenarios.

Optimisation model even in 2010: The IAP2 optimises land use even under baseline conditions – this means that the outputs for the baseline year (2010), whilst trained on contemporary data, are *modelled land uses* that result from optimisation – they may not therefore exactly reflect current land use by virtue of i) the optimisation not completely reflecting local profitability (e.g. local subsidy payments – which are particularly important in the context of UK forestry)) and ii) other factors beyond profitability which drive land use in reality (e.g. policy targets, financial capital constraints, farmer behaviours, other ecosystem service benefits).

Limited set of inputs. The IAP2, like all models has a limited set of inputs and algorithms that allocate land use. There are a range of issues that would also have a bearing on future land use that are not included in the model; for example demand for food exports or future change in climate on soil quality. The inputs are listed below and discussed in more detail in Section 4 where they are defined for the Adaptation and 5thCB scenarios.

Factors Considered in the modelling	**Comments**
Climate / spatial pattern of climate	
Soils	Soil type and quality doesn't change with time
EU population change	Other demographic info aren't considered (age, gender, wealth and skills distributions)
Water savings due to behaviour and/or technology	
Change in dietary preferences (for red and/or white meat)	Includes impacts on stock feeding and requirement for alternative food sources
Urban development preferences (coast, urban/rural, compact/sprawling)	
Change in agricultural mechanisation	
Change in agricultural yields	
Change in irrigation efficiency.	
Increase in arable land used for biofuel production (% change from 2010)	Wood-based biofuel is not considered
Food imports(% change from 2010)	Food exports are not considered
GDP as % changes relative to current.	
Change in energy price(oil; % of2010)	
Land allocated to set-aside/buffer strips/beetle banks etc.	
Reducing diffuse source pollution from agriculture by reduced crop inputs of fertilisers and pesticides	
Plant Climatically Appropriate Trees? (Yes/No)	
Protected Area changes	Includes change in total coverage and distribution. Is based on Natura 2000 so excludes other non Natura 2000 PAs.
Afforestation targets (Post-processing)	Targets for other land uses
	Ecosystem service related factors that influence profitability are not included – decisions are made with respect to provisioning services rather than other values (e.g. cultural or regulating services).

Table 2 Overview of inputs considered within the modelling.

The IAP2 allows a user to test a variety of scenarios by changing the settings on a number of sliders that vary the socioeconomic conditions described above, which are then inputted to the land use model. In varying these assumptions, the IAP2 is not attempting to model a realistic future world, but to provide information on how different socioeconomic inputs might change land use at a broad level. The resulting scenarios should be viewed as 'what if' scenarios and not predictions of future change. This is an important caveat especially when considering socioeconomic changes that have particular social and political importance, such as the level of self-sufficiency for food.

2.2 Assessing the IAP2 for UK Baseline

The following section focusses on identifying the implications of the assumptions previously outlined for the mapping of UK land use into the future by first assessing the IAP's fit against data for 2010 baseline conditions. By comparing the IAP2's modelled baseline projections for the UK in 2010 with the best available land use data for Great Britain, the Land Cover Map of Great Britain for 2007 (LCM2007, http://www.ceh.ac.uk/services/land-cover-map-2007).

The LCMGB was released in 2011 and is the most up-to-date land cover map covering the UK (Morton et al., 2011; a new map for 2015 is due to be released in 2017, but is currently unavailable). The LCM2007 is generated derived from the classification of 70+ satellite images in combined summer and winter pairs. 99.5% of the classified land parcels are classified using automated procedures and the product was field validated between 2006 and 2008 using 9127 field visits. The overall classification accuracy was 83% although the accuracy of classification of individual classes varies: it is stronger at classifying the major classes of woodland, arable land, improved grasslands and wetlands than at separating natural vegetation classes such as rough, neutral, calcareous and acid grasslands, heaths and heather grasslands and montane habitats (see Appendix B).

Before considering the results it is worth noting that we would not expect an exact correspondence between the two for a number of reasons:

1) ***Modelled vs observed***: The LCMGB is based on observed data collected via satellite and classified automatically. Contemporary land cover reflects the decisions of land owners driven by a complex web of social and political factors in addition to the constraints of the land. The IAP2 land use is modelled based on profitability, and so reflects optimised land use given a broader European land use context. As discussed in the previous section there are a number of reasons why this optimised land use may not be the land use found in reality (e.g. inertia, local/national priorities and policies).

2) ***Use vs cover***: The IAP2 is showing *land use and management intensity* whereas LCMGB is showing *land cover* with little indication of management intensity. This is not a like-for-like comparison and some differences are inevitable and may have implications particularly for classes on a continuum, such as grasslands. It is also significant for forests as the LCMGB map land cover with respect to species is spectrally distinguishable on satellite images whereas the IAP2 is mapping land suitable for meeting timber demand and less profitable areas where trees could grow for unmanaged natural forests.

3) ***Reality will be different from both***: It is also worth remembering that neither should be taken as “reality”. LCMGB 2007 has been independently validated against observed ground data, with an overall correspondence of 83%, whilst the IAP2 is not aiming to map ‘reality’ but a world that would occur if land use distributions were driven by the assumptions within the model (e.g. profit maximisation across Europe within biophysical constraints). Furthermore, land use, particularly in the agricultural sector is not static and will change on an annual basis in response to climatic and socio-economic drivers.

The results should be interpreted keeping these considerations in mind and remembering the purpose of the project is to allow the CCC to run multiple scenarios to explore a number of far futures (2050s and 2080s), and investigate how changing certain socioeconomic inputs affect land use, mitigation and adaptation. For this purpose at baseline **the modelling does not have to “predict” accurately what future land use for the UK will be but present a reasonable reflection of the broad-scale patterns in UK land use**. The strength of the modelling is in the exploration of future scenarios and the priority for the modelling is to **allow multiple future scenarios to be explored to enable better understanding of the impact of different decisions on land use change, and to highlight where synergies and trade-offs between sectoral priorities result**.

2.2.1 Analysis

Initial pre-processing

The results of the IAP2 model are output for each of the 1,331 grid cells covering the UK. To allow outputs to be processed at national and regional scales each grid cell was allocated to the country/ region that occupied the majority of the area of that cell.

Data extraction

Outputs from a run of the IAP2 model using baseline settings were compared against a recognised national land use dataset to validate the accuracy of the model in predicting baseline conditions at a UK scale. The Land Cover Map of Great Britain (LCM-GB) 2007 was used as the source of the observed baseline; this did not include data for Northern Ireland.

Each IAP2 grid cell contains information on the proportion of each modelled land use in the classes described in section 2.1.2. For comparison, ESRI ArcMap 10.2 GIS software was used to calculate the proportion of each of the LCM-GB 2007's land use classes within each IAP2 grid cell.

2.2.2 Assessing spatial patterns in land use

It is important to understand the IAP2's projection of the world at baseline to be able to better interpret its projections of the future and to identify steps that are needed to better customise it to the UK in Phase 2. The real strength of the IAP2 is in its ability to explore the implications of the future land management pathways driven by a wide range of "what if" scenarios. As such, the model doesn't have to be able to perfectly reproduce current day land use patterns – but it needs to demonstrate a reasonable fit to expected spatial patterns for UK land use at baseline (e.g. arable more in the east, grasslands more in the west, and the major forests and areas of natural land identified in appropriate locations). Spatial patterns can be visually interpreted by comparing IAP2 output with the distribution of cells and comparing them with the appropriate matching classes from the LCMGB. These comparisons are illustrated by Figures 4 to 10 below.

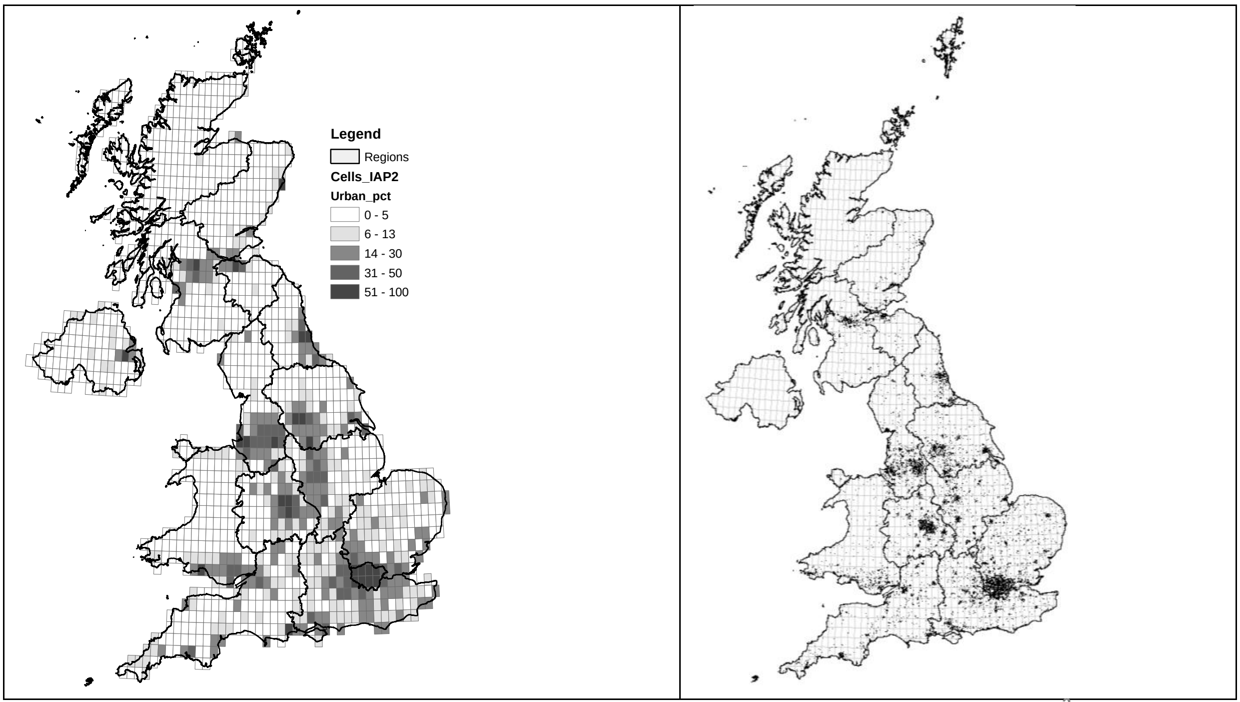


Figure 4 Comparison of spatial pattern of urban area from (left) IAP2 to (right) LCMGB 2007[3]

The urban land class from the IAP2 is compared with the sum of LCMGB' land use classes for Urban and Suburban (values 22 and 23) in Figure 4. The match here is very strong and captures the major urban centres well.

Explanation

The IAP2's urban distribution is heavily driven by the CORINE urban land cover layer (CORINE is a European land cover dataset also based on satellite interpretation). At baseline, none of the drivers that impact urban development (i.e. population, dwelling preferences etc.) have changed and so the baseline distribution directly reflects CORINE inputs. Thus a high degree of fit is expected.

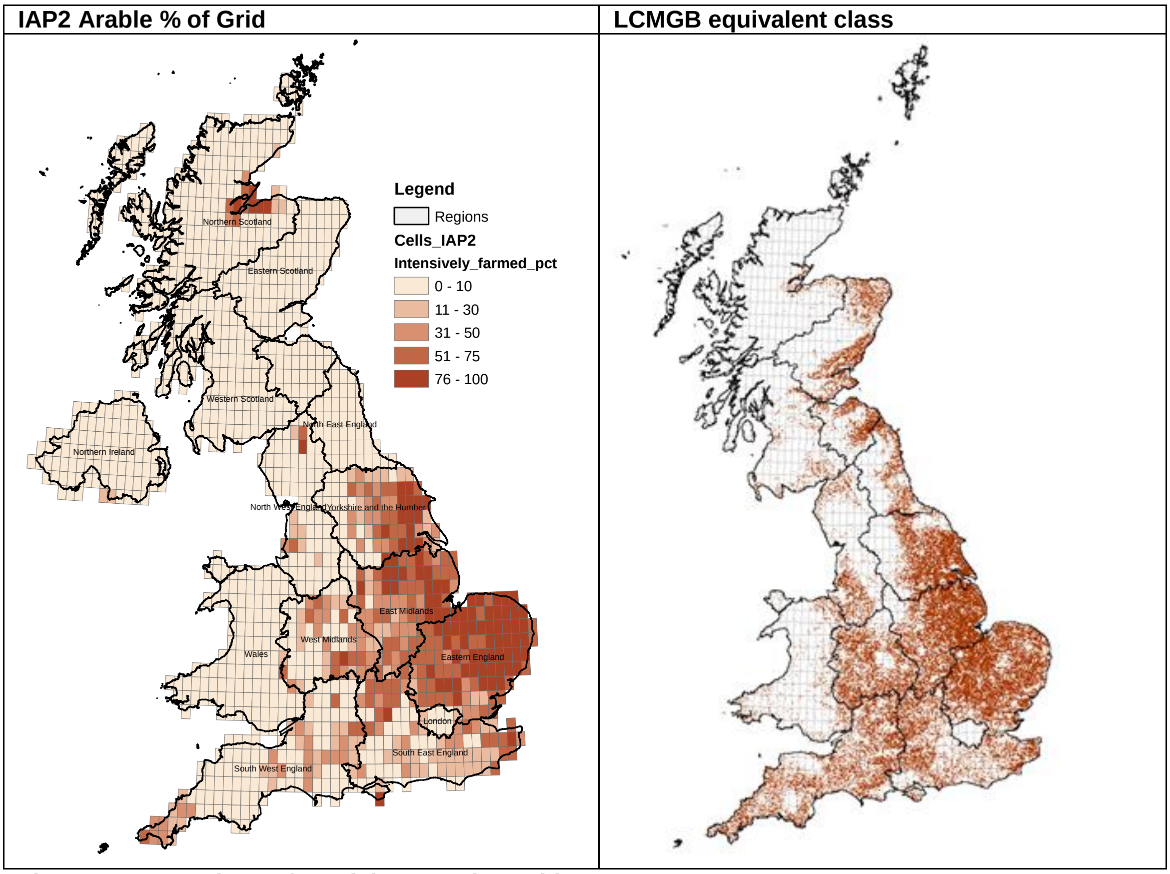


Figure 5 Comparison of spatial pattern in Arable Crop IAP2 to LCMGB

The Arable class from the IAP2 outputs was compared with the LCMGB's Arable and Horticulture class (Value 3) in Figure 5. Arable land in the southern and eastern England is well projected by the modelling system. However, underestimations of arable area in the North East of England, Scotland and Devon are apparent. A correction for these problems, particularly those in Scotland and north east England has been identified and could be applied for Phase 2. However this entails the insertion of a new DLL module within the IAP2 and so it has not been possible to do this and validate it within the timeframe of Phase 1. Figure 6 illustrates the resulting changes.

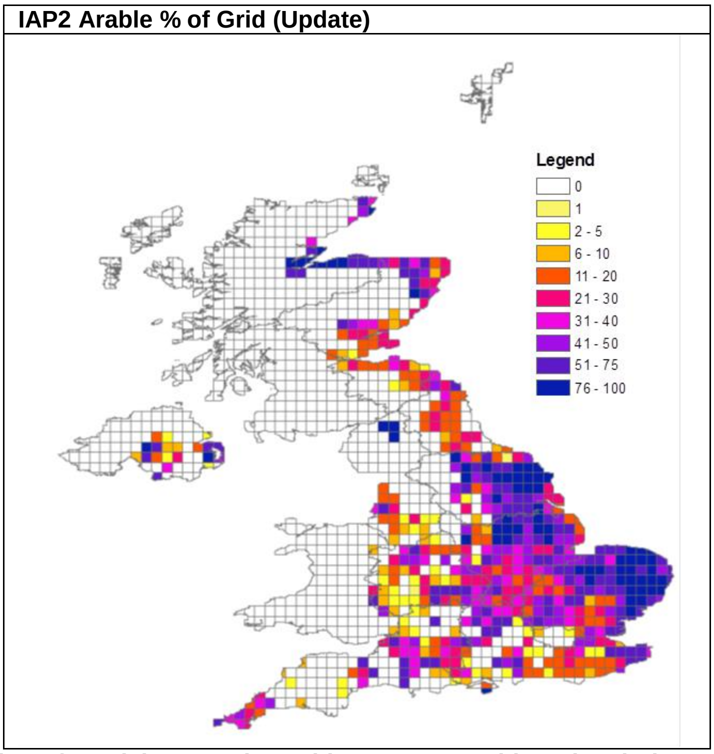


Figure 6 Demonstration of spatial pattern in Arable Crop IAP2 with updated Phase 2 IAP2 DLL (units are % of grid cell that is arable).

Explanation

Within the IAP2 the distribution of arable land is driven by the suitability of soils and climate. Socio-economic settings (e.g. population increase, diet preferences agricultural mechanisation, irrigation etc.) will not have changed from baseline settings derived from contemporary European datasets (e.g. population from Eurostat). However, as previously discussed the levels of mechanisation described by the model will reflect European average settings. Even without the updated DLL module (explained in Section 2.1.1 above), the spatial distribution is sensible and reflects the broad patterns of crop production expected in the UK, particularly the focus on the east of England. With the update the pattern in Scotland fits better to the LCMGB data. The pattern is driven by the suitability of the soils and climate in these regions for crop production, however the total amount of arable production is lower than shown in the LCMGB due to areas of Europe being modelled as more profitable for crop production than the UK (in the absence of socio-political factors such local priorities, national or international subsidy and cultural factors such as inertia or preference).

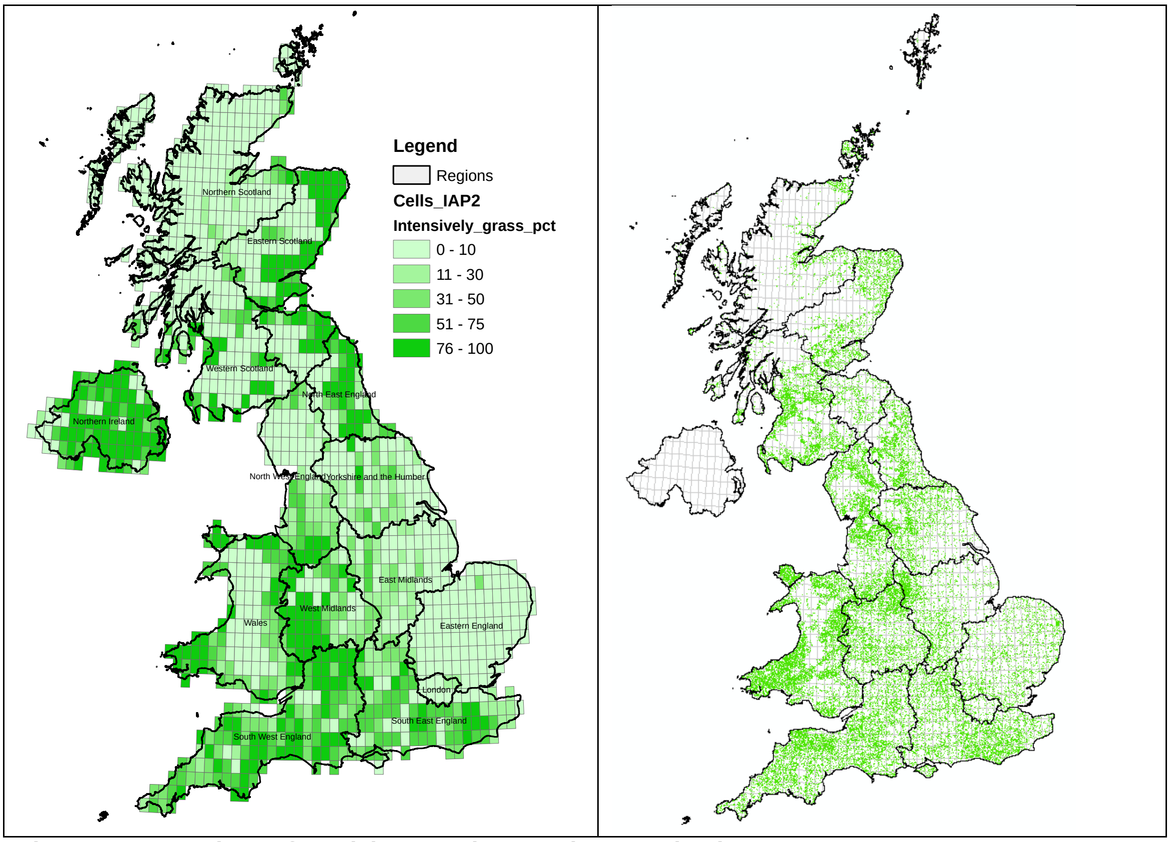


Figure 7 Comparison of spatial pattern in Intensive grassland IAP2 to LCMGB

Figure 7 compares the intensive grass class from the IAP2 outputs with the LCMGB's Improved Grassland class (Value 4).The intensive grassland class appears well matched with IAP2. This is particularly evident in areas where there are defined gaps in both IAP2 and LCM 2007 data (e.g. central Wales; coastal areas of North East England; central Dumfries and Galloway).

Explanation

Within the IAP2 model, intensive grassland is allocated in areas where the profitability for grass is >350€ and the profit for grass-based commodities (milk, meat etc.) is greater than the potential arable profit from the same cell. The IAP2 modelling suggests that in the UK the climate and soils are well suited for grasslands, especially when considered at a European scale. This is the opposite story to that for croplands. So, in the IAP2's optimised world, the UK focuses more on grassland and less on crops, leaving crop production to areas of mainland Europe with better suited soils and climate. This is reflected in an overestimation (+20%) of the UK's grassland area relative to LCMGB whilst the arable area is underestimated (-30%) relative to LCMGB.

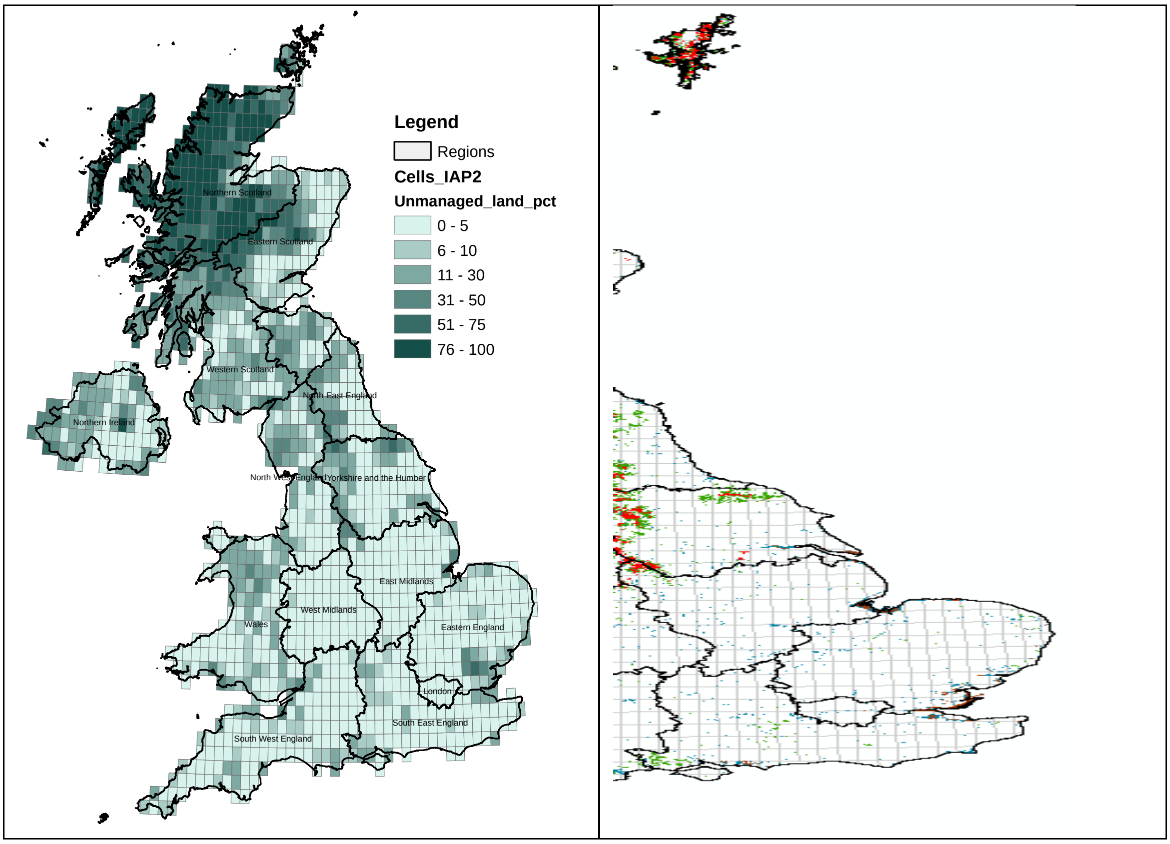


Figure 8 Comparison of spatial pattern of unmanaged land IAP2 to LCMGB

The unmanaged land class is compared with the sum of LCMGB' land use classes from Values 9-21 (Fen, Marsh and Swamp; Heather; Heather grassland; Bog; Montane Habitats; Inland Rock; Saltwater; Freshwater; Supra-littoral Rock; Supra-littoral Sediment; Littoral Rock; Littoral sediment, and Saltmarsh) in Figure 8. The match here is strong reflecting the fact that the soil data is an input to the IAP2. The soils that underlie these land use classes is often too poor for agriculture or forestry.

Explanation

At baseline, the presence of unmanaged land is driven by the very poor quality of the soils in these areas. As such the fit is relatively good with the LCMGB classes, the majority of which have very poor soils for productive purposes. Land use is a continuum and it is possible that heather and heather grassland classes should be considered under the very poor end of the extensive grassland. This should be borne in mind, but the purpose here is to illustrate comparison and the areas are small and the fit is good between the IAP2 and LCMGB for unmanaged land.

Total forestry (the sum of managed and unmanaged forest classes) from the IAP2 outputs are compared with the LCMGB's total forestry (as calculated as the sum of the Coniferous and Broadleaved wood class Values 1 and 2) in Figure 9.

The extensive grassland class from the IAP2 outputs map most directly on to the Rough Grassland class (value 8, in dark purple in Figure 10). Figure 10 also illustrates natural grassland classes of acid, calcareous and neutral grasslands (classes 5-7, lighter purples/pinks) which could be classified by the IAP2 as either extensive grassland or unmanaged land classes.

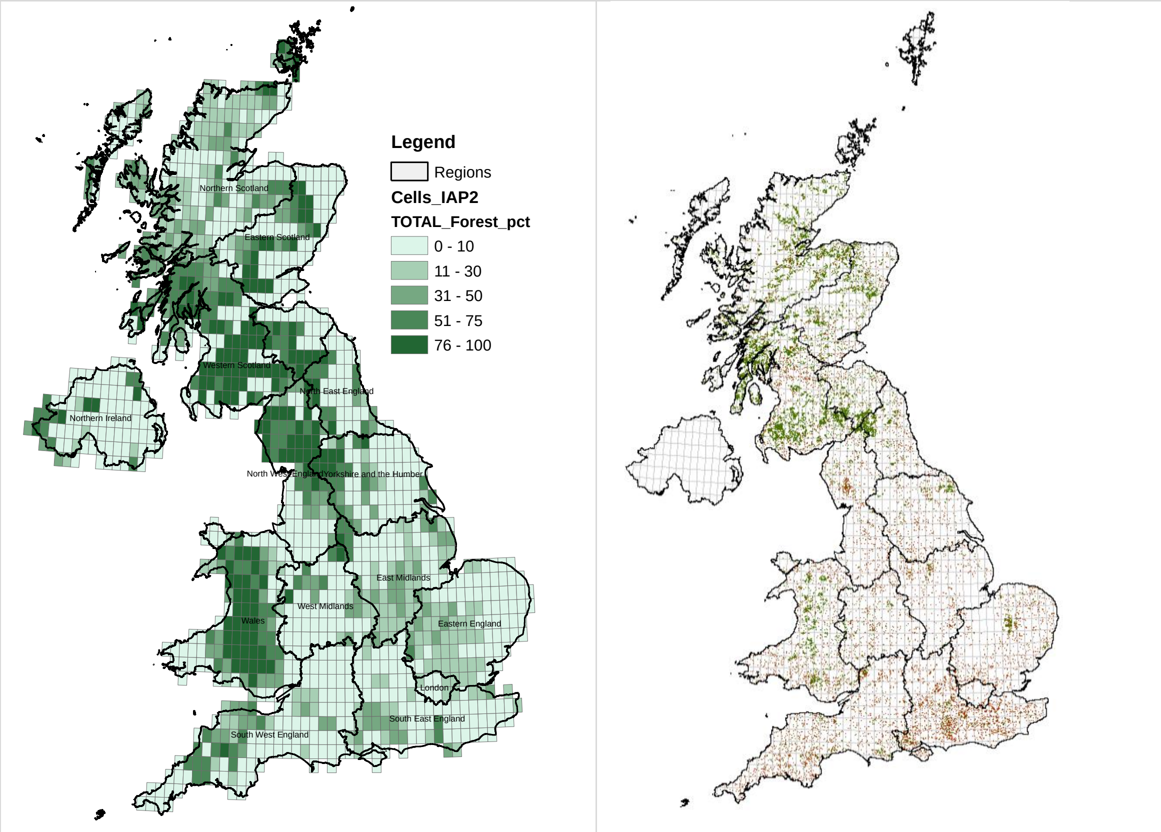


Figure 9 Comparison of spatial pattern of total forest area IAP2 to LCMGB

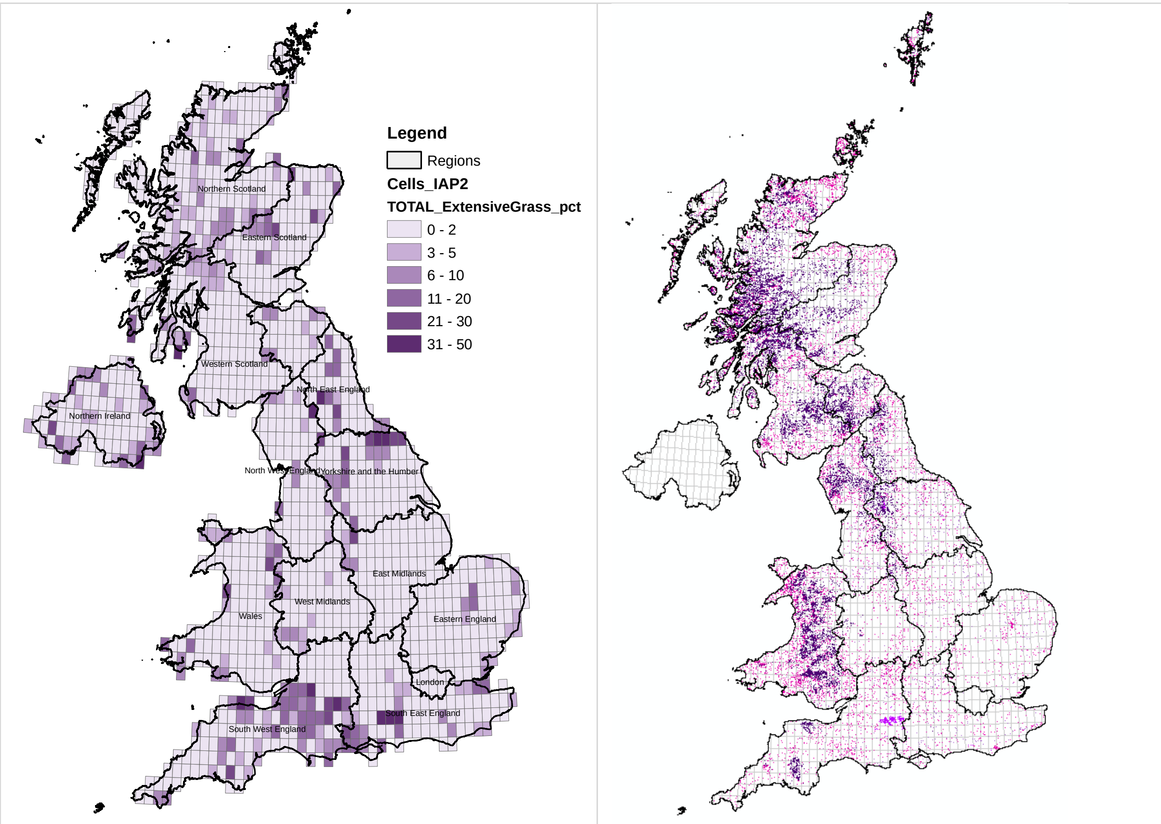


Figure 10 Comparison of spatial pattern of extensive grassland area IAP2 to LCMGB

The IAP2 overestimates forestry and underestimates extensive grasslands. The IAP2 identifies the UK's major forest areas well, but overestimates the total amount of forestry present and almost all of it is considered to be “managed forest” i.e. forestry that can contribute to meeting the EU’s demand for wood products (note the absence of unmanaged forest in Figure 9). This reflects the fact that the IAP2 modelling interprets the UK’s climate and soils as having significant potential for productive forestry, and that in many areas (such as Wales, Scotland and Cumbria) which are, in LCMGB, dominated by extensive, rough, acid, neutral or calcareous grassland would be more profitable if managed as forest.

Explanation

There are a number of possible reasons for this mis-match between the model and the LCMGB data with respect to extensive grasslands. Firstly, the extensive grassland land *use* class output from the IAP2 would not be expected to have a 1 to 1 fit with the LCMGB’s land *cover* classes related to grassland type (rough, calcareous, acid, neutral). Secondly, within the IAP2, land use is on a continuum. Land will be allocated as either managed forestry or extensive grassland if the profitability is between €150 and €350 depending on whether grass or timber profitability is higher in the scenario. As such, in areas where rough or natural grasslands are allocated as forest occur as a result of the cells value for timber profitability being greater than grass. Similarly, in areas where rough and natural grasslands in LCMGB are mapped to intensive grassland, this reflects the profitability of grasslands tipping over the 350€ threshold. It may be that some of the low end of the intensive grassland category should be reclassified as extensive grassland in Phase 2.

2.2.3 Correcting for discrepancies in forestry and extensive grassland

To adjust for the discrepancies between LCMGB and the IAP2 a simple correction was applied to the IAP2 output data (Figure 11). The process calculated and compared the over and under-estimation of forest and extensive classes respectively. Where forest was overestimated, the process reallocated as much of this overestimated area from forestry to extensive grassland as was needed to compensate for the underestimation of extensive grassland in the same grid cell. The process was applied to each IAP2 grid cell.

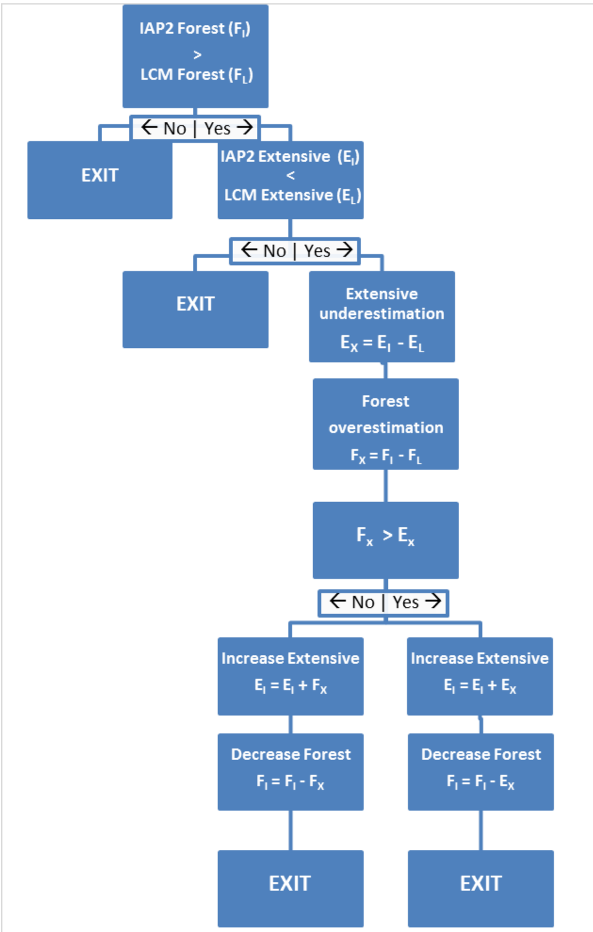


Figure 11 Post-processing approach to correct for IAP2-LCMGB discrepancies. The Process is applied to each grid cell of the IAP2 output. F = total forest; E = extensive grassland; $_I$ = IAP2, $_L$ = LCMGB 2007.

The post-correction diagrams for extensive grassland and forestry (Figures 12 and 13, below) show considerable improvements in fit to UK land use particularly in Extensive grassland shows considerable in Wales and Scotland; corrected forestry shows a noticeable lessening in over estimation in these same areas.

Implications of post-processing

Applying a post-processing approach to force an adjustment to baseline conditions implies a number of assumptions. Raw land use outputs from the IAP2 are internally consistent. They are achieved by balancing a large number of interlinked factors across Europe that lead to projections for timber and grass yields on which profitability is determined. Manually adjusting the land use is only consistent with the modelling by making the assumption that somewhere else in Europe a counterbalance is reached that ensures the total food and timber demands are still met. In addition, the assumption that baseline conditions (e.g. LCMGB2007 land cover) can be used as a “truth” to “correct” modelled land use to, becomes less robust the further in to the future to corrections are applied (due to climate and socio-economic change between the two time periods). This is particularly true in extreme scenarios where the land suitability may change considerably from baseline, and the areas of Europe that might be appropriate to counterbalance at baseline, may be in greater demand for e.g. food production due to climatic/socio-economic change. For this reason the area corrected from forestry to extensive grassland is calculated as a separate land use class, and shown as such on figures and diagrams that follow. In addition, a scenario variable has been added, which tells the “converter” whether or not to apply the post-processing step or to leave the areas as forest as originally modelled.

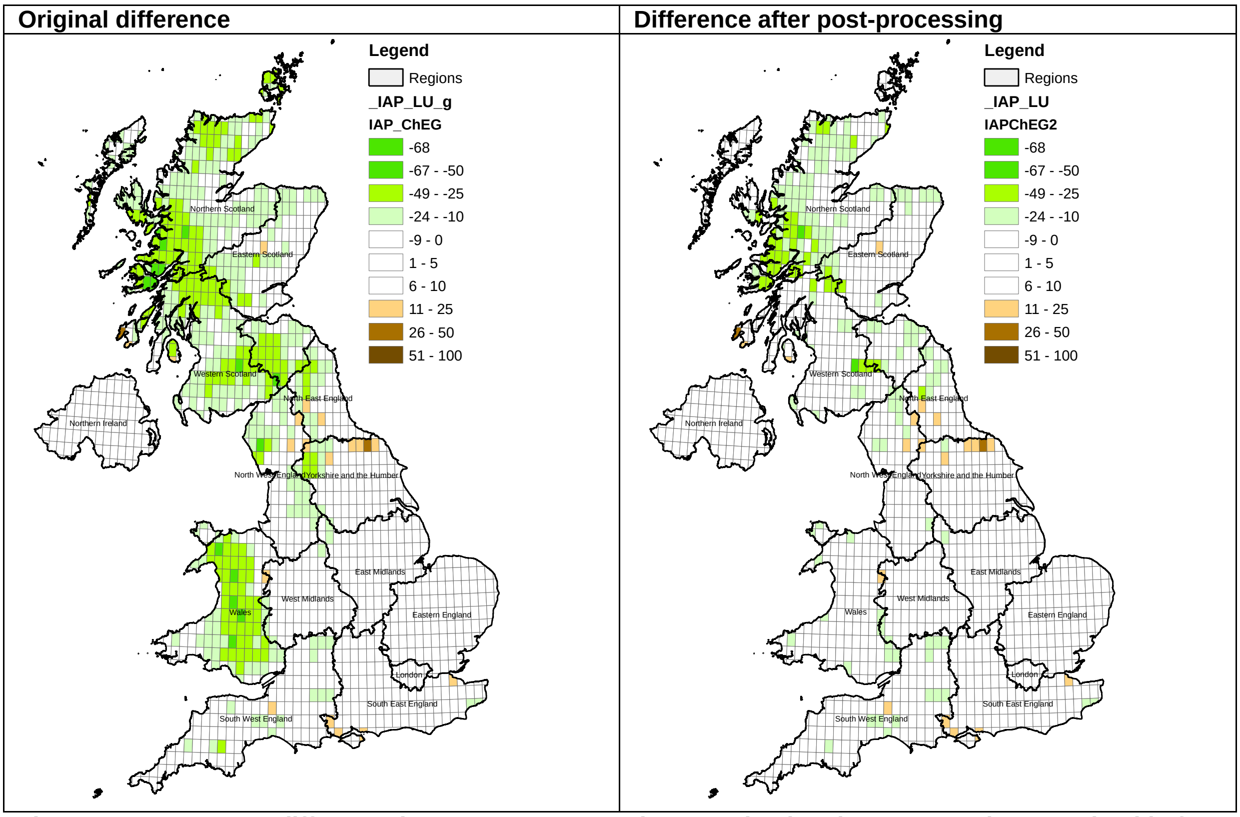


Figure 12 Percentage difference between IAP2 extensive grassland and LCM extensive grassland before and after post-processing applied.

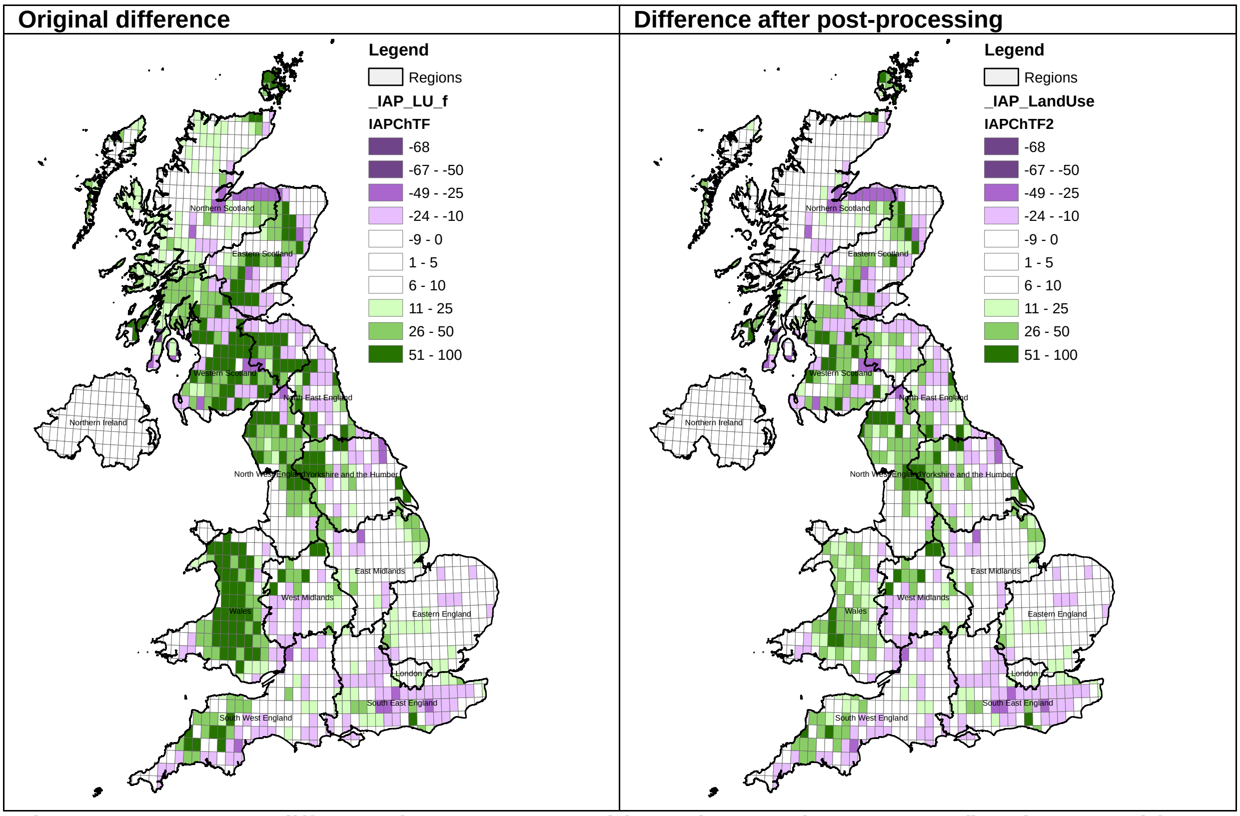


Figure 13 Percentage difference between IAP2 total forest (managed + unmanaged) and LCM total forest (conifer + broadleaf) before and after post-processing applied.

2.2.4 Assessment of Total GB land use

Figure 14 and Table 2 summarise the IAP2 and LCM land use classification at the GB scale. The bright yellow class shows the result of the post-processing correcting forest to grassland (section 2.2.3). The comparison of the final distributions shows broad agreement for some land types. Changes relative to baseline proportions are quite large: even using post-processed values for most classes are in the range of +/- 30%, with the exception of forestry which is overestimated by +60%. The values are smaller relative to the total land area: the greatest difference in mapped proportions is only 7% relative to the total coverage of land use in the UK. Urban area and unmanaged land are relatively well estimated with differences of 1% and c. 0% respectively. However, it is clear that arable land and extensive grassland remain underestimated, whilst forestry and intensive grassland are overestimated. As discussed above further post-processing of forest and grassland classes would be needed to better adjust the values to match the LCMGB.

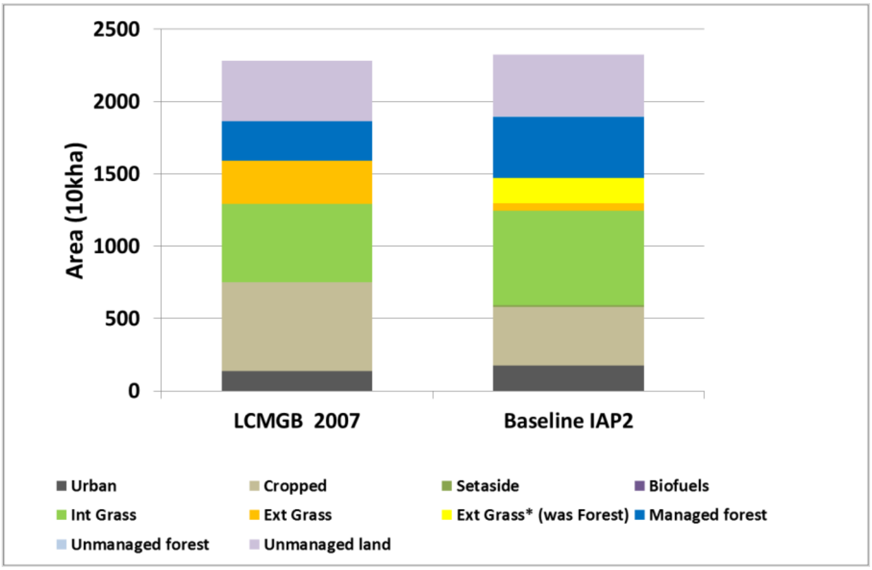


Figure 14 Comparison of LCMGB2007 with IAP2 modelled land use, for baseline (excludes Northern Ireland)

	Urban	Arable	Int. Grass	Ext. Grass	Forest	Unmanaged Land
Change as proportion of total land use	+1%	-7%	+4%	-2%	+5%	0%
Difference Change (kHa)	+39.3	-207.8	+112.9	-64.2	+156.3	+9.0
Change relative to LCMGB land use	+30%	-30%	+20%	-20%	+60%	0%

Table 3 Comparison of LCMGB2007 with IAP2 modelled land use, for baseline.

2.2.5 What are the reasons for the differences between IAP2 and LCMGB?

The IAP2 is a model designed to explore far-future scenarios (2050s and 2080s) under which climatic and socio-economic changes may lead to marginal lands becoming more profitable (and lands that are profitable now becoming less so). As such, the modelling needs to be based on core biophysical principles such as soil and climate, which provide the key constraints on land use potential. The model then needs to allocate, within the areas that are capable of delivering needed commodities, which areas get prioritised over others given the socio-cultural settings of the future world. The IAP2 model uses the *potential profitability* of different land uses as the means to determining allocation. In doing so it takes into consideration both the demand for commodities determined as a factor of socio-economic inputs (e.g. population, diet preference) and supply as constrained by soil and climate-related conditions (e.g. yield, water availability, relative profitability of other sectors) and socio-economic changes (e.g. changes in technology, irrigation etc.). The resultant maps from the IAP2 are therefore profit optimised maps of potential land use.

These maps differ from LCMGB as, in reality, land use is not driven solely by profitability, but by a number of factors that include a range of socio-political and economic factors (e.g. tradition, inertia, subsidy, policy constraint etc.). Furthermore, the difference is exacerbated by the fact that the profit is being optimised at a European scale. As such the -30% cropland and +20% intensive grassland reflects the fact that the IAP2 has optimised demand by producing cropland elsewhere in Europe and prioritising intensive grassland in the UK. Similarly, the +60% forest relative to baseline reflects the fact that many areas of the UK are modelled to be more profitable than the extensive grassland given the UK's soils and climate.

It is possible to post-process the outputs to better fit them to known conditions (e.g. to correct the over-estimation of forest to extensive grassland, or to ensure targets for forest planting are met). The corrections reflect the fact that land use is a continuum and that the thresholds used to separate classes to best fit at the European scale, may not be the best when applied in detail to a single country. Doing so assumes that the commodities no longer produced in the UK are possible to be produced else in Europe. In extreme scenarios (e.g. high-end climate or considerable population change) analysis at the European scale would be needed to ensure that this assumption is internally consistent with the model (i.e. to ensure that the pressures on the rest of Europe aren't so great that there is not sufficient flexibility within the system).

It is important to understand the IAP2's projection of the world at baseline to be able to better interpret its projections of the future and to identify steps that are needed to better customise it to the UK in Phase 2. However, the real strength of the IAP2 is in its ability to explore the implications of the future land management pathways driven by a wide range of "what if" scenarios. As such, the model doesn't have to be able to perfectly reproduce current day land use patterns – the patterns should be judged in light of the question: is this a reasonable distribution of UK land use were land use to be driven by profit maximisation within bioclimatic constraints? The IAP2 can then be used to monitor change from this baseline to explore the impact of different scenarios of the future in a way that considers cross-sectoral interactions and socio-economic and biophysical constraints. This allows the scenarios produced to "sense check" guidance developed in the absence of these considerations.

The following observations can be made as a result of the Phase 1 modelling outputs presented here:

- Believable patterns in land use are produced by the IAP2
- There are notable under-estimations in some classes and over-estimations in others
- It is possible to post-process to correct land use to better reflect baseline conditions
- Any corrections need to be assessed at the European scale to ensure internal consistency is preserved, particularly in extreme scenarios
- Purpose isn't perfect replication of current land use but to sense check guidance in a way that takes cross-sectoral interactions and socio-economic and biophysical constraints into consideration.

3 Step 2: Exploring the MACC

3.1 What is the MACC?

The MACC is the Marginal Abatement Cost Curve developed by the Scotland's Rural College (SRUC) and Ricardo-AEA in 2015 for the CCC to estimate cost-effective emissions abatement for the UK's Fifth Carbon Budget (2028-32). The model exists in an MS Excel workbook with integrated macros. This easily accessible format allowed our team to have full access to the model's internal functions and integrate it with outputs from IAP2.

The MACC model was originally used to analyse the abatement potential of 24 mitigation measures. The abatement potential of each mitigation measure was calculated using methods recommended by the *Guidelines for National Greenhouse Gas Inventories* (IPCC 2006); input data from the 2012 and 2013 National Atmospheric Emissions Inventories (NAEI), and projected data on agricultural activities between 2010 – 2022 from the FAPRI-UK study (Agri-Food and Biosciences Institute 2015).

The MACC model is capable of analysing four different abatement scenarios which represent different degrees of uptake of mitigation measures:

i. Maximum technical potential (theoretical maximum abatement achievable by a measure, assumes 100% uptake). This scenario was estimated using a linearly increasing uptake from the current level (starting from zero additional uptake in 2015).

ii. High feasible potential (Measures have a high potential for abatement, but can be difficult to implement/monitor/enforce. Requires more stringent policy)

iii. Central feasible potential (Includes financial incentives for uptake, and consequences for emissions; focus on carbon price and energy costs)

iv. Low feasible potential (lowest uptake is for measures that are most expensive; requires information/education policies)

The 'High feasible potential' abatement scenario (bold above) was used for the CCC's Central Scenario recommended for the Fifth Carbon Budget. The CCC's estimates also included abatement from a further three measures external to the MACC based on existing Defra analysis. Taking into account interaction of measures, the CCC central scenario identified cost-effective abatement potential by 2030 of: 8.6 $MtCO_2e$ in agriculture and a further 2.4 $MtCO_2e$ from planting more trees.

The Central Scenario assumes a 'more stringent policy framework' will be in place to implement mitigation measures than is currently the case. The influence of levels of uptake and the applicability of individual measures for each different land use on the abatement potential of mitigation measures is also built into the MACC model.

In addition to abatement scenarios, the MACC has been manipulated to use IAP2 land use scenarios as inputs. These scenarios reflect changes in livestock numbers or crop coverage as a result of cross-sectoral changes. This means that the MACC can be customised to reflect the land use changes associated with the 5th CB land use scenario both with and without applying the 5th CB abatement scenario's mitigation measures. To do this we modified the following settings:

- **Crop inputs** – crop inputs from the IAP2 are converted to the crop inputs needed for the MACC (section 3.2.1)
- **Livestock inputs** – livestock inputs for the MACC are approximated using IAP2 land use proportions of intensive and extensive grassland (section 3.2.2.)

The following section describes the process of matching currently applied. The final scenarios are described in Section 5 of this report.

3.2 Comparing 5th CB MACC inputs with IAP2 baseline outputs

This project aims to use the land use and crop-related outputs of the IAP2 as input parameters to the MACC, so as to enable the MACC to calculate emissions, abatement-related indicators and the impact on land use change that reflect the land use scenarios modelled. The first step towards this is to identify the crop and livestock input variables the MACC based its emissions/abatement projections on. The MACC model contains several input spreadsheets, each contributing underlying inputs to calculation and results sheets. These inputs include:

i. Agricultural information based on national statistics (e.g. June census data https://www.gov.uk/government/statistical-data-sets/structure-of-the-agricultural-industry-in-england-and-the-uk-at-june)
ii. Projected estimates for future scenarios (.e.g. land use in 2050) based on these data but extrapolated to the future using the outputs of the FAPRI model by SRUC (Eory et al. 2015). These projections were typically generated using either linear or logarithmic trends.

Within this project the aim is to replace these input variables with the same variables using different data based on an interpretation of the IAP2's outputs (e.g. IAP2's crop yields, approximations of livestock numbers from grass land cover). The following sections put forward methods by which the MACC input variables (crops and livestock) can be estimated from IAP2 outputs. It also compares these IAP2-based inputs with the inputs the MACC used in the research underpinning the 5th CB.

3.2.1 Input data for crops

The IAP2 calculates the total crops required to meet European food and animal feed demand (not including demand from any exports). However, it models a subset of all potential crops (see Arable land in section 2.1.2), and doesn't go to the same level of categorical detail as the MACC. As such the IAP2 categories needed to be mapped to the MACC crop types. Where the mapping was not 1:1, it was necessary to use expert judgement, based on knowledge of the broad crop types that the IAP2 models (e.g. that potatoes are used to reflect all high value vegetables) in order to map the IAP2's crop types to those included in the MACC (Table 3). A justification of this approach is provided below.

However, please note the initial matching is illustrative to demonstrate proof of concept. It would be further refined in consultation with sectoral experts in future research (e.g. Phase 2).

Justification for linkages:

- **Other cereals:** this is allocated to winter wheat as winter wheat represents the major cereal crop modelled.
- **Other crops not for stockfeeding (linseed etc.**): this was allocated to spring wheat as it is often considered as a potential spring crop.
- **Oats:** this was allocated to winter barley, but could equally be allocated to winter wheat.
- **Peas and beans for human consumption** and **"other horticultural crops"**: these were allocated to potatoes as the IAP2 potato class is used to reflect a range of high-end products targeted at human consumption.
- **Peas for harvesting dry and field beans:** this was allocated as a subset of winter oil seed rape, which represents the broader class of lower value break crops.
- **Maize:** in the IAP2 maize (corn for human consumption) is modelled separately from forage maize (for livestock feed). In the MACC the two are reported together as Maize as a subset of fodder crops. To link the two the IAP2's [Maize + forage maize] were linked to the MACC's [Maize + Other Fodder Crops] and distributed using the MACC input data's proportions.

Where more than one variable was mapped to a single IAP2 class a conversion factor is calculated that reflects the baseline proportions of the two variables combined using the original MACC data. For example the conversion "factor" of 99% for winter wheat shown in Table 4 is calculated based on the MACC data's proportional relationship between "winter wheat" area (1755 kHa) and "other cereals" (24kHa) area: 0.99 = 1755 / (1755 + 24). The relationships were calculated using devolved administration data where the information was available, as this is the format of the MACC inputs.

The final outputs (Figure 15 and Table 4) do correlate closely with the MACC input data, particularly for the major crops (covering >500kHa) winter wheat and winter oilseed rape both of which are within 10% of the MACC baseline values, as are potatoes. Winter Barley, Spring Wheat and Oats are overestimated whilst spring crops of barley and oil seed rape are underestimated, although the baseline amount of Spring oilseed rape is negligible (30kHa). Maize is significantly over-estimated; three times the MACC's input values (Figure 15 and Table 4). However, relative to the total crop area, all changes are <5% and the majority are <1%.

MACC input variable		Factor		IAP2 Class
Winter Wheat	=	99%	of IAP2	Winter wheat
Other cereals	=	1%	of IAP2	Winter wheat
Spring Wheat	=	55%	of IAP2	Spring wheat
Other arable crops not for stockfeeding (linseed, hops, other)	=	45%	of IAP2	Spring wheat
Winter Barley	=	75%	of IAP2	Winter barley
Oat	=	25%	of IAP2	Winter barley
Spring Barley	=	100%	of IAP2	Spring barley
Winter Oil Seed Rape	=	76%	of IAP2	Winter oilseed rape
Peas for harvesting dry and field beans	=	24%	of IAP2	Winter oilseed rape
Spring Oil Seed Rape	=	100%	of IAP2	Spring oilseed rape
Potatoes	=	41%	of IAP2	Potatoes
Peas and beans for human consumption	=	18%	of IAP2	Potatoes
Other horticultural crops	=	42%	of IAP2	Potatoes
Sugar beet (not for stockfeeding)	=	100%	of IAP2	Sugar beet
Maize	=	89%	of IAP2	Forage maize + Maize
Other fodder crops	=	11%	of IAP2	Forage maize + Maize
Grass over 5 years old	=	100%	of IAP2	Permanent grass
Temporary grass under 5 years old	=	100%	of IAP2	Grass
Sole right rough grazing	=	100%	of IAP2	Extensive grass
Uncropped arable land	=	100%	of IAP2	Setaside % * Arable
Other land on agricultural holdings	=		kept constant	
On-farm woodland	=		kept constant	
Land used for outdoor pigs and All other non-agricultural land	=		kept constant	

Table 4 Example mapping MACC input parameters from IAP2 outputs for England.

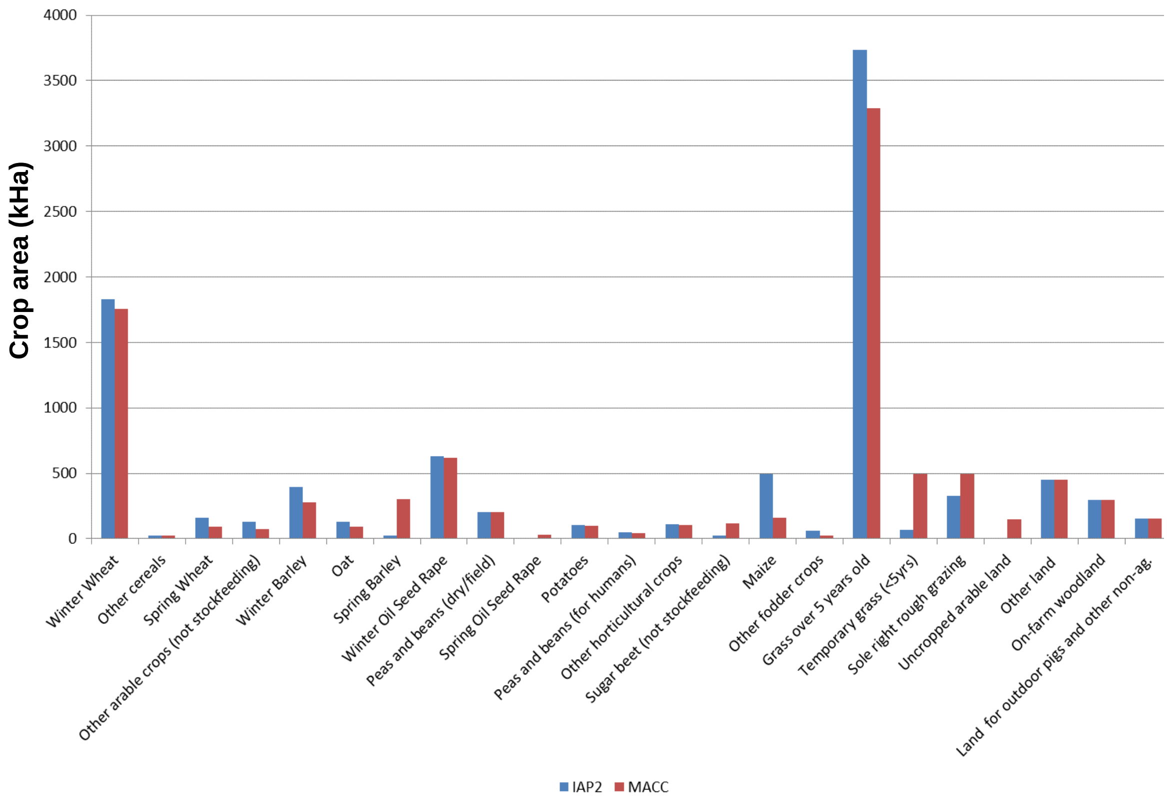


Figure 15 IAP2-based estimations of UK baseline crops as used by the MACC (y axis is crop area in kHa)

Crop (kHA)	IAP2	MACC 2010	Proportion of baseline value (%)	Change % total crops
Winter Wheat	1827.1	1754.7	104%	-0.8%
Other cereals	25.1	24.1	104%	0.0%
Spring Wheat	162.8	92.4	**176%**	-0.7%
Other arable crops (not stockfeeding)	130.9	74.2	**176%**	-0.6%
Winter Barley	392.1	275.7	142%	-1.2%
Oat	128.5	90.3	142%	-0.4%
Spring Barley	23.4	302.8	8%	**3.0%**
Winter Oil Seed Rape	632.5	619.7	102%	-0.1%
Peas and beans (dry/field)	205.1	201.0	102%	0.0%
Spring Oil Seed Rape	0.0	30.9	**0%**	0.3%
Potatoes	107.0	99.9	107%	-0.1%
Peas and beans (for humans)	46.0	42.9	107%	0.0%
Other horticultural crops	109.4	102.2	107%	-0.1%
Sugar beet (not stockfeeding)	22.0	118.5	**19%**	1.0%
Maize	492.0	161.7	**304%**	**-3.5%**
Other fodder crops	63.7	20.9	**304%**	-0.5%
Grass over 5 years old	3736.7	3288.4	114%	**-4.8%**
Temporary grass (<5yrs)	64.1	492.6	**13%**	**4.6%**
Sole right rough grazing	325.8	493.0	**66%**	**1.8%**
Uncropped arable land	1.2	149.3	**1%**	**1.6%**

Crop (kHA)	IAP2	MACC 2010	Proportion of baseline value (%)	Change % total crops
Other land	452.0	452.0	100%	0.0%
On-farm woodland	295.3	295.3	100%	0.0%
Land for outdoor pigs and other non-ag.	156.7	156.7	100%	0.0%

Table 5 IAP2-based estimations of UK baseline crop (proportion of baseline value as %) as used by the MACC.

3.2.2 Input data for livestock

The IAP2 does not output livestock units as a variable. It does however calculate them internally within the system in order to meet red meat demand as a factor of grassland area and grass yields. Both grassland area and yields (t/ha) are outputs from the IAP2 allowing total tonnage of grass to be calculated. As such it was necessary to develop a post-processing mechanism to estimate livestock numbers based on this (total grass tonnes) data.

6a	1000 Head of Cattle (approximated from IAP2 intensive grass tonnage)	1000 Head of Cattle (MACC 2015)	Proportion (IAP2 estimate divided by original MACC numbers)
England	5364	5311	101%
Scotland	1980	1781	111%
Wales	1103	1093	101%
Northern Ireland	1498	1762	85%
TOTAL	9946	9946	100%

6b	1000 Head of Sheep (approximated from IAP2 extensive grass tonnage)	1000 Head of Sheep (MACC 2015)	Proportion
England	8100	10382	78%
Scotland	8937	4288	208%
Wales	4372	6031	73%
Northern Ireland	572	1281	45%
TOTAL	21982	21982	100%

Table 6 Projected IAP2-based livestock numbers compared to MACC data for 2010.

Livestock numbers were originally modelled on the basis of FAPRI projections in the MACC. This allowed the MACC access to projections of livestock numbers to 2030. To ensure that the IAP2 livestock numbers matched the MACC numbers underlying the 5th Carbon Budget a method was developed to calculate a UK stocking density from the MACC's input data and the IAP2's land use information. The IAP2-based MACC input variables for livestock (Table 6) were calculated by taking the FAPRI numbers for UK total cattle and sheep numbers (9.946 million and 21.982 million respectively) and the total tonnes of intensive and extensive grass calculated by the IAP2. Grass tonnage was calculated by multiplying the IAP2 modelled grassland area (ha) by the modelled yield (t/ha). Cattle densities were calculated using intensive grassland tonnage and sheep densities were calculated using extensive grassland tonnage. The resulting stocking densities are 0.0001303 cattle/tonne grass yield per hectare, and 0.0017426 sheep/tonne grass yield per hectare.

The resulting projection is mathematically bound to provide the correct numbers at the UK scale (as total national grass tonnage was used in the equation). At a devolved administration level the projected cattle numbers are very close to the MACC figures within +/- 7% (Table 5). The sheep numbers are less well projected, with the number of sheep in Scotland double that expected and those in England, Wales and Northern Ireland lower than expected (Table 5).

The proposed approach is an initial demonstration that should be further refined in future research, in consultation with sectoral experts. For example, it would be possible to use a regionally-weighted approach to stocking density rather than the national scale approach currently applied. This is available as an option within the current “converter” post-processing. It assumes that the weightings of the devolved administrations would remain constant, and that the current distribution of sheep were not distributed by as much by the availability of appropriate grass as by national stocking practices.

Within the MACC, livestock classes are broken down in greater detail in terms of the various categories within each type of livestock (e.g. within “total cattle” to “beef cattle” and “cows”) and then further still within these classes (heifers, replacement females 1-2yrs etc.) (as shown in Table 6).

IAP Land Cover category	**External input**	**Corresponding MACC variables**
Intensive grassland (kha) Permanent grass yield (t/ha) Grass yield (t/ha)	Ratio of dairy and beef cattle numbers per hectare	All cattle (1000 head)
		Dairy cows Dairy heifers Dairy replacement females, 1-2y Dairy replacement calves, 0-1y Beef cows Beef heifers Beef replacement females, 1-2y Beef replacement calves, 0-1y Dairy cattle for meat, 6-18m, female Dairy cattle for meat, 6-18m, male Beef cattle for meat, 6-18m, female Beef cattle for meat, 6-18m, male All calves, 0-6m Other cattle
Extensive grassland (kha) Extensive grass yield (t/ha)	Ratio of sheep numbers per hectare	All sheep (1000 head)
		Ewes Lambs, 0-1y Other sheep
Change in white meat demand (%) scenario input.	*No input – we will not change estimates for pigs in the MACC*	*All pigs*
		All pigs *Sows* *Other pigs*

Table 7 Mapping IAP2 land use outputs to MACC livestock variables

To calculate these values from the IAP2 projected livestock land use we assume the proportions evident in the MACC 2015 values remain constant in all scenarios. For example, according to the MACC 2015 input values for livestock, 1,156,400 of the total 5,310,578 cattle in England were dairy cows. This equates to a relative proportion of 21.8% of all cattle being dairy cows. This proportion was then applied to the total estimated number of cattle (from IAP2 data), to calculate the IAP2 estimate of dairy cow numbers in England. The results of applying this method are illustrated in Figure 16. It should be noticed that whilst this method was used to calculate the numbers of cattle in different classes the total number of cattle was driven by scenario parameters that influence demand for meat (i.e. dietary preference for meat, total population etc.). Future work could look to better modify the proportions of dairy and beef cows in the different classes in scenarios where diet preferences change (i.e. to reduce beef cow numbers).

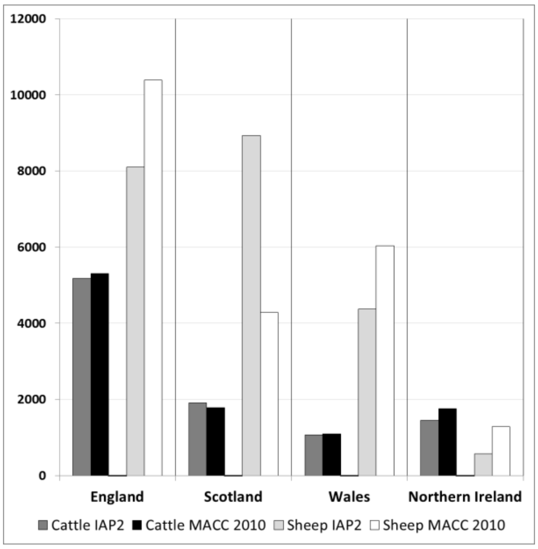


Figure 16 Estimated sheep and cattle numbers by devolved administration

Increased pig and chicken numbers influence land use via feed provision (increasing white meat consumption increases the feed required and thus arable land area). Unlike sheep and cows, the land use needs of non-ruminants are considered to be much smaller (they do not forcibly need grass for grazing). As such, chicken/pig numbers are increased/ decreased proportionally from their MACC 2015 baseline numbers by the scenario parameter "change in dietary preference for white meat". Sub-classes within these classes are calculated proportionally in the same way as discussed above for sheep/cattle.

3.2.3 Abatement scenarios

The MACC has a number of abatement scenarios embedded within it. Within Phase 1 of this project we are focussing only on the 'High feasible potential' scenario used to derive the CCC's 5th Carbon Budget central scenario. However, when the MACC is run it also produces outputs for a "reference scenario" which uses the same land use inputs without any abatement options applied. This reflects the raw effects of land use and livestock change in the absence of mitigation. For the "High feasible potential" scenario, the maximum potential abatement of mitigation options in addition to those demonstrated by land use change can be calculated for each mitigation option individually (this is discussed further in Section 6.2). **The CCC's 5th CB report considered the interactions between measures and in Phase 2 this is something that will be possible to apply to the IAP2-MACC linked system abatement options.**

4 Step 3: Scenario development

This sub-section defines the scenarios which were run during Phase 1 of the Project. Scenarios were run through the linked IAP2 and MACC models to generate the results in Section 6 of this report.

The first scenario reflected a “true baseline”: current climate with 2010 socio-economic settings. In addition, three future socioeconomic land use scenarios were run: an adaptation scenario that seeks to maximise the benefits to biodiversity from land use choices; a mitigation scenario that replicates the fifth carbon budget and a future “baseline” control scenario run using a baseline scenario with no changes made from 2010 settings for any driver. Each of the three socioeconomic scenarios was run with two climate model projections for the IPCC’s Representative Concentration Pathways (RCP) climate scenarios (IPCC 2013; Table SPM-2):

- **RCP 2.6 (c. 1.5°C rise):** Global annual GHG emissions will peak between 2010 and 2020, and decline substantially from 2021 onwards. Projects a mean of 1.0°C increase[4] in the Global Mean Surface Temperature (likely range between 0.4 to 1.6°C) between 2046 and 2065.

- **RCP 4.5 (c. 2°C rise):** Global annual GHG emissions will peak between around 2040, and then decline. Projects a mean of 1.4°C increase in the Global Mean Surface Temperature (likely range between 0.9 to 2.0°C) between 2046 and 2065.

Thus, the seven land use scenarios run to demonstrate the function of the IAP2 and MACC models as they are linked together were as follows:

i. Current socioeconomic baseline under baseline climate conditions
ii. 5th Carbon budget scenario – 2050, under RCP 2.6
iii. 5th Carbon budget scenario – 2050, under RCP 4.5
iv. Adaptation scenario (for biodiversity) – 2050, under RCP 2.6
v. Adaptation scenario (for biodiversity) – 2050, under RCP 4.5
vi. Current socioeconomic baseline under RCP 2.6
vii. Current socioeconomic baseline under RCP 4.5

Of these scenarios the future baseline land use scenarios (vi and vii) reflect additional analysis brought in to help distinguish changes in land use and adaptation indicators driven by climate from those driven by socio-economics. They are discussed in section 6.1 on adaptation metrics. MACC analysis focused only on the scenarios put forward by the CCC and, as such, land use scenarios i–v are discussed in section 6.2 (mitigation).

4.1.1 Socio-economic scenarios underpinning the IAP2’s land use scenarios

Socio-economic scenarios within the IAP2 are fed in as quantified slider values reflecting a number of factors driving land use change. The default settings for sliders in the IAP2 model are those of the 2010 baseline and the CCC’s scenarios were modified from this starting point. Downscaled European settings for the IPCC shared socio-economic pathways (SSPs) were used to provide a comparable context when determining slider settings for future scenarios in Phase 1 (as described below). These settings are downscaled to Europe from the global SSPs within stakeholder processes within the IMPRESSIONS project (e.g. Kok et al., 2015 at www.impressions-project.eu).

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[4] Relative to the reference period of 1986-2005 (IPCC 2013; Table SPM.2, p23

The CCC specifications for Phase I focus on two scenarios:

- The mitigation scenario will be based on the central abatement scenario estimated by the CCC for the fifth carbon budget (2028-32)[5]. This mitigation scenario to be called the ***'5th CB mitigation scenario'*** will comprise abatement pathways in agriculture and forestry.

- **The adaptation scenario** should seek to maximise the land use and management options to benefit biodiversity under a changing climate, and provide resulting values for all of the adaptation-related metrics available in the model.

When considering the slider settings it is important to note that the scenario settings reflect Europe-wide changes in the given indicator. The IAP2 is not designed to customise for a given country. This means that for some variables (e.g. population) where there are considerable inter-country differences (e.g. spatial disparity in growth rates and indeed projected population decline in some) the slider setting needs to reflect the overall European level of change within which the UK's trend sits.

The settings chosen also do not reflect a likely future world; they have been chosen as example settings to match the scenarios requested by the CCC in order to test the capability of the IAP2 model.

The settings used can be further modified in the second phase of the project: the intention of this phase of the project is to demonstrate the potential impacts of the socio-economic drivers on land use, and to demonstrate the IAP2's ability to match the 5th CB scenario inputs. Socio-economic sliders settings are customised for the year 2050 to match the IAP2's climate data.

Justification for slider settings:

Slider values for the 5th CB land use scenario were quantified with reference to the "central scenario" underpinning the 5th Carbon Budget. Slider values for the adaptation land use scenario were quantified in a way that minimised pressure placed on the food system to prevent arable expansion with the intention of minimising impacts on non-arable biodiversity. Table 7 below summarises the settings used and the following section details the logic behind the selection of each scenario setting in turn. For both future land use scenarios, setting levels were made with reference to pre-defined 2050s socio-economic scenarios for the IPCC's shared socio-economic pathways as downscaled for Europe within the stakeholder processes embedded within the IMPRESSIONS project (Kok and Pedde, 2016[6]). These scenarios were used to give a 'scope of possibility' for slider settings drawing on an existing stakeholder process.

Population change:

The 5th CB quantifies UK population change as one of its macro drivers of emissions. It uses DECC (now BEIS) interim projections from October 2015 to describe a 10% increase in population by 2030. Using a linear trend this would suggest a 24% rise (relative to 2014) by 2050. However, to reflect this as a 24% increase in European population would not be consistent with current projections of European population[7] which indicate a total European population increase of 6.4% - and includes,

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[5] CCC (2015) *'Sectoral scenarios for the fifth carbon budget'.*
[6] IMPRESSIONS Deliverable found at: http://www.impressions-project.eu/documents/1/
[7] http://www.iiasa.ac.at/web/home/research/researchPrograms/WorldPopulation/PublicationsMediaCoverage/ModelsData/EuropeanDataSheet2016_web.pdf

within it, a UK rise in population of 24%. Thus, 6.4% was used as the value underpinning the population change in Europe.

As the purpose of the hypothetical adaptation scenario is to focus on land management and land use change options to benefit biodiversity, and increasing population will put additional pressures on the food system, there is no population change within the adaptation scenario.

	5^{th} CB	Adaptation	Baseline	SSP1 (Ad ☺.Mit☺)	SSP3 (Ad ☹.Mit☹)	SSP4 (Ad ☹.Mit☺)	SSP5 (AD ☺.Mit☹)
EU population change. (% from current)	+6.4%	0	0	+11%	-20%	-6%	+37
Water savings due to behavioural change (% change from current)	0	20	0	+21.5	0	0	+0
Change in dietary preferences for beef and lamb (% change from current)	0	-55	0	-55	0	0	+22
Change in dietary preferences for chicken and pork (% change from current)	0	-55	0	-11	+21	+21	+67
Household externalities (Preferences for lived environment: 1 = Urban; 5=Country)	3	1	3	4	4	3	5
Compact vs sprawled development (Low = Sprawl; Medium or High = Compact)	Med	Compact	Med	Compact	Sprawl	Med	Low
Desire to live by coast (Low – High)	Med	Low	Med	Low	High	Low	High
Change in agricultural mechanisation (change in the amount of labour saving mechanisation) % from current	+10	+30	0	+49	-18	+49	+49
Water savings due to technological change (% from current)	0	+30	0	+29.1	29.1	+29.1	+29.1
Change in agricultural yields (%change of current)	+10	+10	0	-10%	-18%	+35	+35
Change in irrigation efficiency. Percentage increase in water efficiency relative to current (2010).	+10	+20	0	0	0	0	0
Increase in arable land used for biofuel production (% change from 2010)	+4%	0	0	+4.1%	+8.3%	+4.1	+6.2
Food imports(% change from 2010)	0	+20%	0	-5.3%	-5.3%	+4.3	+4.3
GDP as % changes relative to current.	+95%	+95%	0	+173%	+51%	+144%	+334%
Change in energy price(oil; % of2010)	140%	140%	100%	162%	267%	267%	75%
Land allocated to set-aside/buffer strips/beetle banks etc.	4	5	3	4%	3%	4%	0%
***Post processing:** Targeting of “set-aside” at woodland (UK)*	50%	100%	33%	-	-	-	-
Reductions in diffuse pollution by reduced crop fertiliser/pesticide inputs 1= no change; >1 is a decrease in crop inputs	1.2	1	1	1.4	1	1	1
Plant Climatically Appropriate	No	Yes	No	No	No	No	No

	5th CB	Adaptation	Baseline	SSP1 (Ad ☺.Mit☺)	SSP3 (Ad ☹.Mit☹)	SSP4 (Ad ☹.Mit☺)	SSP5 (AD ☺.Mit☹)
Trees?							
Protected Area Increase	0	+100%	0	0	0	0	0
Protected Area target land use (Target Forest, Grassland or "Other" unmanaged land uses – or "even split")	N/A	Even	N/A	N/A	N/A	N/A	N/A
Process for new areas: prioritise buffering existing areas or target connectivity by prioritising areas without existing PA.	N/A	Connect →Buffer	N/A	N/A	N/A	N/A	N/A
Afforestation target (UK, 10kHa)	370.6	None	None	-	-	-	-
Keep Extensive Grassland where present at LCMGB Baseline over Forest (% of possible correction → EG) (UK)	0%	100%	100%	-	-	-	-

Table 8 Scenario settings for the 5th CB scenario and the adaptation scenario. Also, for reference, the 2050 scenario settings for the 4 IPCC socio-economic pathways for Europe developed within the IMPRESSIONS project and the settings for 2010 baseline.

Behavioural changes in Diet and Water Savings

These social factors are kept at baseline levels (no change) within the 5th CB scenario as there is no mention of behavioural change of the general populous.

Behavioural changes in water savings modify the water used by in people's homes (i.e. domestic water use). Water savings were included within the adaptation scenario to remove some of the pressure on the water system, and by proxy increase the amount of water potentially available for the agricultural system. By making this change more water is available for both the environment and for irrigation, where needed. The value was set to 20% saving relative to baseline, based on that of SSP1, an optimistic scenario where innovations are successful and there are limited challenges for adaptation.

Dietary change can be set for both red and white meat. Initial levels of per person demand and prices for commodities are set within the model based on EU statistics. Dietary change sliders modify the demand for these commodities from these initial settings. As such, setting dietary preference for meat to -55% would reduce the per person demand for meat commodity and any associated feed to 45% of baseline demand (100% -55% = 45%). This would then be multiplied by the population, modified by wealth and the proportion of food imported to calculate a European food demand. In a situation with no changes in other sliders (population etc.), current prices would over-produce meat and associated feed (as demand has lowered). The model would then reduce the price of meat and associated feed and run again, iterating until the demand was met.

Diet change influences the demand for meat and feed related commodities which in turn influences the relative profitability of land use through land requirements for grazing (with increased red meat demand) and through increased need for feed and/or fodder crops (with an increase in either red or white demand). In the 5th CB scenario dietary preferences were kept the same. In the adaptation scenario dietary preferences for both red and white meat were reduced significantly (reduced by 55%) in line with the European SSP1 settings for 2050 which has similar trends towards vegetarianism as a means to reduce the pressure on the food system.

Social preferences for lived environment

Social preferences for lived environment (i.e. whether people prefer to live in cities or the countryside, in sprawling or compact settlements and closer to the coast or not) were set to no change from baseline within the 5^{th} CB scenario.

Within the adaptation scenario, to minimise the impacts of urban growth on the environment, settings were selected that would prefer compact developments in urban rather than rural areas and avoiding coastal developments to minimise negative impacts in these areas.

Changes in agricultural practice and agricultural and water-industry technology

Within the 5^{th} Carbon budget scenario there is an implied focus on development of agricultural technologies and efficient farming. As such it seemed reasonable to assume an increase in agricultural mechanisation, yields and irrigation efficiency. Without any specific guidance on these, within the 5^{th} CB reports mechanisation, yields and irrigation efficiency were set to increase 10%, well within the plausible limits of the IPCC scenarios. In the adaptation scenario, higher levels of mechanisation and irrigation efficiency were used (+30% and + 20% respectively).

Water savings through technological change reflects changes in water saving technology in domestic, industry and power sectors. Increased efficiency leaves more water available for irrigation, if needed. In the adaptation strategy this was considered to be important as a way to reduce impacts on the agricultural system, and an increase in efficiency of 30% was modelled. Settings for water savings were left at no change from baseline for the 5^{th} CB scenario.

Fertiliser application

The slider reflects the reduction in diffuse source pollution by using less fertiliser than the optimum – which is set to 1. The actual fertiliser usage, which is then considered in the yields modelling can be calculated as: **fertiliser use = optimum use / diffuse pollution slider**.

So a slider value of 1.2 would equate to 1/1.2 = 83.33% of optimum use. The t/ha would vary by crop.

Agricultural yields

The agricultural yields slider reflects changes in yields due to technology (e.g. genetic modification, breeding and disease management). It feeds into the modelling as a direct modifier on the agricultural yields. A setting of 10 would increase the agricultural yields by 10%.

Changes in Biofuel crops

The CLIMSAVE IAP2 models biofuel crops as a proportion of additional arable crops required that are not used for human consumption or livestock feed. Forest-product-based biofuels are not modelled within the IAP2. In the 5^{th} CB there is a stated intention to increase bioenergy to 10% of primary energy. However, this is not a 10% increase in agricultural land set aside for biofuel crops, nor is it reflective of the *European* value for biofuel change. To reflect an increase in interest in Biofuel crops across the European continent, including the UK, the biofuels settings of SSP1 were used (+4% increase in arable land) in the 5^{th} CB scenario.

Increasing the amount of land area taken out of agricultural production for biofuels increases the total land area needed to meet the additional demand for biofuels on top of existing demands for food + feed and thus reduces the land for other purposes. As a result, within the adaptation scenario biofuels were set to baseline values (no change) to prevent arable expansion into other land uses.

Changes in food imports

Changes in food imports were not a focus of the 5^{th} Carbon Budget for agriculture. As such the value is left as zero, no change from baseline.

Increasing food imports is one of the most effective mechanisms to reduce pressure on the food system, minimising the need to modify European landscape to meet food demand. In the adaptation scenario, there is a +20% increase in food imports. This setting is higher than those proposed within the SSPs (e.g. +5%) but reflects a scenario where land use is maximised to benefit biodiversity) It is, of course, important to recognise that there may well be knock on effects on the land use practices in the areas from which the imports come.

GDP and Energy price

These values were specified within the central scenario macro drivers (GDP +47%; Oil price +19%). They were then extrapolated to 2050s values as a +95% increase in GDP and a +140% rise in energy price. The same values are used for both the 5th CB scenario and the adaptation scenario.

Agricultural land allocated to non-productive purposes.

Referred to as “set-aside” within the IAP2 terminology this variable represents the proportion of arable land that is taken out of crop production for any other purpose. Though conceived to reflect agri-environment type schemes (on-farm woodlands, set-aside, buffer strips, beetle banks etc.) it could equally be used to include an increase in on farm development. It is a very useful variable with respect to customising the IAP2 for the UK as beyond specifying that the land must be capable of producing crops (and therefor would be sufficiently fertile for most other land uses) the exact land use component it represents can be determined by post-processing.

The 5th CB includes an increase in agro-forestry of 0.6% in addition to existing 1% of land that is hedgerows and shelter belts. The default value for the “set-aside” slider is 3% and so this increase in agro-forestry is reflected by an increase in set-aside to 4%. Again, this is at a European scale and would imply that there is an increase in agroforestry in all EU member states.

Increasing the “set-aside” slider increases the total amount of arable land required to meet food, feed and biofuel demands plus the additional agro-environmental component. However, new post-processing developed for this project allows a proportion of set-aside to be allocated as agro-forestry. This allows areas dominated by arable land to provide opportunities for forest species they would be otherwise locked out of. In the adaptation scenario set-aside % is set as 5% (above the 5th CB’s 4% and baseline’s 3%) and 100% of the land is allocated to woodland. In the 5th CB 50% of set-aside is allocated to forest.

Reducing diffuse source pollution

This variable reflects a decrease in the application of fertiliser relative to the optimum. Positive numbers are greater decreases in fertiliser use. The 5th CB has a focus on targeting fertiliser to the times of greatest crop need. This is reflected in the 5th CB sliders as a mild decrease in fertiliser application (factor = 1.2), but less than that of SSP1 where there is a move to more extensive, low-input farming is (factor = 1.4). For the adaptation scenario the setting remains at baseline levels (no change).

Planting climatically appropriate trees

Within the IAP2 the default situation is for forests to be planted with trees that are climatically appropriate at baseline, without considering the future climate. This is the setting used within the baseline and 5th climate budget scenarios. In the adaptation scenario the optimum climatically suitable trees are planted within the Atlantic region (including the UK).

Protected areas (PA)

Within the IAP2 protected areas, based on Natura 2000 protected areas, are prevented from becoming more intensive in terms of land use (where the order of “intensiveness” is Arable > Intensive Grassland > Extensive Grassland > Forest > Unmanaged Land). This means, even if an area of land within a PA would be more profitable as a more intensive land use, it will not become that intensive land use.

In the 5^{th} CB scenario there is no increase in protected areas, as none is implied within the 5^{th} carbon budget. However, in the adaptation scenario protected areas are encouraged to increase by 100%, targeting areas with low levels of protected area at baseline. This aims to build connectivity by encouraging many small patches first before then expanding existing areas. The approach to allocating new PA is evenly split to target extensive grassland, forests and unmanaged land (including heaths, moors etc.).

Afforestation Target

The 5th CB has an aspiration for 15.6 kha yr^{-1} of forest planting through to 2030. The baseline forest area from FC statistics was taken to be 3160 kha in 2016 (FC figures[8]). There are 34 years between 2016 and 2050. Thus, assuming that the 5th CB's afforestation planting target continues through to 2050 we would expect the forest area in 2050 to be:

$$3160 \text{ kha} + (34 \text{ years} \times 15.6 \text{kha } yr^{-1}) = 3706 \text{kha forest.}$$

As such, to be consistent with the 5th CB the UK's modelled forest land use should have at least 3706 kha of forest. However, by 2050, many areas may not be projected by the IAP2 to have forests as the most profitable use of land, as grass yields in the UK are likely to considerably increase leading to the IAP2 projecting grassland as the preferred land use in many areas. To customise the 5th CB land use scenarios to better match the 5th Carbon Budget's expectations for the forest sector an additional post-processing module has been developed to ensure the UK meets its afforestation aspiration irrespective of the IAP2's profitability. This post-processing uses an afforestation target value which ensures that a minimum of that amount of forestry is found in the scenario. The target value is set to 3706kha in the 5th CB scenario. There is no target applied in the Baseline or Adaptation scenarios. The post-processing module, and its underlying assumptions, is discussed in 5.1.1.

Maintain extensive grassland

The IAP2's profitability calculations at baseline suggest that many areas of the UK would be more profitable as forests than as natural or extensive grasslands. This includes significant areas of Wales and Scotland (see Section 2.2.3). A post-processing option has been added that compares baseline LCMGB grid cell proportions of extensive/natural grasslands and forest and identifies the area of land in which there is an underestimation of extensive grass that is matched by an, at least equal, overestimation in forestry. A scenario parameter is used to determine, of the proportion that could be either extensive grass or forest, how much is allocated to each class. This approach is used to allocate 100% of this land to grassland in the baseline and adaptation scenarios. In the baseline scenario this is so as to better reflect current UK land cover, and in the adaptation scenario it is to protect grassland areas from land use change to encourage landscape diversity. In the 5th CB scenarios the correction is not used and 100% of the land is maintained as forestry. The details of the post-processing module, and its underlying assumptions, are discussed in Section 2.2.3.

[8] https://www.forestry.gov.uk/forestry/infd-7aqknx

5 Step 4: Linking the IAP2 and the MACC

5.1 Creating the "converter"

IAP2 outputs are produced as downloadable CSV files that can be opened directly in MS Excel. The MACC is a macro-enabled spreadsheet. To automate the processing required for this project a series of interlinked spreadsheets were developed in Excel that allow the user to import an IAP2 output file for a given scenario and then automatically produce:

1) The land use correction for Forest → Extensive grassland, if scenario appropriate (described in section 2.2.3)
2) The conversion of IAP2 crop outputs to MACC inputs (described in section 3.2.1)
3) The conversion of corrected IAP2 land use outputs to MACC livestock inputs (described in section 3.2.2.
4) The correction of land to forest to ensure that forest-related policy targets can be met through land use correction (describes in section 5.1.1 below)
5) The processing of adaptation indicators (described in section 5.1.2 below).

5.1.1 Post-processing to meet afforestation targets

As afforestation is a fundamental component of the 5th Carbon budget (see Afforestation section of 4.1.1) it is important that the IAP2 can recreate scenarios where forest planting takes place. However, it is not possible with the way that the IAP2 is currently set up to set an afforestation target – afforestation is driven by balancing profitability at the European scale to demand. It is possible to encourage forest growth by increasing the amount of protected areas and targeting them at forestry, and by encouraging foresters to plant the most climate appropriate trees but these approaches are not the same as a policy-driven target to achieve a given area of forest as set out by the 5th Carbon budget.

As a result a new post-processing-based method was developed to convert the IAP2's land uses manually to forestry. First the area of forest within the given scenario is calculated with reference to the afforestation target set (e.g. 3706 kHa or15kha yr^{-1}) until 2050. This is set as the target and land is removed from other land use classes and allocated to forestry in order of land productivity: 1st land is removed from the corrected Forest→Grassland amount post processed to correct for extensive grass underestimation (if this correction is applied in the scenario); 2nd land is removed from extensive grassland; 3rd land is removed from intensive grassland and finally land would be removed from arable. Beyond targeting areas based on yield, there is currently no further spatial targeting of change (as this would require more complex analysis). Instead, any losses are applied proportionally to all grid cells across the UK, i.e. if 60% of extensive grassland is converted to forest, all cells with extensive grassland will have 60% of their grassland area converted to forest and the remaining 40% left as extensive grassland. Note that forestry was not allocated to unmanaged land; if the soil and climate were suitable the land would already have been classified as unmanaged forestry.

As with the previous correction (section 2.2.3), it is important to remember that this post-processing has some inherent assumptions underpinning it. There are two main considerations. Firstly, the IAP2's allocation is driven by profitability, in the context of the scenario. Forcing the model to ignore this reflects (realistic) assumptions that land owners and policy makers are deliberately acting in a way that is prioritising other goals. Whilst this may be a logical choice reflecting the implementation of a top-down policy framework for carbon sequestration / forest ecosystem services above all else it is important to reflect on what this might mean in some scenarios quite different from today. It could for example mean choosing not to make the most of some of the opportunities offered by climate change in terms of increased agricultural yields. Equally, in some of the more extreme climates, it could also reflect the UK not responding to the food/timber crises that occur when production in more southerly nations are put under considerable pressure by the changing climate.

Additionally, from a modelling perspective, care must be taken to avoid unbalancing the internally consistent world modelled by the IAP2. Food and timber production distributions are inherent within the land use patterns the IAP2 creates. If one area is post processed into a different land use this can only be kept internally consistent with the assumption that another area of Europe produces those commodities – which may be harder to justify in more extreme scenarios where there is less flexibility in the land use system due to climatic and socio-economic constraints.

5.2 Generating indicators for adaptation

Post-processing was required to convert some of the outputs of the combined models into indicator values; namely for indicators which function as indices (combining multiple outputs to give an overall assessment of condition). As described in Section 2.2 of this report, model results from each of the individual grid cells of the IAP2 model were aggregated to regional level order for each scenario. This meant that results for indices, which were originally calculated for individual grid cells, needed to be re-calculated manually at a regional scale.

Indicators, based on those used in Dunford et al., (2015) are used to compare adaptation-related impacts between scenarios:

- Food provision;
- Timber provision;
- Water Exploitation Index;
- Irrigation usage;
- People flooded (in a 1/100 year event);
- Carbon sequestration;
- Landscape Experience Indices (x2);
- Land Use Diversity index
- Biodiversity indices.

Adaptation indicator	Contributing outputs from IAP2	Calculation method
Food provision*	Food production per region (TJ)	Sum grid cell total food production by region
Timber provision*	• Timber production per region (Mt) • Area of managed forest within each region (10 kHa)	Multiply timber produced by area of managed forest (including metric conversions) to calculate tonnes produced per hectare
Carbon sequestration	Total carbon stored in the biomass of areas of intensive and extensive agriculture; forests, and unmanaged land (Mt per year)	Sum grid cell total carbon stored by region
Water Exploitation Index (WEI)	• Total water use per region (mill. m^3/year) • Water availability (mill. m^3/year)	Divide total water use by water availability to calculate a value for WEI (no units). Compare WEI value against conditions to assess degree of water stress. If WEI is > 0.4, the region will be under severe water stress. If WEI is < 0.2, the region will be under low water stress (thresholds from Alcamo et al, 2006)
Irrigation required	• Total irrigation usage (mill. m^3/year)	Sum grid cell total usage by region
People flooded	• People flooded (x100 people)	Sum grid cell flooded people by region based on coastal and fluvial flooding modelled at the European scale.
Landscape Experience Index I (non-productive land)	• Total land area of each region (kHa) • Area of unmanaged land per region (kHa)	Sum areas of unmanaged land; unmanaged forest; extensive grassland and set-aside land within each region. Divide by the total regional area, and then multiply by 100 to calculate the percentage of the total area that is not

Adaptation indicator	Contributing outputs from IAP2	Calculation method
	• Area of unmanaged forest per region (kHa) • Area of extensive grassland per region (kHa) • Area set-aside for future agricultural use (kHa)	managed intensively for provisioning services.
Landscape Experience Index II (non-productive land)	As above but also including managed forests	As above but also including managed forests
Land Use Diversity*	Shannon Index values for the six major land use classes (forestry; arable; intensive grassland; extensive grassland; abandoned land, and urban).	Calculate Shannon index values based on the proportions of the six land use classes by region. Shannon index = $H' = -\sum_{i=1}^{R} p_i \ln p_i$ /ln(R)
Biodiversity Existence/Bequest indicators based on species indices	For each species: Amount of climate-habitat space that remains stable under the given scenario Amount of existing climate-habitat space lost Proportion of each region covered with suitable climate-habitat space	For each species baseline sum the number of grid cells for which each species is projected to have appropriate climate and habitat space. Sum by region. Sum the regional counts for individual species into groups (e.g. arable species, forest species, charismatic species etc. see table 13) and divide by the size of the number of cells I the region. Calculate these indices at baseline and for each scenario calculate proportional changes from these baseline figures.

Table 9 Indicators for adaptation, using outputs from IAP2 (from Dunford et al. 2015 and Berry et al. 2006)[9]

The calculation of Biodiversity Existence/Bequest Indices (Table 8) required grouping of several species from the IAP2 model into categories. The species included; the groups they are collected in, and information on the habitat masking applied is detailed in Appendix C.

[9] *Sources:* *Dunford et al. 2015; ^Berry et al. 2006, in Dunford et al. 2015

6 Step 5: Running the linked IAP2-MACC system

Following the completion of Steps 1-4 above it was possible to run the linked system. In practice this involved:

- In the IAP2
  - Creating scenario input files based on the settings in Table 7 for both the 5th CB and adaptation scenarios
  - Running the two scenarios under an RCP 2.6 and 4.5 climates (four model runs)
  - Running the IAP2 baseline scenario (fifth model run)
  - Exporting each of the seven scenario runs as CSV files
- In the converter
  - In turn, copying each CSV file into the converter which then
    - Applied corrections
    - Calculated adaptation indicators
    - Estimated livestock and crop values
  - Copy the livestock and crop values
- The MACC
  - Input the livestock and crop values
  - Run the MACC macro
  - Extract mitigation-related variables.

The following sections highlight the outputs of the linked system both in terms of land use, adaptation and mitigation indicators:

- Section 6.1: results on land use change, changes in emissions and adaptation indicators (without 5th CB mitigation) for each of the scenarios derived from the IAP2 outputs.
- Section 6.2, results on land use change, abatement and emissions following 5th CB mitigation measures (6.2)

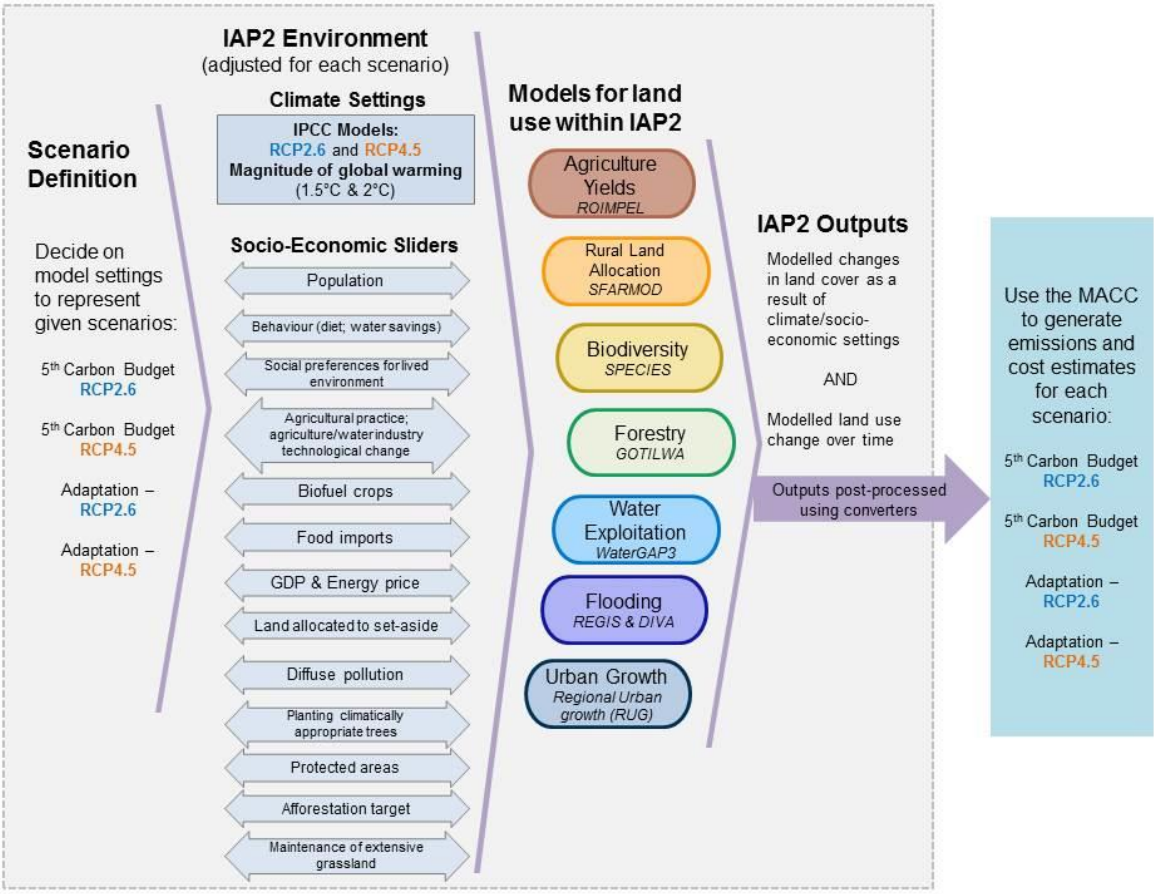


Figure 17 Overview of the Phase 1 modelling approach at Step 5

6.1 Results: Adaptation related indicators

6.1.1 Baseline (2010)

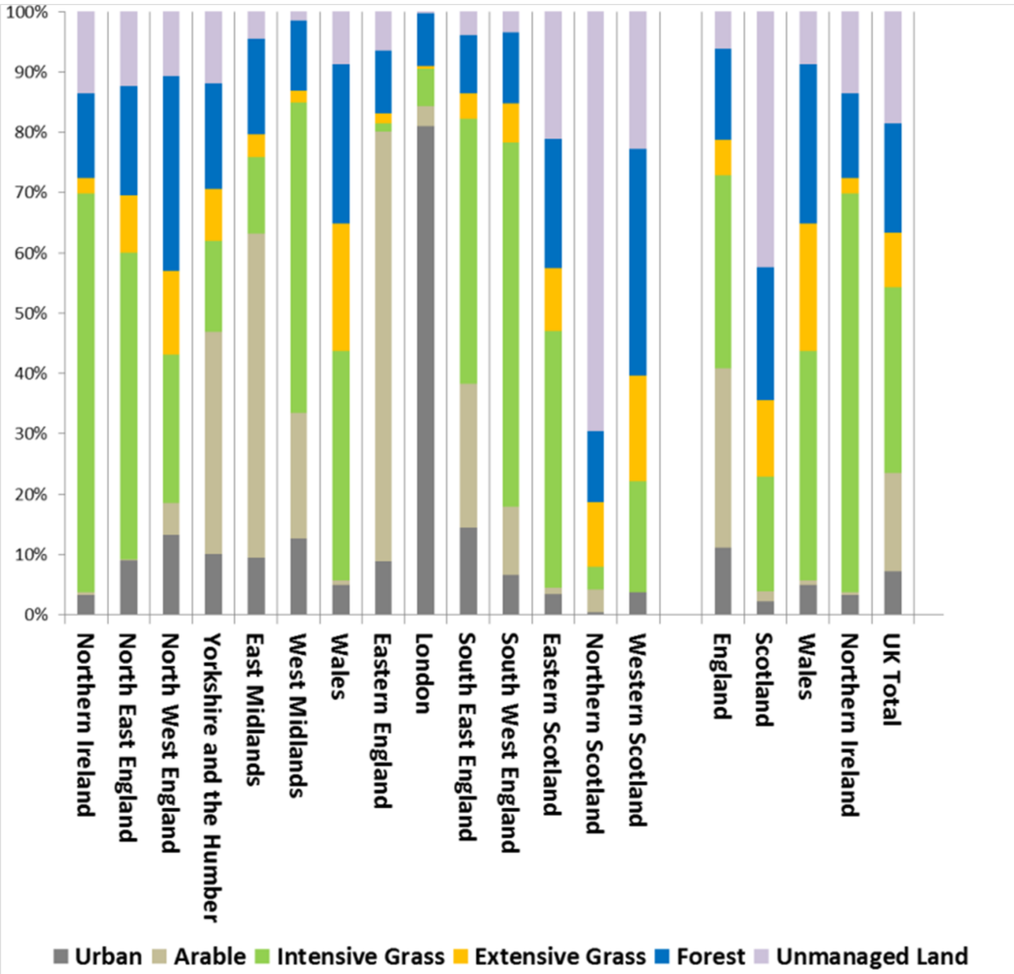


Figure 18 2010 Baseline regional distribution of land use

Figure 18 highlights the regional distribution of land use as output from the IAP. Stacked bar graphs such as these are very useful for getting a quick overview of the regional impacts of combined climate and socio-economic change on the land use system. At baseline the distributions are sensible, and reflect the spatial analysis discussed in section 2.2. Urban land dominates the London region, arable land dominates the east of England and major forested areas in the North of England and Scotland are clear. Scotland has the greatest proportion of unmanaged land; Northern Ireland has the greatest proportion of intensive grassland. Wales and Scotland both have larger proportions of extensive grassland than England and NI and England has more arable land than any of the devolved administrations.

In terms of adaptation indicators (Table 9), the east of England is highlighted as the largest food producing region of the country. Water exploitation is highest in London where, even at baseline, water use is 70% of the available water suggesting severe water stress, the threshold for which is 0.4 (or 40%) (Alcamo et al., 2008). A number of other regions are also close to the moderate water risk threshold of 0.2 particularly the South East and West, the Midlands and Wales. Irrigation usage is highest in Eastern England (c. 80 mill m^3) but it is also modelled as profitable to apply in Yorkshire and Humber, both Midland regions and the south west – where it is likely to be contributing to the potential for water stress. Flood-related problems are modelled to be greatest in South Eastern England, Yorkshire, the East Midlands and the South West.

Region	Food Production (TJ)	Water Exploitation Index	Irrigation usage (mill. mÂ^3)	People flooded (x100persons)	Timber production (Mt)	Landscape Experience Index (I)	Landscape Experience Index (II)	Land use Diversity
Northern Ireland	35394	0.03	0.00	505	1034	16.4	30.2	0.59
North East England	12461	0.02	0.00	183	856	21.9	40.0	0.76
North West England	17721	0.06	0.00	469	2673	24.7	56.9	0.92
Yorkshire and the Humber	64375	0.12	17.11	3234	1210	20.5	37.9	0.92
East Midlands	95040	0.16	36.17	1105	924	8.3	24.1	0.77
West Midlands	48517	0.15	16.96	462	499	3.6	15.1	0.74
Wales	27585	0.15	0.00	538	3801	29.7	56.2	0.81
Eastern England	137625	0.15	78.97	2188	591	8.9	18.6	0.56
London	678	0.70	0.02	0	46	0.6	9.5	0.39
South East England	74329	0.17	12.94	4005	582	9.1	17.8	0.82
South West England	70649	0.15	1.86	1101	909	10.0	21.6	0.71
Eastern Scotland	28727	0.02	0.00	286	1501	31.9	53.5	0.79
Northern Scotland	14709	0.02	0.00	210	2020	80.5	92.1	0.57
Western Scotland	12854	0.02	0.00	269	5273	40.3	77.9	0.81
England	521395	0.116	164	12747	8290	12.4	27.1	0.89
Scotland	56291	0.023	0	765	8793	55.2	77.1	0.80
Wales	27585	0.147	0	538	3801	29.7	56.2	0.81
Northern Ireland	35394	0.025	0	505	1034	16.4	30.2	0.59
UK Total (2015)	640664	0.063	164	14555	21918	27.8	45.8	0.94

Table 10 Adaptation indicators values at baseline (2010) (indicator definitions in Table 9)

Timber production and carbon sequestration are both greatest in Scotland, particularly the west (for timber production) and the north (where the unmanaged land and forestry both contribute to carbon sequestration). The land use indices (experience & diversity) are designed to highlight overall changes in land use distribution to highlight broad comparisons with respect to whether the land is more or less intensively managed. Landscape experience is greatest in Scotland and Wales – where large areas of land aren't allocated to intensive purposes – the northern region of Scotland scores particularly high as it has only 7.9% of its land that isn't modelled to be forest, unmanaged land or extensive grassland. A comparison of this region with the Land Use Diversity index helps to highlight the difference between the two indicators. For Land Use Diversity to score highly a region must have a broad range across the six land use classes, representing a multi-functional landscape. Whilst the Northern Scotland region is modelled to have a very natural landscape (with a corresponding high Landscape experience index) – its lack of food producing land (arable and intensive grassland) and urban development leads it to a relatively low diversity index. As such it is on a par with the East of England – whose land use is heavily biased towards arable production. London, dominated by the urban land use (c. 75-80%) has the lowest diversity index (0.39).

The final adaptation indicators focus on the combined climate and habitat space for the 104 species modelled within the IAP2. The indicator uses the "SPECIES" climate envelope model (Pearson and Dawson, 2002) which uses a classification algorithm trained on the modern day distribution of species to project the potential climate space appropriate for that species under other scenarios. This is then compared with the available habitat (land use) projected by the IAP2 (see Appendix C).

No. Species in group-->	9	18	18	24	9	8	8	10	104
Grouping -->	Pollinators	Agriculture	Wetland	Forest	Heathland	Coastal Grazing Marsh	Charismatic	Saltmarsh	TOTAL
Northern Ireland	73.4	24.2	58.1	23.2	32.4	15.8	16.2	0.9	31.3
North East England	80.7	31.0	49.0	26.4	30.4	8.2	15.2	10.2	32.4
North West England	75.8	46.0	56.4	44.6	35.5	21.0	19.1	14.0	42.1
Yorkshire and the Humber	85.2	76.0	45.2	55.8	34.2	18.3	13.9	2.4	46.9
East Midlands	87.9	93.2	33.2	59.9	32.5	14.4	11.5	6.4	48.7
West Midlands	88.0	96.1	34.6	48.9	34.8	0.0	11.1	0.0	45.4
Wales	77.2	30.7	52.4	40.6	35.1	32.9	18.1	7.1	38.1
Eastern England	88.9	97.2	41.1	63.2	31.5	36.6	10.6	15.3	54.0
London	88.9	88.1	23.0	70.8	44.4	25.0	12.5	0.0	50.0
South East England	88.3	97.3	45.3	61.3	33.3	33.4	10.6	10.2	53.7
South West England	81.6	71.4	40.6	41.0	26.5	27.5	11.2	3.0	41.5
Eastern Scotland	69.7	20.4	47.0	27.0	34.3	3.7	20.7	3.0	29.1
Northern Scotland	54.1	21.1	51.7	34.6	35.2	25.4	20.9	0.3	31.9
Western Scotland	67.7	21.9	55.8	40.7	37.2	24.5	21.4	2.7	35.7
England	84.8	79.0	42.6	51.7	32.1	22.4	12.5	7.6	46.5
Scotland	62.1	21.2	51.7	34.4	35.6	19.5	21.0	1.7	32.3
Wales	77.2	30.7	52.4	40.6	35.1	32.9	18.1	7.1	38.1
Northern Ireland	73.4	24.2	58.1	23.2	32.4	15.8	16.2	0.9	31.3
UK Total (2015)	75.4	50.8	47.7	42.7	33.6	21.8	16.2	5.0	39.7

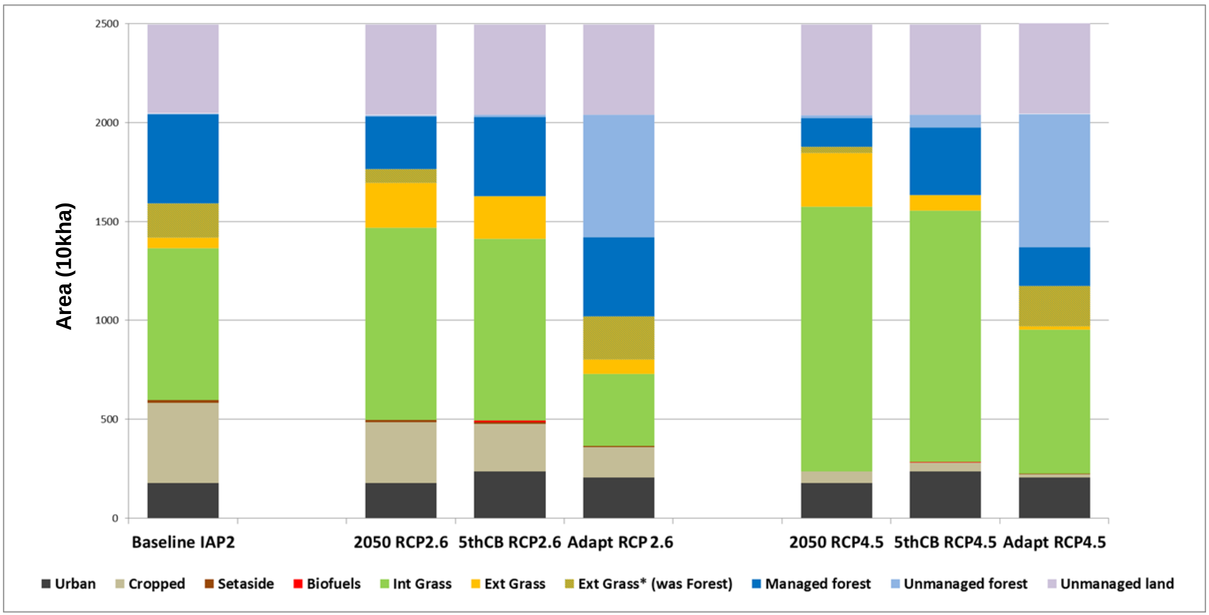
Table 11 Average proportion (%) of species occurrences that have both available climate and habitat in 2010 baseline.

At baseline the indicator assessed (Table 10) is, for a given species group, the average proportion of the species occurrences as a percentage of the possible 1331 cells. It should be noted however that, unlike the other groups, Pollinator species are not masked by land use which will explain why they have relatively higher numbers. Also, Saltmarsh and coastal grazing marsh species are only found in coastal areas, thus their proportional coverage of the 1331 cells will necessarily be low. Finally, many of the charismatic species are selected because of their rarity / specificity to a particular habitat, and would be expected to have smaller projected climate space. In addition, they are selected to reflect European diversity and as such many have limited climate space within the UK at baseline.

However, the biodiversity indicator used in the scenarios reflects *change* from these baseline conditions. As such, it is not the specific numbers that matter as much as how much they increase or decrease as a result of scenario-related changes in climate and habitat.

6.1.2 Land use in each scenario

The results presented below are direct IAP2 outputs for land use scenarios that result by running the IAP2 using the input slider settings introduced in section 4 (i.e. those options in green in Table ES1). Land use changes therefore reflect changes in settings such as population increase, diet change, afforestation targets and improvements in agricultural yields and technology etc. (see section 4) but do not include mitigation measures implemented by the MACC that relate to land management (e.g. those in black in Table ES1). These mitigation measures are the focus of section 6.2.



Source/IAP2 Scenario	Land use (UK area, 10 kHa)											
	Urban	Cropped area	Set-aside	Biofuels	Intensively grass	Extensively grass	New grass (from forest)	Unmanaged land	Managed forest	Unmanaged forest	Total forest	Total area
LCMGB 2007	136	613	-	-	541	300	-	417	273	-	273	2281
IAP2 Baseline	181	406	13	0	767	53	174	449	448	5	453	2497
5th Carbon Budget - RCP2.6	241	240	8	8	919	215	0	456	399	12	419	2497
5th Carbon Budget - RCP4.5	241	44	1	1	1270	80	0	457	341	62	405	2497
Adaptation - RCP2.6	210	154	5	0	363	73	218	456	400	618	1023	2497
Adaptation - RCP4.5	210	15	5	0	727	14	205	457	195	673	869	2497

Figure 19 a) Overview of land use change as a result of scenarios by 2050 b) table showing the underlying data.

The three sets of bars shown in Figure 9 represent a) baseline (2010) socio-economics and climate; b) RCP 2.6 climate and c) RCP 4.5 climate. The three bars within each of the two climate scenarios are:

i) baseline socio-economics (i.e. contemporary, 2010 socio-economic settings); by 2050;

ii) the 5th CB socio-economic scenario by 2050 and
iii) the adaptation socio-economic scenario by 2050.

The results in Figure 19 show that both climatic and socio-economic scenarios have considerable impact on the future land use. The climate-only scenarios (2050 RCP 2.6 and 4.5) allow the impacts of climatic change to be separated from socio-economic change (they represent what would happen if climate changed but socio-economics did not). For these scenarios the climate models are run without changing the socio-economic scenarios (i.e. using baseline socio-economics). They can therefore be seen as 2050 baselines for the two RCPs.

Comparing the climate only scenarios shows intensive grassland covering increasing area, whilst arable agriculture declines. Extensive grassland increases from baseline, and, without any socio-economic change, forestry declines. Under RCP4.5 these changes are more extreme, with arable land all but disappearing and forestry declining to around 30% of its initial 2010 levels. In RCP2.6 the land use changes, though notable, are less severe.

The 5th CB scenario (3rd and 6th bars in Figure 18) achieves its goal of ensuring forest planting targets are met in both scenarios despite climatic drive to reduced forest area (due to increase in yields and an absence of adaptation of tree species towards climatically more appropriate ones). In the RCP 4.5 5th CB scenario some of the afforestation target (in terms of total forest area) is met by unmanaged forestry suggesting that, in this scenario, the UK doesn't have to maximise its timber production capacity.

The Adaptation scenario demonstrated the considerable influence of socio-economic change on future land use possibilities. Under both climate scenarios the adaptation scenario's efforts to remove the pressures on the agricultural system (e.g. the demand for agriculture-related commodities of food and feed, see Figure 19c below) to benefit biodiversity have led to a significant decline in arable cropping beyond that driven by climate alone. There is a significant expansion in unmanaged forestry, and, if the forest→ extensive conversion is used, a significant amount of extensive grassland is maintained.

Interpreting changes in land use in response to the climate and socio-economic drivers

	Food pressure	Key Sector
EU population change. (% from current)	↑	All Food
Change in dietary preferences for beef and lamb (% change from current)	↑	Int/Ext
Change in dietary preferences for chicken and pork (% change from current)	↑	Arable
Increase in arable land used for biofuel production (% change from 2010)	↑	Arable
Land allocated to set-aside/buffer strips/beetle banks etc.	↑	Arable
Reducing diffuse source pollution from agriculture by reduced crop inputs of fertilisers and pesticides (higher=less)	↑	Arable
Plant Climatically Appropriate Trees?	↑	Forest
Protected Area Increase	↑	*Non-food*
Afforestation target (UK, 10kHa)	↑	Forest
Food imports(% change from 2010)	↓	All Food
Water savings due to behavioural change (% change from current)	↓	Irrig
Change in agricultural mechanisation (change in the amount of labour saving mechanisation) % from current	↓	Irrig
Water savings due to technological change (% from current)	↓	Irrig
Change in agricultural yields (%change of current)	↓	Arable
Change in irrigation efficiency. Percentage increase in water efficiency relative to current (2010).	↓	Irrig
Keep Extensive Grassland where present at LCMGB Baseline over Forest (% of possible correction → EG) (UK)	⇆	Ext
Household externalities (Preferences for lived environment: 1 = Urban; 5=Country)	⇆	*Urban*
Compact vs sprawled development (Low = Sprawl; Medium or High = Compact)	⇆	*Urban*
Desire to live by coast (Low – High)	⇆	*Urban*

Figure 19c) Drivers of land use change in terms of their influence on the land use system.

As an integrated modelling system that works across sectors the link between the IAP2 drivers and the resulting land use change can be hard to interpret. Figure 19c provides an overview of the main drivers and their impacts on the land use modelling simplified in terms of:

i) their primary impact on the food system *at the European scale*: either in terms of increasing pressure/demand – leading to agricultural expansion; or decreasing pressure – freeing up land for other uses (such as extensive and unmanaged land classes) and
ii) the primary sectors that are affected by the slider (e.g. does it encourage a particular sector (e.g. forest, arable) or via irrigation water availability for example).

These socio-economic impacts apply at the European scale but are constrained by the biophysical conditions of the soils and climate in each scenario. As such, the decline in arable area reflects the model projecting arable crop demand to be best met by other European countries with more suitable soil and climate. Conversely, the increase in intensive grassland area in the UK shows that, in both 2050s scenarios, the UK's climate and soils are increasingly well suited to contribute to the EU's demand for beef and milk commodities. Land abandonment (an increase in unmanaged classes) doesn't occur in the UK in either the 5th CB or the Baseline Scenarios. This suggests that the whole UK's land area is needed to meet the demands of the European population.

The decline in total forest area seen in the 2050s scenarios reflects an increase in timber yield that results from a changing climate. With greater yields more timber can be produced in a smaller area and as such less forest area is required to meet timber demand. The change in unmanaged forestry can be explained as follows: under baseline and 5th CB targets there is very little land left unproductive in 2050, with the UK contributing towards meeting the EU's timber and food demand targets, so that only naturally unproductive areas (the unmanaged land class) is left unused; this means that there is little room left for unmanaged forests. The reduction in the pressure on Europe to supply its own food and timber due to e.g. the increase in imports and the change in diets within the scenario means that the model is able to identify areas within Europe to meet food and timber demand without having to use the whole of the UK's productive area: this leaves unmanaged land area that is capable of growing trees and thus leads to an expansion in unmanaged forestry.

Carbon sequestration

Carbon sequestration in forestry is calculated as a direct output from the IAP2, but would need further post-processing to ensure it reflected the current post-processed land use (forest → extensive and meeting the forest target). Preliminary, raw outputs from the IAP2 are shown below in Table 12. At baseline the over-projection of forestry leads to a higher value than FC published data by 57Mt C. Future projections show the dramatic increase in forestry within the adaptation scenario leading to a near tripling of carbon sequestration relative to modelled baseline values (847 at BL to 2473 MtC under RCP2.6). Conversely, the mitigation scenario, in which the food system is under more stress and forest cover would decline in the absence of the forest target, shows a decline in total carbon sequestration. However, it should be noted that this decline is based on forest cover **before post-processing**. It would be expected that the baseline value would be lower (once land was post-processed to extensive grassland) and the 5th CB levels should be higher (once the forest target was met). In future research (e.g. Phase 2) a post processing method would need to be developed to allocate sequestered carbon to forest areas established by post processing.

	Carbon sequestered in forests	
	Mt Carbon	$MtCO_{2e}$
FC Published data[10]	790	2897
Baseline	847	3107
5th CB 2050 RCP 2.6	582*	2134
5th CB 2050 RCP 4.5	747*	2740
Adaptation 2050 RCP 2.6	2473	9066
Adaptation 2050 RCP 4.5	1991	7300

Table 12 Preliminary results for carbon sequestered by forests by scenario. Note that the carbon sequestered here reflect the initial distribution of trees modelled by the IAP2

6.1.3 Adaptation Indicators by scenario

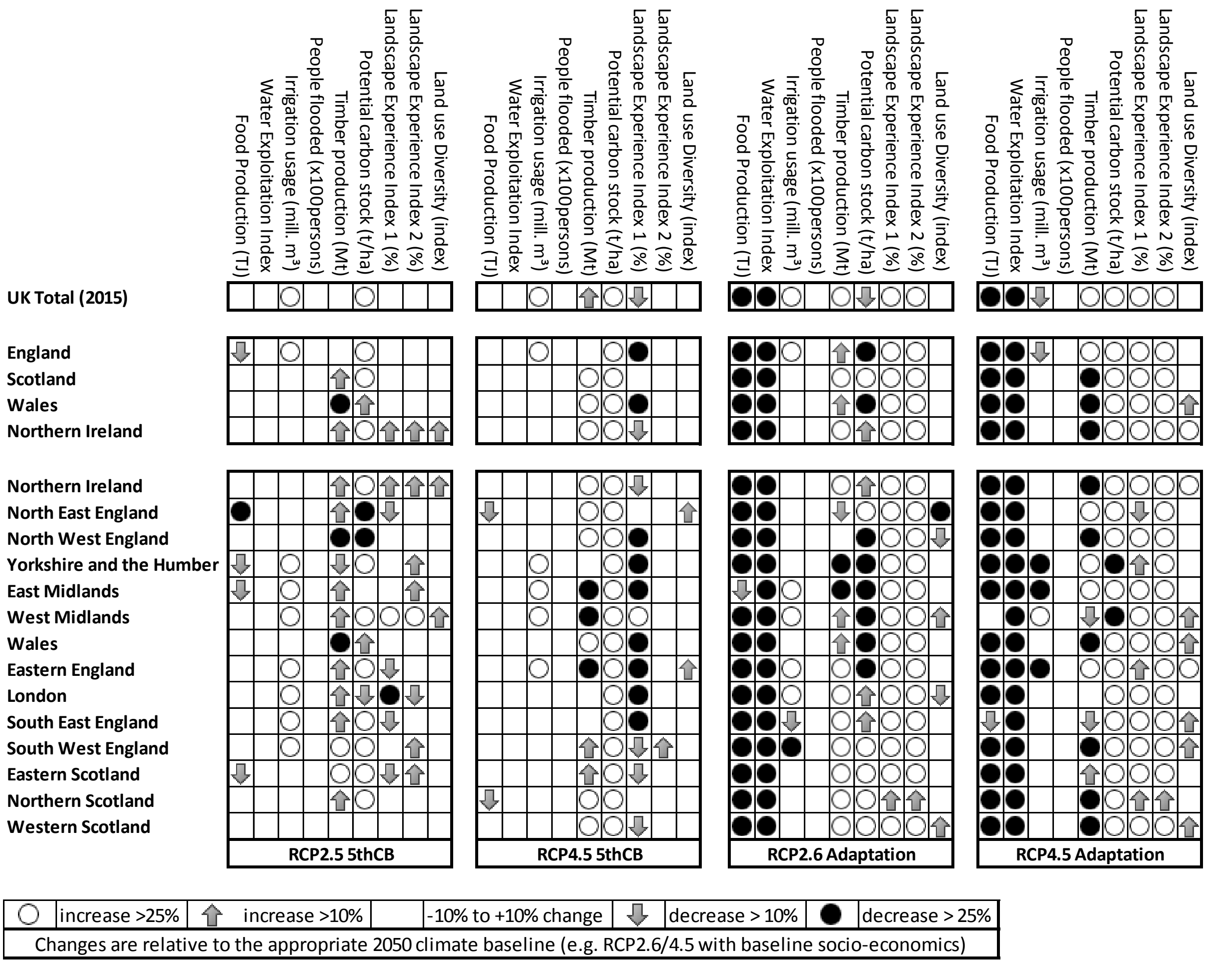


Figure 20 Adaptation indicators by scenario – synergies and trade offs

An analysis of the changes in adaptation indictors relative to 2050s climate with no change in socio-economics highlights the contrast between the socio-economic scenarios' impacts on adaptation indicators (Figure 20). Under the 5th CB scenario at the UK scale, food production, water exploitation,

[10] Combatting Climate Change: forestry commission synthesis report. https://www.forestry.gov.uk/pdf/SynthesisUKAssessmentfinal.pdf/$FILE/SynthesisUKAssessmentfinal.pdf

flooding, landscape diversity and landscape experience (with forest) levels are unchanged relative to their baseline climates. Conversely, under the adaptation scenario, in both climate scenarios there is a significant reduction in food provision, a reduction in the water exploitation index (e.g. more water available, less water stress), an increase in timber production and a significant increase in both landscape experience indices. These differences make sense given the different foci of the two scenarios: with the adaptation scenario focusing on the expansion of natural areas for biodiversity.

There are also differences in the ways the two socio-economic scenarios play out under the different climates. For example, under RCP 2.6 irrigation increases >25% in a number of UK regions in both the 5^{th} CB and the adaptation scenario: however, under RCP 4.5 in the adaptation scenario irrigation use declines <25% in some of the same regions. Similarly, in the 5^{th} CB scenario, the >25% increase in irrigation seen in the south east and south west is no longer present under RCP 4.5. This reflects the decreasing profitability of irrigation in these areas under RCP 4.5.

The ability to delineate inter-regional differences in adaptation impact is a useful aspect of the spatially explicit nature of the IAP2, which makes it clear that the different devolved administrations will have different adaptation challenges to face, as will the different sub-regions within them. The challenges will also vary dependent on both climate and socio-economics. In the adaptation scenarios, for example under RCP 2.6, Scotland, Wales and Northern Ireland show increases in terms of timber production under RCP2.6, but this decreases by more than 25% under RCP 4.5. Conversely, England's timber provision increases by >10% in RCP 2.6 and increases further to >25% under RCP 4.5. This will reflect the increase in timber yields in these scenarios due to changes in climate and atmospheric CO_2.

Identifying synergies and trade-offs

Figure 20 highlights the synergies and trade-offs between sectors in different scenarios by identifying indicators that head in similar and opposite directions within a scenario. For example, in the RCP4.5 adaptation scenario there are synergies between the landscape indicators, timber production and the water exploitation index all of which improve as a result of improvements in water savings and a reduction in agricultural areas (NB a decline in the water exploitation index is an improvement in water availability), whilst there is a trade-off with EU self-sufficiency in food production, that declines as a result of the increased imports. In future research species outputs in the following section and mitigation outputs from section 7 could be added to the diagram to provide a broader range of synergies and trade-offs.

6.1.4 Change in appropriate climate and habitat space for species by scenario

In this section we discuss the availability of suitable climate and habitat space for species: e.g. the area where climate is within the parameters for which a species is comfortable and where there is sufficient habitat for that species. This is not the same as projecting where a species will actually be found which will be affected by other factors such as the ability of species to move into these areas (e.g. species dispersal) and other factors such as predation. However the indicator does provide an indication of where suitable climate and habitat are found..

NB: In contrast to Section 6.1.3, changes are shown relative to 2010 baseline in this section to look at overall change in species with time rather than to enhance the differences between scenarios.

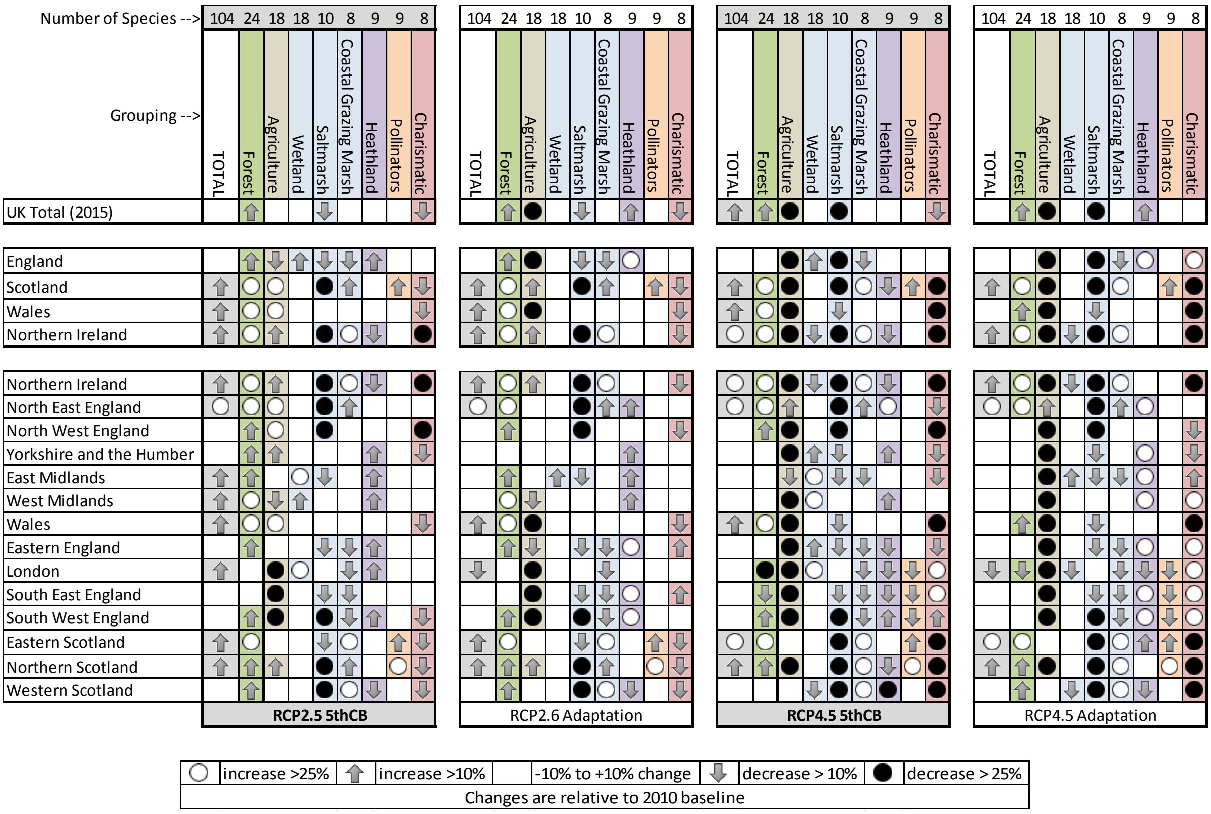


Figure 21 Scenario impacts on species

The spatial nature of the impacts of combined climatic and socio-economic change on the projected suitable climate space available for species is well illustrated in Figure 21. At a national level none of the scenarios show total change in the climate/habitat space available.

Forest species do well in both scenarios under both climates as both scenarios ensure similar or greater forest area under both climates. Climatic differences are apparent, with greater proportional increases in climate/habitat space apparent in the milder RCP2.6 climate. Interestingly, the 5^{th} CB scenario shows stronger increases in potential climate space in some areas than the adaptation scenario. This is because, whilst the adaptation scenario has a greater increase in total forest area (in RCP 2.6, 10kHa of forest for adaptation = 1,018,000 Ha; 5^{th} CB = 370,000 Ha), the number of cells with forest >10ha forest is slightly higher in the 5^{th} CB (adaptation = 1,180,000 Ha; 5^{th} CB = 1,210,000 Ha). This is important to recognise as it highlights the difference between size of habitat patches, and total numbers of them. It is also important to reflect on how differently those habitat patches might be managed, in 5^{th} CB where the priority is carbon sequestration vs the adaptation scenario where the priority is biodiversity.

Agricultural species show notable losses of climate/habitat space under RCP 4.5 reflecting the extreme decline in arable habitat. In addition, in some locations the adaptation scenario provides less habitat space for these species than the 5^{th} CB scenario in an equivalent climate. This is more noticeable in the milder RCP 2.6 as climatic constraints are putting less pressure on land use. This is most noticeable in Wales where there is an increase >25% of climate/habitat space for agricultural species under the 5^{th} CB but a loss >25% under the adaptation scenario (both under RCP 2.6).

Saltmarsh and Grazing Marsh species, both are driven mostly by climatic conditions with similar levels of climate/habitat space shown between the two socio-economic scenarios. They show decreasing climate/habitat space availability within increasing climate change from RCP 2.6 to 4.5.

Heathland species, show considerable increases in climate/habitat space as a result of the Adaptation scenario. This will reflect the higher levels of extensive grassland within these scenarios (extensive grassland or unmanaged land are needed for a heathland species to have suitable climate space). Within a socio-economic scenario, heathland species show greater increases in available climate/habitat space better under RCP4.5 than under RCP2.6.

Pollinator species as modelled within the IAP2 only respond to climatic change (they are not allocated with a specific habitat mask). They show increasing climate space in Eastern and Northern Scotland under RCP 2.6 and a decline in the South of England in RCP 4.5.

Under RCP 2.6, ***(European) Charismatic species*** show general declines in climate and habitat space, but there is some evidence of increase in the south east and eastern England under the adaptation scenario. Under RCP 4.5 there is an overall decline in the climate/habitat space for the modelled charismatic species in Wales, Scotland and N. Ireland but some evidence of increases in species in Southern and Midland England under the adaptation scenario. Further analysis would be required to understand these changes in detail, but they may well reflect an increase in the climatic potential of the UK to support non-native charismatic species with climate change. However, habitat availability is clearly the key aspect here, as the adaptation scenario shows more areas increasing than the 5^{th} CB.

A note on the adaptation scenario

The purpose of the adaptation scenario was to maximise land use allocation and management for biodiversity, for the 2050 time period. The approach taken was just one way to do this by focussing on reducing the agricultural system's pressure on European land use and so promoting the expansion of unmanaged land. The losses in habitat for arable species serve to highlight that there will be winners and losers in all scenarios that involve habitat change. However, within this scenario it is possible that land management could play a role to reduce these impacts. In model terms, the "unmanaged forest" class represents areas which are not needed for agricultural purposes (i.e. to meet demand) on which trees can grow. It is quite reasonable to argue that some of these areas could be managed as a different land use (e.g. as buffer strips targeted at arable-loving species) to reduce habitat loss for arable species.

Furthermore, the approach taken is just one way of producing a scenario focussed on biodiversity. An alternative might be to explore a scenario closer to the 5^{th} CB scenario, but with a greater area dedicated to "set-aside" (land not used for food production). The "set-aside" land could then be allocated to on-farm-woodland or natural grasslands. This scenario would lead to an expansion in arable land (in climates where sufficient land is available) and maintain pockets of different habitats within the agricultural landscape and might see more balanced impacts on habitats.

6.2 Results: Mitigation

Using the combination of the IAP2 land use outputs and the MACC emissions calculations, we were able to estimate the changes in agricultural emissions that may occur under each of the six modelled land use scenarios set out in Figure 19. We also estimated the potential abatement that could be achieved under each scenario, if individual mitigation measures consistent with the 5^{th} Carbon Budget were applied.

This section focusses on the modelled total greenhouse gas (GHG) emissions from both livestock and crops in terms of CO_2 equivalent emitted per year ($CO_2e\ y^{-1}$) from different sources. The overall emissions for each of the four land use change scenarios are shown in section 6.2.1 (Livestock) and section 6.2.2 (Crops). *NB it is important to remember that changes in livestock numbers are driven by changes in land uses as shown in Figure 19a and the yields of grass driven by climate and* *technology. The equations used to calculate cattle / sheep numbers from total grass tonnage are shown in section 3.2.2.*

Total net emissions/sequestration for each land use type for each scenario after adoption of mitigation measures can be calculated in Phase 2.

6.2.1 Livestock emissions (from enteric sources and manure)

Total greenhouse gas (GHG) emissions from livestock before the adoption of 5th CB mitigation measures are depicted in Figure 22. Overall, emissions from livestock were greatest in the 5th Carbon Budget scenario targeting RCP 4.5, and lowest for the adaptation scenario under RCP2.6.

Dairy cattle were the major contributors of emissions in all scenarios, with beef cattle a close second. In the adaptation scenario under RCP 2.6, the relative proportion of emissions contributed by dairy and beef cattle and sheep were more evenly distributed, contributing 38%, 31% and 29% respectively. In all other scenarios, the relative contribution of emissions from sheep was less than 16%. These figures are driven by the changes in livestock numbers – which are themselves driven by the areas and yields of intensive grassland and extensive grassland in the different scenarios (see Figure 19, Section 3.2.2). Emissions are considerably lower in the adaptation scenario in RCP 2.6 because so little of the total land area is dedicated to agriculture. Conversely, in the 5th CB scenario in RCP4.5 intensive grassland makes up around 50% of the total land area of the UK (compared to 32% at baseline).

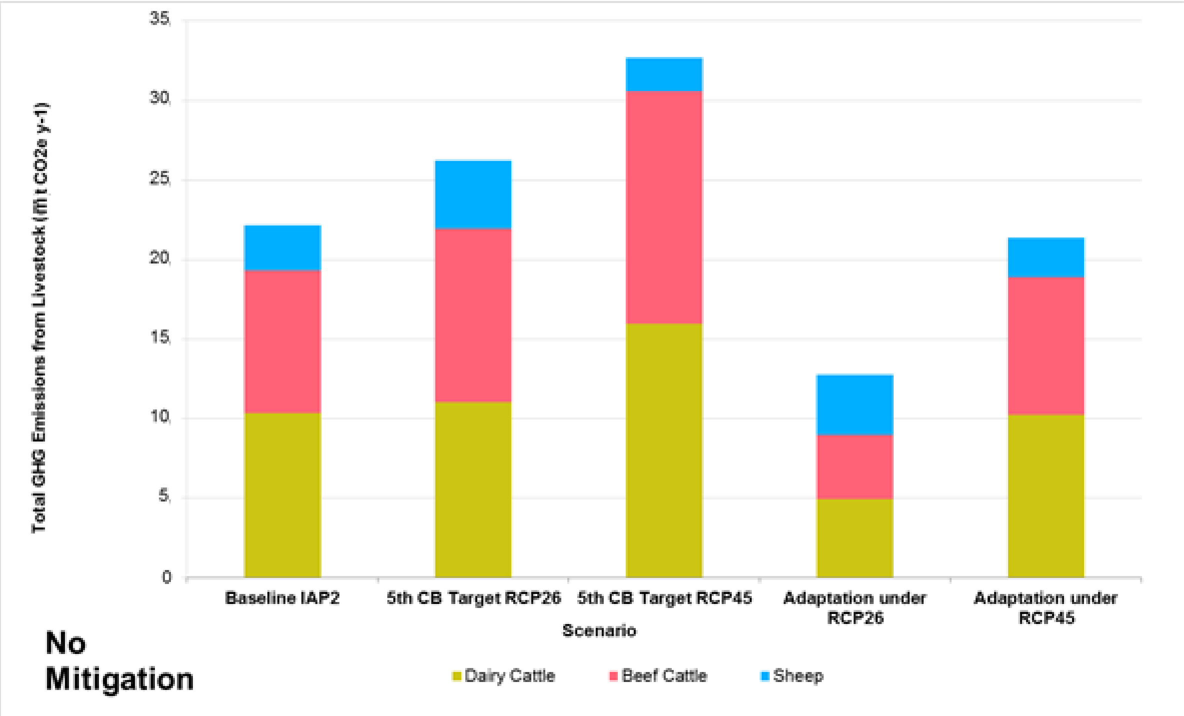


Figure 22 Total GHG emissions from livestock (Mt CO_2e y^{-1}) by land use scenario, without mitigation

Relative contributions of emissions from livestock enteric sources and manure

The relative sources of emissions from livestock are compared in Figure 23. It is clear, at the macro-scale that the relative contributions of emissions from enteric sources (CH_4) and manure (CH_4 and NO_2) remain stable throughout all the scenarios, without mitigation measures. However, the differential contribution of different livestock units by scenario (Figure 24) demonstrates that in different scenarios the relative contributions of different livestock types changes. For example in the adaptation scenario under RCP 2.6 sheep provide the greatest enteric CH_4 contribution (c.3.5 $MtCO_2e\ y^{-1}$; relative to 3.4 $MtCO_2e\ y^{-1}$ from dairy cattle) whereas dairy cattle are the major contributors in all other scenarios. This is because the adaptation scenario in RCP 2.6 has the greatest proportion of extensive grassland of the four scenarios and the least proportion of intensive grassland. As such it has the greatest number of sheep and the lowest number of cows. This highlights the different mitigation challenges that are faced in different socio-economic futures.

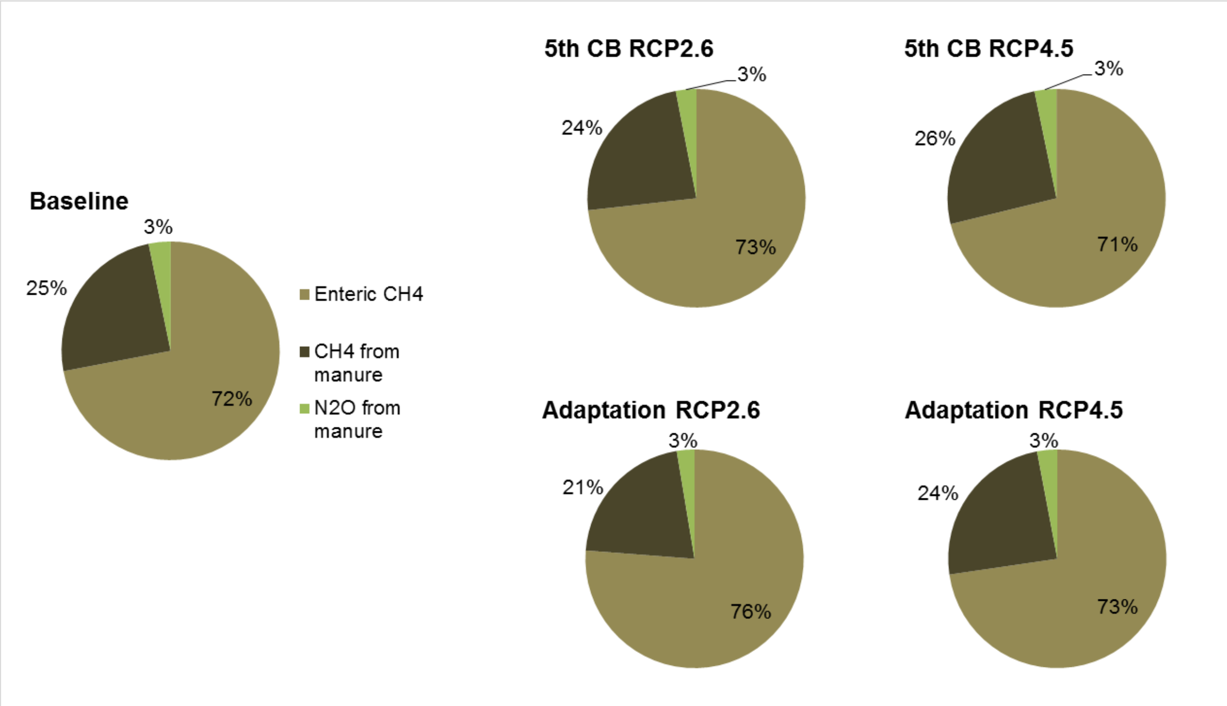


Figure 23 Relative contribution of livestock emissions from enteric and manure sources (based on total GHG emissions as $MtCO2e\ y^{-1}$)

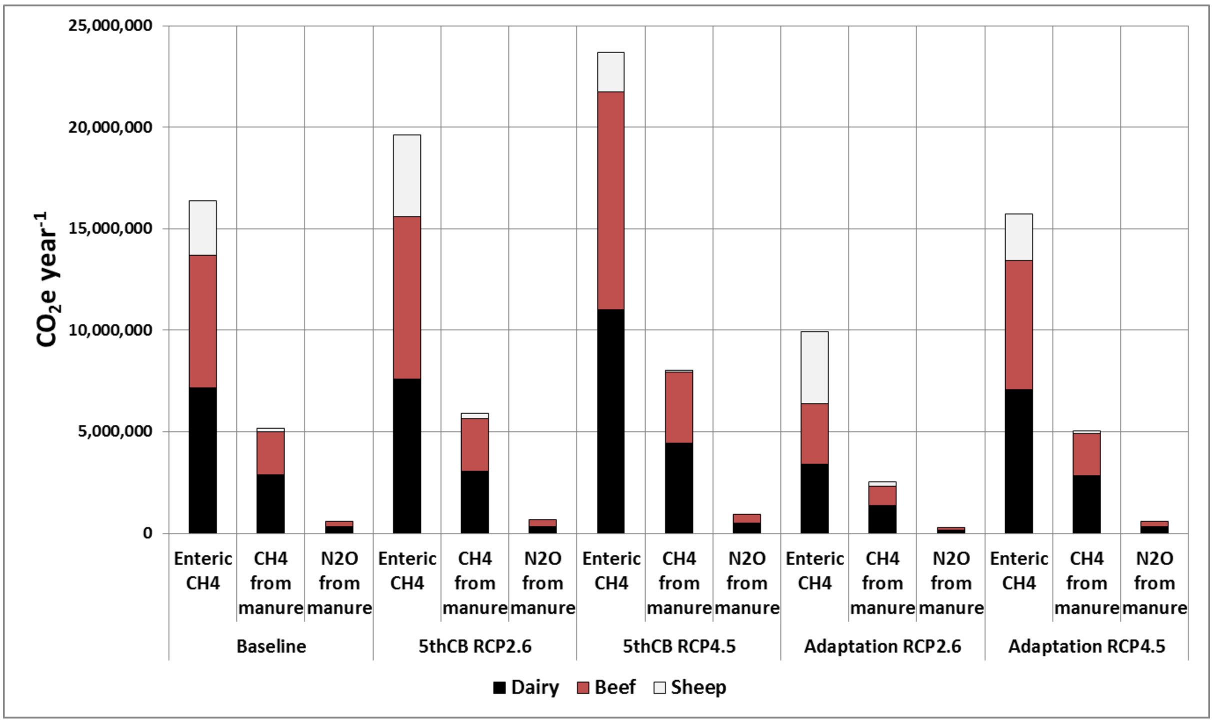


Figure 24 Emissions by source and livestock class

6.2.2 N_20 Emissions from agriculture

Below we compare the distribution of emissions between the overall crop categories of permanent grass, temporary grass and tillage. Table 13 provides an overview of the types of crops which make up each of the four categories analysed by the MACC. Note that the MACC does not currently include 'Woodland' and 'Rough Grass' in any of the four aggregated categories when calculating N_2O emissions.

MACC Crop Category	**Individual crop types (MACC name)**	**Description (from SRUC 2015)**	**IAP2 equivalent input.**
Permanent Grass	PermGrass	Grass over 5 years old	Permanent grass (ha)
Temporary Grass	TempGrass	Temporary grass under 5 years old	Grass (ha)
Tillage	WWheat	Winter wheat	See Table 3
	SWheat	Spring wheat	
	WBarley	Winter barley	
	SBarley	Spring barley	
	Oat	Oats	
	OthCer	Other cereals	
	WOSR	Winter oilseed rape	
	SOSR	Spring oilseed rape	
	Pot	Potatoes	
	SugBeet	Sugar beet; not for stock feeding	
	FieldPeaBean	Peas for harvesting; dry and field beans	
	OthAra	Other arable crops not for stock feeding (linseed, hops, other)	
	Maize	Maize	
	OthFod	Other fodder crops	
	VegPeaBean	Peas and beans for human consumption	
	OthHort	Other horticultural crops	

Table 13 Aggregation of individual crops to three crop categories in the MACC model

The MACC model converts N_2O emissions from soil into CO_2 equivalents for cropping land uses; it does not assess any other atmospheric gas emissions related to crops (soil carbon is not included). The total N_2O GHG emissions from soil for each of the land use scenarios are illustrated in Figure 25.

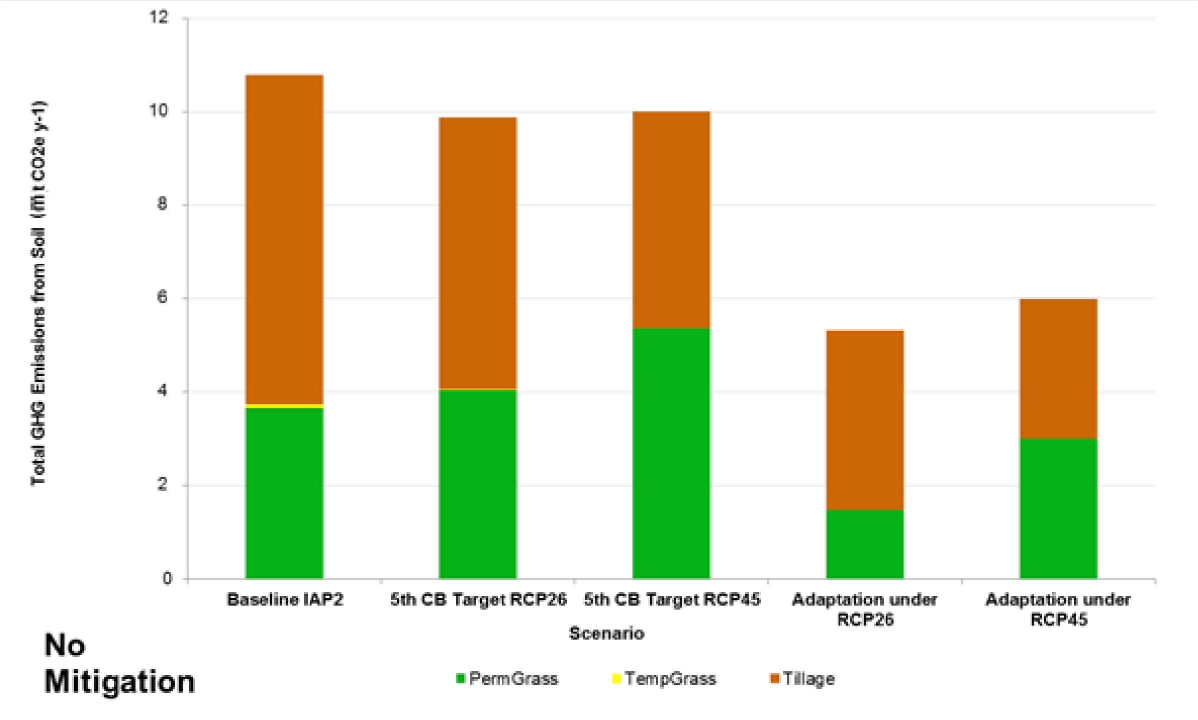


Figure 25 Total GHG emissions from soil for each of the four land use change scenarios, without mitigation

All of the land use change scenarios predicted lower total N_2O emissions from soils than the current baseline scenario because there is a reduction in arable land in all scenarios. Areas used for tillage activities were the greatest contributors of emissions in all scenarios, with the exception of the 5th Carbon Budget Target under RCP 4.5. In this scenario, 54% of all N_2O emissions were predicted to come from permanent grassland, compared to 46% of emissions from tillage. In all scenarios, less than 1% of all emissions were attributed to temporary grassland.

6.2.3 Potential abatement of emissions

Once the emissions based on IAP2 land use, *in the absence of any mitigation options applied*, have been calculated (as above), the MACC is designed to explore the performance of a range of mitigation measures under its four abatement scenarios (Maximum technical potential; High feasible potential; Central feasible potential and low feasible potential, see Section 3). These set the level of abatement applied across a range of 24 mitigation measures (Table 14).

Mitigation Measure ID	Description	Most relevant land use type	Included in Phase 1 analysis?
MM1	Improving synthetic N use	Crops	Yes
MM2	Improving organic N planning	Crops	Yes
MM3	Low emission manure spreading	Crops	Yes
MM4	Shifting autumn manure application to spring	Crops	Yes
MM5	Catch and cover crops	Crops	Yes
MM6	Controlled release fertilisers	Crops	Yes
MM7	Plant varieties with improved N-use efficiency	Crops	Yes

Mitigation Measure ID	Description	Most relevant land use type	Included in Phase 1 analysis?
MM8	Legumes in rotations	Crops	Yes
MM9	Legume-grass mixtures	Crops	Yes
MM10	Precision farming for crops	Crops	Yes
MM11	Loosening compacted soils and preventing soil compaction	Crops	Yes
MM12	Improving ruminant nutrition	Livestock	Yes
MM13	Probiotics as feed additive	Livestock	Yes
MM14	Nitrate as feed additive	Livestock	Yes
MM15	Dietary lipids for ruminants	Livestock	Yes
MM16	*Improving cattle health*	*Livestock*	*No*
MM17	*Improving sheep health*	*Livestock*	*No*
MM18	*Selection for balanced breeding goals*	*Livestock*	*No*
MM19	Slurry acidification	Livestock	Yes
MM20	*Anaerobic digestion: cattle slurry with maize silage*	*Livestock*	*No*
MM21	*Anaerobic digestion: pig/poultry manure with maize silage*	*Livestock*	*No*
MM22	*Anaerobic digestion: maize silage only*	*Livestock*	*No*
MM23	*Afforestation on agricultural land*	*Forestry*	*See carbon sequestration in section 6.1.2*
MM24	*Behavioural change in fuel efficiency of mobile machinery*	*Livestock* *Crops* *Forestry*	*No*

Table 14 Mitigation measures currently included in the MACC model

It should be noted that the measures included within the MACC were specifically selected in order to define a cost-effective scenario for the Fifth Carbon Budget and the calculation functions of the MACC (for example, specific IPCC emissions calculations) were formulated accordingly.

Here, we are using the MACC to demonstrate that emissions, potential abatement and cost effectiveness can be calculated on the basis of IAP2 land use data inputs. However, the analysis completed in Phase 1 was limited to those mitigation measures already incorporated into the MACC. Additional mitigation measures could potentially be integrated into the model during Phase 2.

Furthermore, the MACC is currently set up to investigate the abatement potential and cost-effectiveness of each of the measures listed in Table 14 individually (i.e. not cumulative abatement should two or more of the measures be implemented together). The MACC is capable of dealing with interactions between measures, but it would require extra processing and expert involvement of SRUC to ensure that the interactions were correctly interpreted. As such, for Phase 1 the focus is on interpreting the maximum potential abatement values currently output. The model compares the individual performance of each mitigation measure, under each of the four emissions scenarios (i.e. all scenarios excluding the baseline). This performance is presented below.

Understanding the 'reference' scenario

Within the linked system, a "reference" scenario is calculated for each IAP2-based scenario. This scenario represents the emissions (in e.g. 5^{th} CB RCP 2.6) without any abatement options applied. That is, the un-abated emissions data discussed in sections 6.2.1 and 6.2.2. There is therefore a reference scenario for each socio-economic scenario from the IAP2.

Abatement is then calculated relative to these reference scenarios. Overall changes in emissions for each scenario, and by mitigation measure, are shown in section 6.2.4 (livestock emissions) and 6.2.5 (emissions from soil) below.

6.2.4 Changes in livestock emissions

Outputs from the MACC model allowed for an assessment of the abatement potential of overall livestock emissions that could occur under each of the land use change scenarios (Figure 26). The overall trends reflect the patterns of land use change: the adaptation scenarios have lower grassland areas, leading to lower livestock numbers and less abatement; and within RCPs grassland area, livestock and abatement are lower in RCP2.6 than RCP 4.5 (see Figure 19). Figure 26 compares the abatement achieved under each scenario for each of dairy cattle, beef cattle and sheep. Five mitigation measures included in the MACC are directly relevant for livestock emissions; all five measures appeared to have an impact on emissions, for all land use change scenarios.

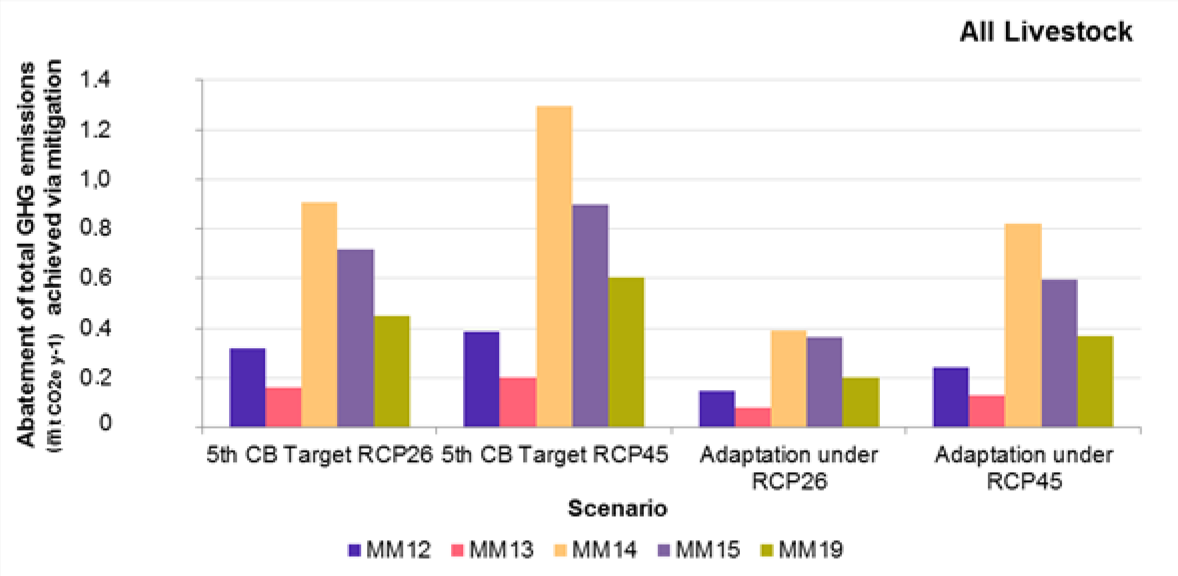


Figure 26 Abatement in emissions from livestock predicted for each land use change scenario

MM14 (use of nitrate as a feed additive) achieved the greatest reduction in overall GHG emissions under all four scenarios, compared to the baseline. The greatest abatement in GHG emissions from livestock would be achieved by the 5th Carbon Budget Target scenario, under the RCP 4.5 climate change trajectory. MM14 contributed to a reduction of almost 1.3 MtCO_2e per year GHG emissions under this scenario. Of this abatement, 81% (1.05 MtCO_2e per year) would be attributed to reductions in dairy cattle emissions. The next greatest reduction was 0.908 MtCO_2e per year, under the 5th Carbon Budget Target – RCP 2.6 scenario.

The least effective mitigation measure for reducing livestock emissions was MM13 (use of probiotics as a feed additive), where again the greatest reduction in emissions (0.201 MtCO_2e per year) would be achieved under the 5th Carbon Budget Target – RCP 4.5 scenario.

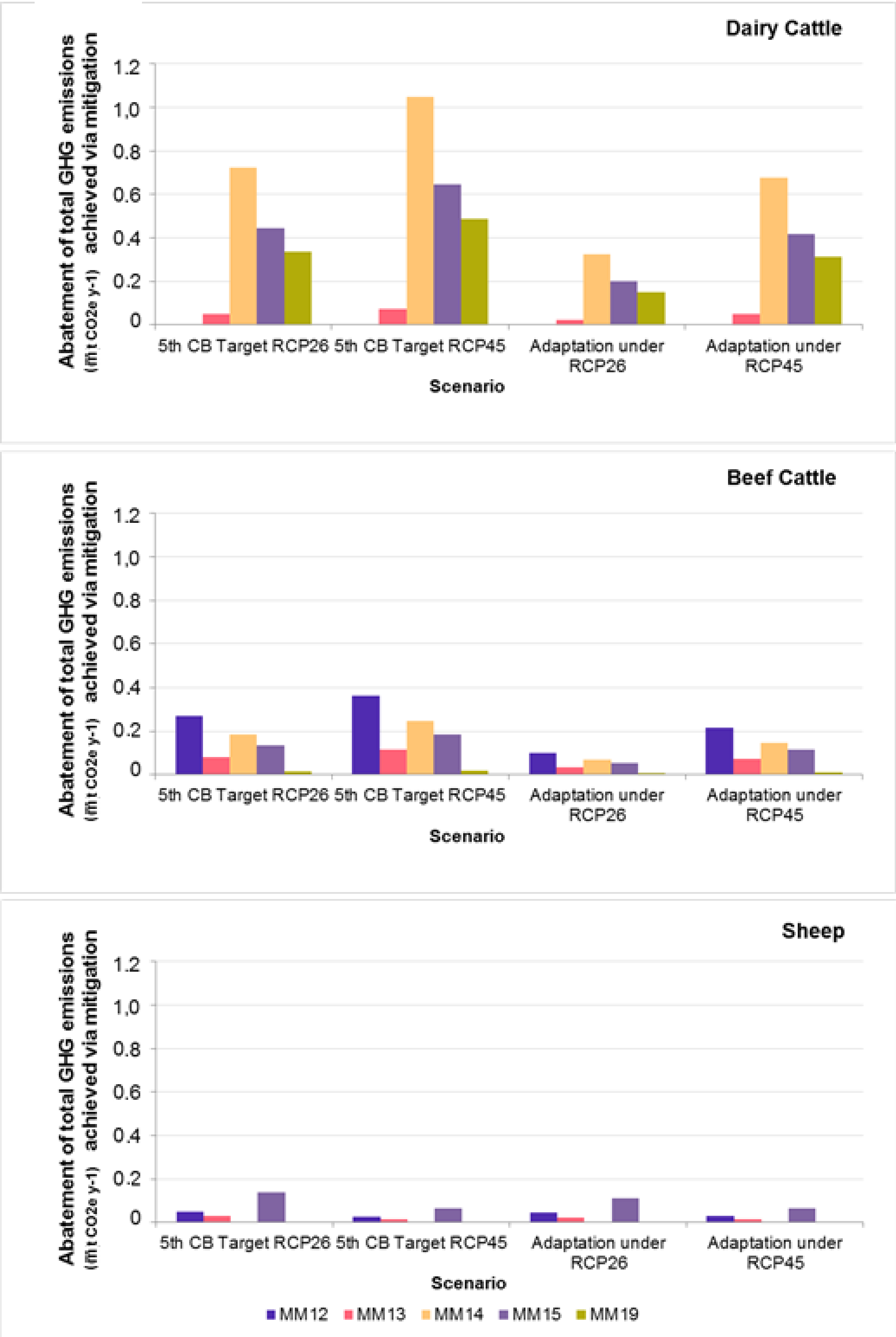


Figure 27 Comparative abatement for dairy cattle, beef cattle and sheep under each land use change scenario

Figure 27 illustrates that all five mitigation measures had an impact on emissions from dairy cattle and beef cattle, although MM19 was comparatively ineffective in reducing emissions from beef cattle. MM19 involves changes in slurry management (introducing acidification of manure slurry), which would be most applicable for dairy farming systems. Emissions from sheep were not reduced as effectively across all scenarios; in particular, implementation of mitigation measures MM14 and MM19 resulted in zero abatement. This is likely due to the fact that sheep manure is largely unmanaged on farms; therefore it would be difficult to have an impact on emissions from sheep manure using changes to manure management systems (such as implementing MM19). The MACC model is currently less adept at accounting for emissions from unmanaged manure, as described in Section 7.1.1 of this report).

Of the two adaptation scenarios, the largest reduction in emissions from livestock would be achieved under a RCP 4.5 climate change trajectory.

6.2.5 Changes in N_2O emissions from agricultural soils

Figure 28 compares the changes in overall emissions from soil that could occur under each of the land use change scenarios, while Figure 29 compares the abatement achieved under each scenario for each of three crop categories. Eleven mitigation measures included in the MACC could potentially reduce emissions from soil; one of these (MM8; rotation of legume crops) was excluded from Phase 1 analysis as it skewed all results. MM8 appeared to result in large negative abatement (that is, an increase in emissions) for all scenarios and as this could not be explained with current knowledge of the MACC's calculating functions, we have chosen to exclude it pending further analysis.

The ten remaining measures appeared to have an impact on emissions, for all land use change scenarios, when considering emissions from 'all crops'. However, their effectiveness varied greatly between different crop categories (as shown in Figure 29).

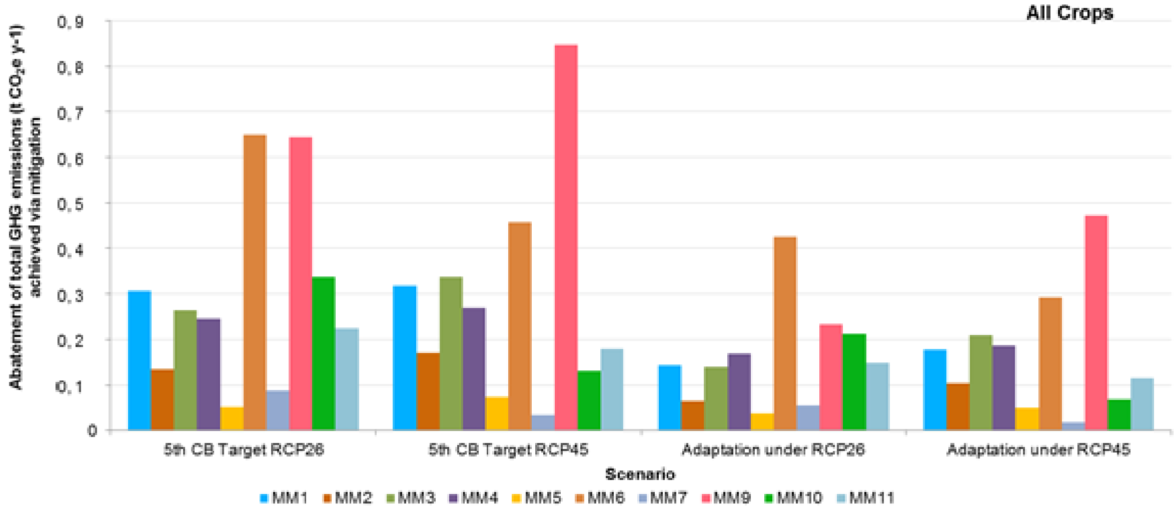


Figure 28 Abatement in emissions from soil predicted for each land use change scenario

The two most effective measures in reducing GHG emissions from soil appeared to be MM6 (use of controlled-release fertilisers) and MM9 (use of legume-grass mixtures); these two measures consistently reduced emissions from soil by more than 200,000 tonnes CO_2e per year, across all land use change scenarios. The largest reduction in emissions was predicted to occur for the 5th Carbon Budget Target – RCP 4.5 scenario, where MM9 would result in abatement of 847,284 tonnes CO_2e per year.

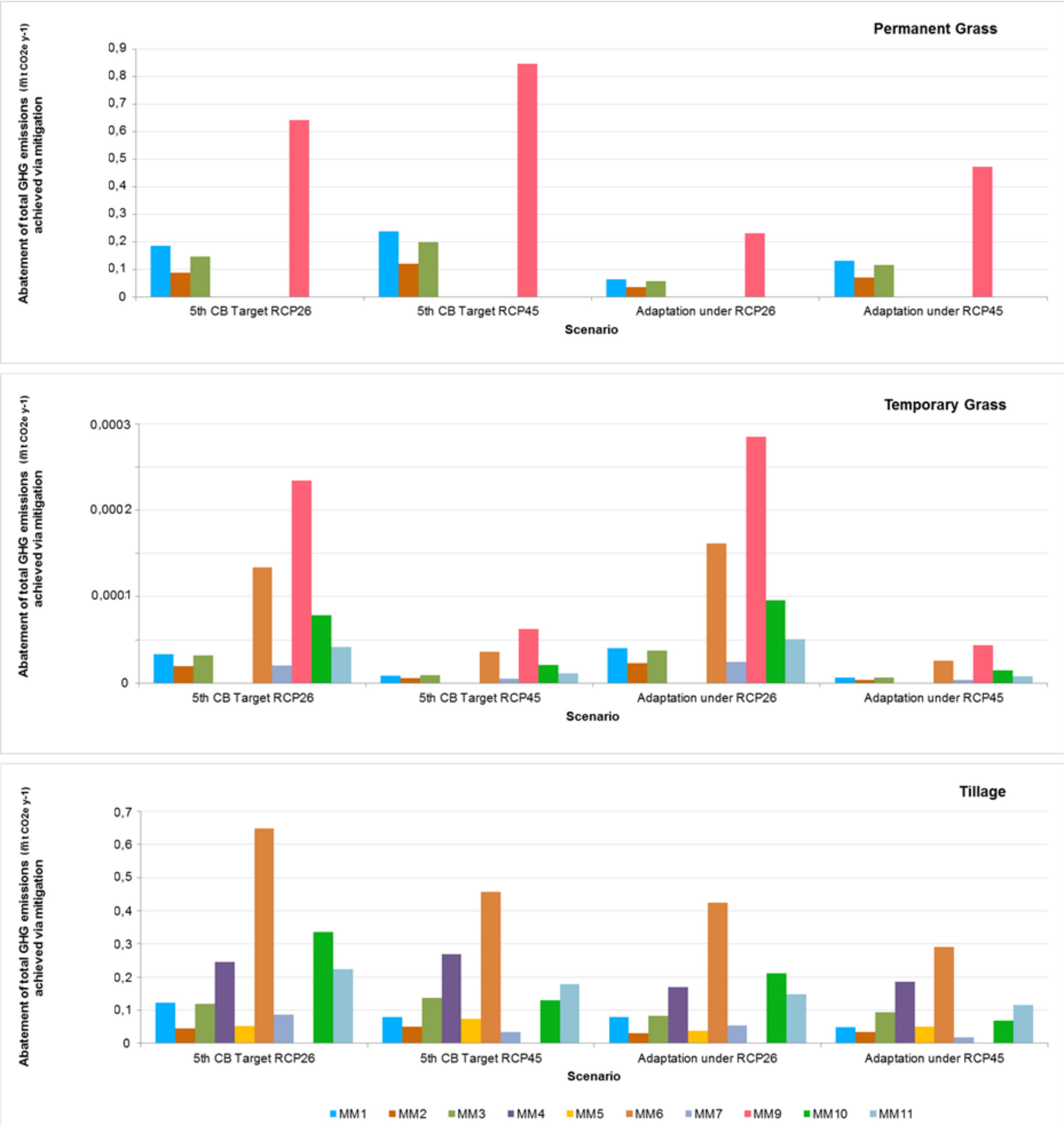


Figure 29 Comparative abatement for permanent grass, temporary grass and tillage under each land use change scenario

Figure 29 illustrates how 99% (847,284 tonnes CO2e per year) of the abatement in emissions achieved by MM9 in the 5th CB RCP4.5 scenario would be attributed to reductions in emissions from permanent grassland. The comparatively small remainder of the emissions reduced by MM9 would be from crops classed as temporary grassland, and MM9 would not achieve any abatement on land used for tillage.

The most effective mitigation measure for reducing emissions from land used for tillage in all land use change scenarios would be MM6 (use of controlled-release fertilisers). Implementation of MM6 would see the greatest reduction in emissions from tillage under the 5th Carbon Budget Target – RCP 2.6 scenario, where emissions would be reduced by 648,266 tonnes CO_2e per year (over 99% of emissions reducing from all crops by MM6). The second most effective mitigation measure for tillage emissions across all scenarios would be MM4 (shifting autumn manure application to spring), with the greatest abatement (reduction of 269,845 tonnes CO2e per year) achieved under the 5th Carbon

Budget Target – RCP 4.5 scenario. MM4 would not be effective in reducing emissions from permanent or temporary grassland in any of the scenarios

Mitigation measure	Total abatement of GHG emissions achieved (UK; Mt $CO_2e\ y^{-1}$) by scenario			
	5th Carbon Budget - RCP2.6	5th Carbon Budget – RCP4.5	Adaptation - RCP2.6	Adaptation – RCP4.5
Livestock	2.56	3.39	1.18	2.16
Crops	1.46	0.76	-5.23	-4.99
UK abatement (livestock + crops)	**4.02**	**4.14**	**-4.05**	**-2.83**

Table 15 Overview of abatement scenarios

In Table 15, 'total' abatement for crops is skewed by the performance of MM8 (Legumes in rotations), resulting in overall increase in emissions (negative abatement values in red). **This may not currently represent a 'real' result when calculated as 'total' UK emissions rather than at an individual measure scale, because it doesn't account for interactions with other measures.** Interactions would be included in Phase 2 of the modelling.

6.2.6 Allocating costs

The MACC model produces estimated costs associated with implementing each mitigation measure, and uses these values to calculate overall cost-effectiveness (units of abatement achieved per unit cost). By comparing the cost-effectiveness of each mitigation measure under the four land use scenarios, we can introduce an element of costs and 'benefits' (in terms of abatement in emissions) to consideration of the scenarios. Figures 30 and 31 below illustrate the cost-effectiveness of mitigation measures under the four land use change scenarios, for emissions from livestock and soil respectively.

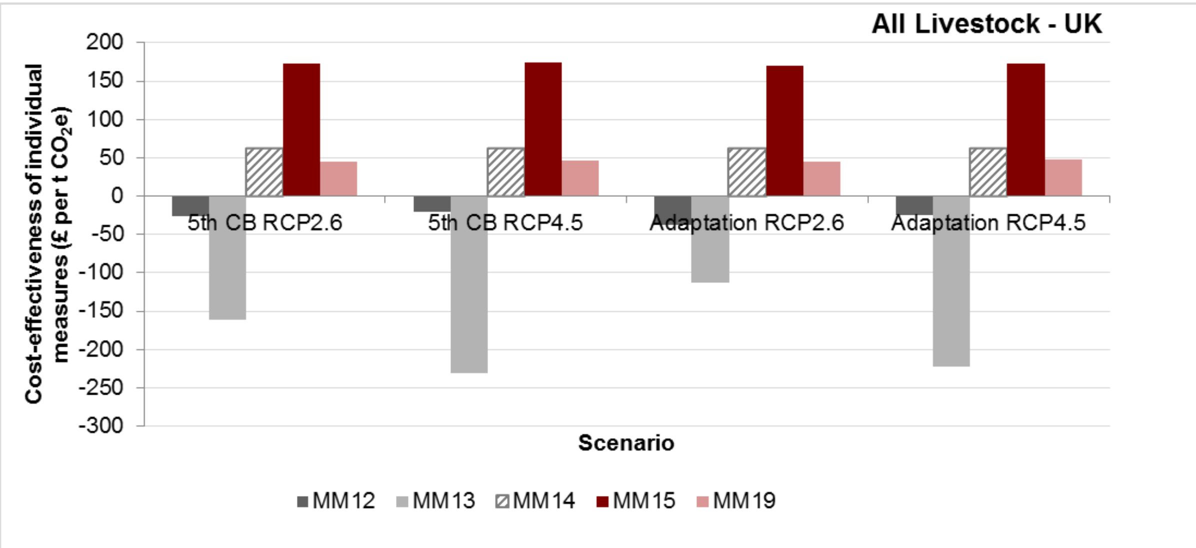


Figure 30 Cost-effectiveness of mitigation measures for reducing livestock GHG emissions

Figure 30 indicates that the cost-effectiveness of individual mitigation measures does not alter significantly between scenarios: the difference in cost-effectiveness does not vary by more than 4% except for MM12 and MM13. It appears that the cost-effectiveness of MM13 would change by almost half as much in the adaptation scenario under RCP 2.6, compared to the 5th Carbon Budget Target – RCP 4.5 scenario. However, MM13 would still remain a less cost-effective option than MM14, MM15 or MM16 given it would result in a loss of £112 per t CO_2e emissions reduced.

The estimates of cost-effectiveness produced here are for individual mitigation measures, implemented. It is possible to use the MACC to generate cost-effectiveness over the lifetime of a scenario (including interactions between mitigation measures). In Phase 2 we could focus on exploring how the MACC calculates cumulative cost-effectiveness and whether it would be appropriate to complete that level of analysis using IAP2 land use inputs.

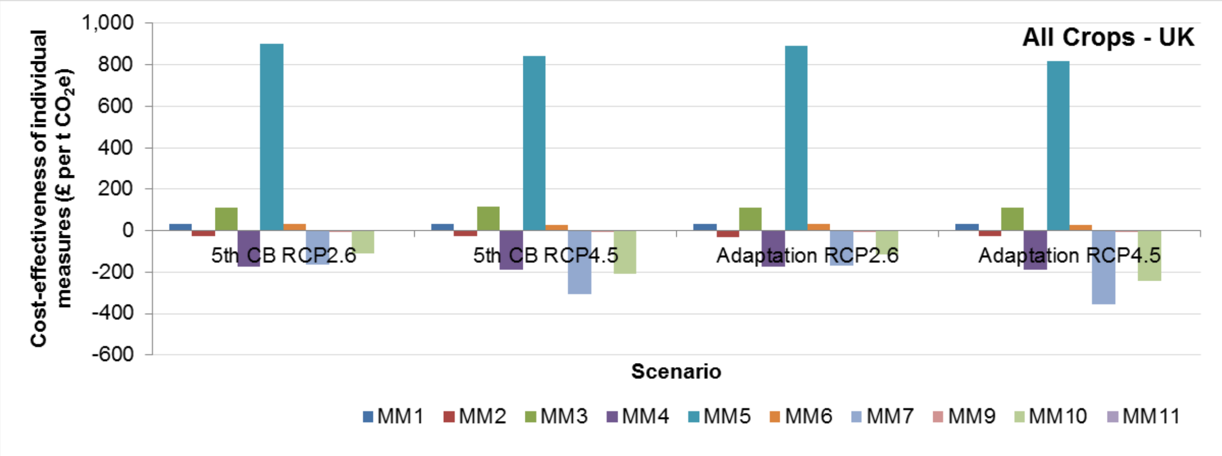


Figure 31 Cost-effectiveness of mitigation measures for reducing crop GHG emissions

Figure 31 provides indicative estimates of cost-effectiveness for mitigation measures which could reduce emissions from soil under each scenario. There is a similar trend to that seen for livestock emissions, where cost-effectiveness for individual measures does not vary greatly between scenarios. Estimates of cost-effectiveness are within 13% of each other for all the mitigation measures shown in Figure 31, with the exception of MM7 (use of plant varieties with improved N-use efficiency) and MM10 (precision farming for crops). Again, both of these measures indicate that implementation would result in higher costs, with the lowest effectiveness in reducing emissions. MM7 would be the least effective if implemented under the adaptation – RCP 4.5 scenario, while MM10 would be least effective under the 5th Carbon Budget Target – RCP 2.6 scenario.

It should be noted that in Phase 1 the MACC is being run without any alteration or addition to the range of costs calculated; there is potential to include estimates for any additional mitigation measures required during Phase 2 of the Project. It should also be noted that as the support for the 5th CB, the MACC focussed on the time period from 2010 to 2035. This means the costs that underpin the analysis above are based on 2030s data. To extend the analysis to 2050 to match with the IAP2, and to 2080 to meet the needs of Phase 2 some additional work will be needed to identify how to extrapolate any cost-related inputs forward in time.

7 Next Steps

7.1.1 Accounting for total UK emissions from ALULUCF

The Phase 1 Project was designed to demonstrate that emissions for the 5th carbon budget scenario can be calculated by linking the IAP2 and MACC models. We have fulfilled that objective by presenting estimated emissions for each of the scenarios described in Section 2.6, using both IAP2 land use outputs and emission calculations form the MACC. However, these outputs should be treated as preliminary results, which do not yet represent the total emissions from all land use in the UK under each scenario.

The MACC was developed by the SRUC for the specific purpose of identifying an optimal scenario for the Fifth Carbon Budget (2016). The MACC therefore contains only the inputs and calculations directly relevant to each of the 24 mitigation measures modelled. The emissions calculated for Phase 1 of the Project do not reflect total emissions from all land use in the UK (as are calculated for the national GHG Inventory); rather they only encompass emissions from land use activities affected by any of the 24 mitigation measures originally modelled using the MACC. To model all the land use types available from IAP2 outputs, we will need to make some adjustments to the way emissions are calculated in the MACC.

We suggest that one of the first tasks completed in Phase 2 of the Project is to conduct a gap analysis of the MACC model emissions calculations, compared with the UK National GHG Inventory methods. From discussions with Vera Eory at SRUC (the original developer of the MACC), we are aware that some of the equations used to calculate emissions in the MACC (based on equations from the IPCC 2006 guidelines) do not cover the entire range of parameters that would be applied within the national GHG Inventory. For example, the MACC emissions calculations for livestock do not account for some aspects of manure management and soil carbon and nitrogen losses. The IPCC Guidelines (2006) and UK GHG inventory provide equations for calculating soil emission factors; the MACC predominantly uses the following factors to calculate emissions from crops:

- EF_1 – Emission factor for N_2O emissions from N inputs
- EF_4 – Emission factor for direct N_2O emissions from the manure management system (livestock only)
- EF_5 – Emission factor for N_2O leaching and runoff
- F_{CR} – Annual amount of N in crop residues (crops only)

However there are other emissions factors calculated for the UK GHG Inventory, also related to livestock and/or crops (for example):

- EF_2 – Emission factor for N_2O emissions from drained/managed organic soils
- EF_{3PRP} – Emission factor for N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals

Table 16 shows how each of these additional emission factors could be calculated. It is recommended that this table could be extended in Phase 2 of the Project to assess gaps throughout the entire MACC (and emission factors required for land use not covered by the MACC, such as urban areas).

Emission Factor	Relevant IPCC 2006 equation	Interacting parameters (currently excluded from MACC)	Land use types affected	Action required
EF_2: Calculating N_2O emissions from drained/managed organic soils	11.1	F_{OS}: Annual area of managed/drained organic soils F_{SOM}: Annual amount of N in mineral soils that is mineralised, in association with loss of soil C from soil organic matter as a result of changes to land use or management	Crops Livestock	*TBC*
EF_1: Calculating N_2O emissions from N inputs	11.1	F_{ON}: Annual amount of animal manure, composts, sewage sludge, and other organic N additions applied to soils *MACC currently calculates amount of animal manure and compost*	Crops Livestock	*TBC*

Emission Factor	Relevant IPCC 2006 equation	Interacting parameters (currently excluded from MACC)	Land use types affected	Action required
		applied, but not sewage sludge or other Organic N additions		
$EF3_{PRP}$: Calculating N_2O emissions from urine and dung N deposited on pasture, range and paddock by grazing animals	11.1	FPRP: Annual amount of urine and dung N deposited by grazing animals on pasture, range and paddock (*essentially unmanaged manure*) *The MACC currently includes estimates of the amount of manure deposited by dairy and beef cattle on pasture and range, but does not calculate the amount of unmanaged manure deposited by sheep. Also, the MACC calculates CH_4 emissions from unmanaged dairy and beef cattle manure, but not N_2O.*	Livestock	Estimate proportion of total manure that would be deposited on pasture, range and paddock depending on the % of time an animal spends grazing. Post-process MACC results.

Table 16 Example of gap analysis between MACC and national GHG inventory emissions calculations

Were Phase 2 to take place, an important early task would be to work with the CCC to identify a priority list of sources of emissions/sequestration not currently included in the linked system and work to develop mechanisms to better integrate them. This may involve not only working more closely with SRUC to improve the issues covered by the MACC but also, looking in more detail at off-farm sources of land use change in terms of soil carbon loss (e.g. peatlands) and better quantification of the impacts of afforestation at the national scale.

7.1.2 Additional scenarios required by the CCC

It is anticipated that Phase 2 of the Project would involve running a far wider range of socio-economic and climatic scenario combinations. The aim will be to explore the implications of pathways to emissions reductions that synergise well with adaptation priorities – within the biophysical, socio-economic and cross-sectoral constraints of the different worlds. In Phase 2 there would be an explicit aim to explore synergies and trade-offs between adaptation and mitigation within and between scenarios and using the exploratory power of the IAP2-MACC linked system.

In terms of potential scenarios to explore, the CCC have suggested:

- Conversion of land to grow woody perennial crops (for example, *Miscanthus spp.*(Elephant Grass), short rotation coppice, and short rotation forestry) for Bioenergy and Carbon Storage (Bio-CCS)
- Increased use of wood for construction purposes
- Use of biomass in carbon, capture and storage (BECCS)
- Increased management of woodlands
- Human diet change
- Changes in agricultural technology to improve yields and land use efficiency
- Peatland restoration

For some of these, the modelling capability is present (e.g. human dietary change is within the IAP2), some is partially implemented (e.g. the IAP2 can identify areas where heath and bog is climatically suitable, but it does not address management) and for others new post processing modules would need to be developed (e.g. to split forest types into conifer/broadleaves, or to approximate the impacts of peatland restoration). However, we would hope to have demonstrated within this bid that with post processing of IAP2 outputs it is possible to get plausible outputs, whilst equally clarifying the limits to the modelling and the types of considerations that need to be understood when post-processing internally consistent data. It is also important to note that the projections presented here are based on the outputs of a single climate model for each RCP. This reflects only one spatial pattern of climate impacts. In Phase 2 multiple climate models would be explored to better understand the impacts of different climates on the UK and its regions.

7.1.3 Extending the MACC to 2050 and 2080

The intention is for Phase 2 to extend beyond 2050 to look towards 2100. The IAP2 includes modelling for 2080s so this is quite feasible from an integrated modelling stance. However, the MACC is currently customised for the 2030s and further analysis is required to determine the extent to which the assumptions within it can be extended further into the future. This is unlikely to be a significant problem, and would be something that could be resolved in consultation with SRUC in the early stages of Phase 2.

7.1.4 European context

The work presented in this report has focussed on the UK in Isolation. However, each scenario created produces output for the whole EU 28 + Switzerland and Norway. This means that there is untapped potential to look at how the UK is positioned relative to the rest of the continent. An understanding of the wider context will help to better interpret the patterns of change seen in the UK and help to understand potential future options for UK exports.

8 Conclusion

In conclusion, the purpose of this report has been to demonstrate the capabilities of the IAP2 as a means to support the CCC in its understanding of the challenges facing the UK government with respect to addressing climate change both in terms of mitigation requirements and adaptation needs. Within the above report we have aimed to demonstrate a prototype linked system that combines the abilities of the IAP2 with the mitigation measures of the MACC in a way that meets the CCC's needs. Specifically we have demonstrated:

- Proof of concept of the modelling capability *(by demonstrating a completed linked system and detailing the results)*
- That the model can simulate the mitigation and adaptation scenarios that the CCC have requested for this phase *(by modelling the 5th CB and adaptation scenarios)*
- That it does it in a way that takes into account of other constraints on the use of land *(constraints are inherent within the integrated modelling framework)*
- That we can model abatement options in agriculture that are consistent or are a close approximation to the measures covered in the 5th Carbon Budget work (*by using the MACC used to support the 5th CB*)
- That we can model afforestation and agro-forestry consistent with the 5th CB assumptions regarding afforestation rates (*through the post processing detailed in 5.1.1*).
- That the IAP2 can produce outputs that relate to the resilience indices relevant to the CCC's adaptation team (*section 6.1*) and suitable outputs for mitigation analysis (*section 6.2*)
- That it will be possible to highlight synergies and trade-offs within and between scenarios (*Sections 6.1 and 6.2 and with future comparisons of these*)
- That we have the capability to complete the rest of the project, and in particular the modelling of additional mitigation scenarios for the second phase (S*ection 7*).

In doing so we have met the proposal specifications:

- Demonstrate the integration of the 5th Carbon Budget mitigation scenario into the modelling

- Provide sufficient relevant outputs to demonstrate the models fitness for purpose for both assessing mitigation impacts and adaptation/resilience. These should include GHG emissions by gas and source, and resilience indicators that relate to the ASC's indicator framework.
- Provide assurance of modelling capability in order to explore further scenarios and outputs for the second phase.

In summary, the ClimSAVE/IMPRESSIONS IAP is leading in its field in i) its ability to deal with combined climatic and socio-economic futures and ii) in being able to do so in a way that highlights the challenges from cross-sectoral interactions. The MACC provides a robust framework and significant existing potential to address a range of LULUCF/ALULUCF-related abatement measures. By combining the two there is real potential to produce an innovative policy-support tool capable of providing appropriate information to address the very real challenges posed by climate change. We hope to have demonstrated this potential within this report, and as well highlighted the model's fitness-of-purpose for the Phase 2 and the potential benefits of the additional scenarios it would explore.

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- Landsat-TMS satellite imagery © 2007 Distributed by Eurimage
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Appendix A: Land use allocation within the IAP: FAQ

1. **What parameters are in the profit function which drives the LU allocation? If output prices are not in the model, how is profitability determined? Please list all the elements that goes to into the profit function, and if it is maximised subject to constraints, which constraints are taken into account?**

"*Setting the price of commodities within scenarios was found to produce unrealistic levels of production of commodities, with levels varying between none at all and treble. Therefore prices were set by an iterative mechanism, which approximately allowed increases in production appropriate for a scenario" … "It is clear that the socio-economic scenarios should define the future level of production and not the price of commodities. The economic scenario cannot know the changes in yields due to climate and soil and the resulting changes in relative gross margins between crops and possible production space, which can generate huge changes in total production. If a given price generates either a huge surplus or virtual absence of a commodity, this is unsustainable in reality and the only realistic alternative is to adjust the scenario price. Thus it is better to fix a target scenario production and allow the price to be adjusted to meet this target.*" Audsley et al., 2006.

The profit function is driven by the net European demand for commodities and the potential for their supply within the scenario.

Demand is driven primarily by: Population, GDP, Dietary Preferences and Food Imports.

- Higher populations have greater total food demand as do wealthier ones.
- Dietary preferences set the level of demand for red meat (provided by grassland systems) and white meat (which are fed on grain and therefore contribute to the demand for grain production for feed)
- Food imports determine what proportion of total food demand does not have to be met within Europe as it is imported from abroad.

The potential for commodity supply is driven by the biophysical conditions of a given scenario in terms of the impacts of climate and soils on crop yields. This is modified by socio-cultural factors such as technology, fertiliser application etc.

Prices are not an output from the model but are calculated internally within the model based on an iteration from initial prices. Prices are inflated to stimulate expansion in production when a commodity is not supplied sufficiently to meet demand. Prices are deflated where a commodity is over-produced relative to demand. Iteration continues until demand for all commodities is met. Or after a set number of iterations (to prevent infinite iteration loops). There is also a constraint that prices cannot rise by more than a factor of 10 (i.e. it assumes that there is limit to willingness (or ability) to pay).

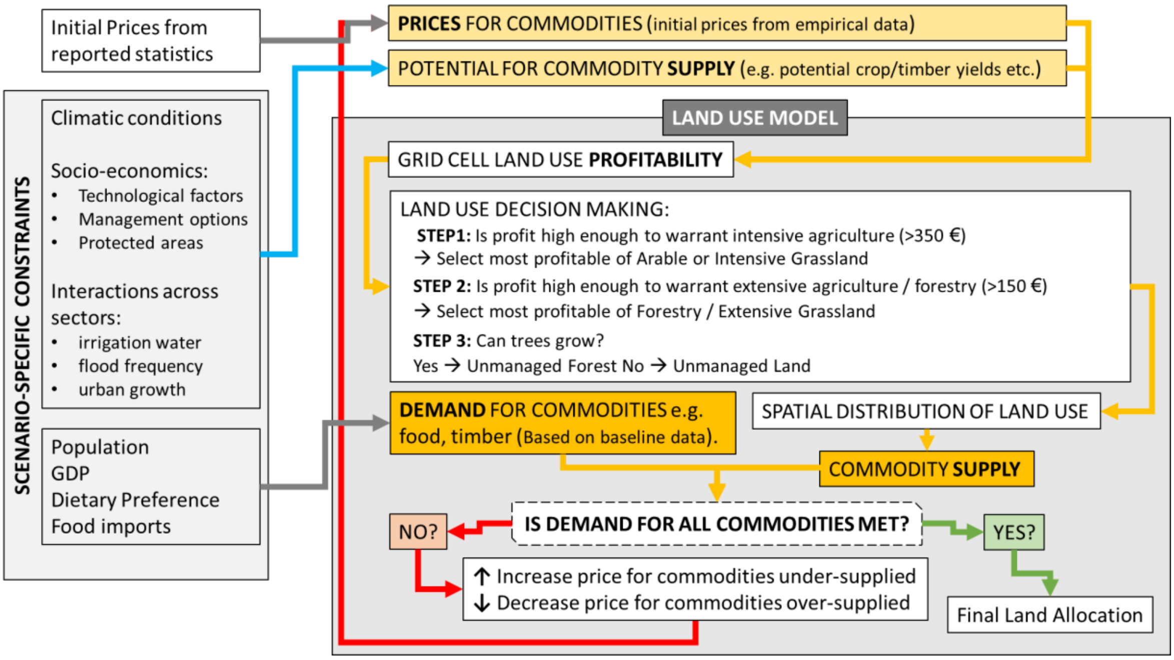
Iteration to calculate demand-based prices is important because:

1) Changing biophysical and socio-economic conditions in 2080 will make areas of land that are currently unproductive productive and vice versa. i.e. baseline prices will not be relevant in these scenarios.

2) Without iterating to take into consideration changes of supply the most valuable commodity at baseline will be produced everywhere – irrespective of whether or not it is needed to meet demand. By iterating, land uses that overproduce are down valued to allow demands for all commodities to be met. This is based on the findings of previous project REGIS that didn't take this into consideration.

The model iterates to meet demand by increasing and decreasing prices to allocate the required level of production to the most profitable land. There is an upper limit on price increases of 10x the baseline price to prevent unrealistic price inflations.

The purpose of the pricing is not to produce a realistic market price but to identify the areas of land that would be best suited for each land use. As such, the question the model is answering is – "what is the best spatial distribution across Europe to meet the demand for land use X?" rather than "what is the market price of land use X?".



2. What is the purpose of the profit thresholds? Why doesn't the model allocate use to the most profitable activity, rather than reaching a particular threshold? How is the level of the threshold determined?

This reflects an assumption in model that reflects baseline empirical evidence that arable and dairy farms tend to make a certain level of profit to be worthwhile. It is based on past modelling experience which shows that without these thresholds there are considerable unrealistic changes in land use. For example, an area of Welsh hillside may be able to produce wheat £1.00 more profitably than extensive grassland, but this might not be expected to warrant the extra investment in the technology and equipment required.

The true thresholds of where intensive farming is considered profitable enough vary by country (Audsley et al., 2006), but the 350 Euro assumption is used to keep the modelling simple. It is based on an assessment of the profit margins across Europe (Audsley et al, 2006; 2014).

It should be remembered that the model is trying to first identify where to put the most profitable land uses – not to project a realistic price for them. As such the threshold is designed to filter down to the most profitable areas for the initial run of the model, if this doesn't produce enough of the desired land use to meet demand, future iterations will increase profitability to push profits over this threshold until the demand is met. (It's also important to remember that just allocating the most profitable land would lead to the over production of a single commodity – which is why the supply/demand balancing is required).

3. If it doesn't value non-market goods and services, are these taken into account elsewhere in the modelling?

To only a very limited extent within the IAP2. They can be by post processing.

Non-market priorities can be taken into consideration through the protected area modelling. This prevents land uses becoming more intensive within protected areas.

Floodplains are also constraint on agricultural land use (through the flooding module).

Non-market priorities are also taken into consideration by both the post-processing modules. One which reflects existing national preferences for extensive grassland over forestry and the other that reflects the desire to meet land use targets (e.g. afforestation rates).

4. **How are the demand functions determined – please list all parameters that go into these. What demands are modelled (eg food, timber, other outputs?). Is demand a function of price and income?**

The demand function is related to population, wealth (GDP), dietary preference and imports from outside of Europe. They are broken down into commodity demands (Audsley et al., 2006). The commodities considered are: cereals, root crops, protein, oil, fibre, milk, meat and timber.

Income affects demand through an (empirically grounded) assumptions relating population wealth and food demand.

Income in terms of ability to pay for food is not explicitly included in the modelling but is recognised within the upper limit to proce increases within the iteration. There is an assumption implicit within the modelling's increases in food price that within Europe there would be sufficient personal income for individuals to adjust their budgets to meet any changes in food costs that result from the climatic / socio-economic changes.

See response to 1 for more information on the role of demand.

5. **What determines supply (ditto above.) If prices are not part of the supply curve, how is supply determined? Is income (eg from CAP, other sources) a part of the supply curve?**

Supply is determined by the iterative process discussed in the *response to 1*. Supply is constrained by the climatic and socio-economic scenario's impacts on crop and timber yields. The iteration of prices to match demand means that supply is also influenced by the demand for particular commodities. Income is not considered to be a significant limiting factor, there is the assumption that people will pay to avoid starvation (subject to a limit of x10 the initial price as an increase). CAP etc. is not specifically considered as in 2080 funding approaches may well be very different.

6. **How does the model find an equilibrium between demand and supply and shouldn't this lead to price information?**

By iteration modifying prices to allow supply to meet demand. Price information is used, but this is only to determine the relative value of different land uses in a given scenario. It is not intended to be used as a prediction of market price. *See response to 1 above.*

7. **How do profits and productivity vary according to climate, soil and other physical conditions? How is this taken into account in the model?**

There is a crop and a forest yield model integrated within the IAP. These provide projections of the productivity of rainfed and (selected) irrigated crops and land use based on soil and climate variables, recognising that some soils are not appropriate for productive uses (eg. shallow, very steep, upland waterlogged soils etc). Soil does not change with scenario but climate does. The yields model takes into consideration socio-economic sliders such as changes in yield from technology, agronomy or fertiliser use.

Irrigation water availability also impacts yields and is itself modified by socio-economic settings for water savings in agricultural, domestic and power/industrial sectors and limitations on available water. Irrigation water use is also priced and iterated up and down to help meet the desired levels of commodities.

In addition, urban growth also takes land out of the land use system for habitation and waterlogging from fluvial flooding also limits agricultural land practice.

All the above factors are therefore constraints on the land use allocation. They interact to determine the land use classes present in a single land use iteration. If – as a result of these constraints – demands is not met, the model increases the price of the commodities under produced and iterates again.

In some extreme scenarios, it is not possible to meet demand within the iteration limit and in these cases the model reports back the proportion of the demand each commodity that is met.

Appendix B: LCMGB Classification accuracy

	Producers	Users
BL wood	87	91
Conifer wood	94	94
Arable and horticulture	91	92
Improved grassland	89	83
Rough grassland	35	49
Neutral grassland	36	63
Calcareous grassland	52	84
Acid grassland	66	48
Fen,marsh and swamp	78	90
Heather	71	85
Heather grassland	51	53
Bog	93	39
Montane habiatats	56	41
Inland rock	77	92
Saltwater	88	69
Freshwater	86	98
Supra littoral rock	82	96
Supra littoral sediment	87	77
Littoral rock	94	93
Littoral sediment	87	86
Saltmarsh	89	95
Urban	88	82
Suburban	86	86

LCMGB accuracy assessment by land use class (data from Table 3.7 of CS technical report No 11/07, Morton et al., 2011); colours are increments of 10% from red < 50% to Dark green > 90%. Users accuracy reflects the percentage of classes on the finished map that accurately reflect the ground truth data (errors are classifications that are wrong). Producers accuracy reflects the percentage of ground truth data that is accurately captured by the classification (errors are failures to identify known ground truth sites)

Appendix C: Modelled species

Category	Species included (from IAP2 output)	Habitat Mask
Agriculture	Broad-leaved cudweed *(Filago pyramidata)* Cleavers / Goosegrass *(Galium aparine)* Common poppy *(Papaver rhoeas)* Cornflower *(Centaurea cyanus)* Long-headed poppy *(Papaver dubium)* Red hemp-nettle *(Galeopsis angustifoila)* Red-tipped cudweed *(Filago lutescens)* Shepherd's needle *(Scandix pecten-veneris)* Small-flowered catchfly *(Silene gallica)* Tower mustard *(Arabis glabra)* Venus' looking-glass *(Legousia hybrida)* Brown hare *(Lepus europaeus)* Corn bunting *(Milaria calandra)* Grey partridge *(Perdix perdix)* Linnet *(Carduelis cannabina)* Pheasant *(Phasianus colchicus)* Rabbit *(Oryctolagus cuniculus)* Skylark *(Alaudia arvensis)*	Presence of arable land use within the grid cell.
Forest	Aleppo pine *(Pinus halepensis)* Cowberry *(Vaccinium vitis-idaea)* Holm oak *(Quercus ilex)* Kermes oak *(Quercus coccifera)* Norway spruce *(Picea abies)* Prickly juniper *(Juniperus oxycedrus)* Scots pine *(Pinus sylvestris)* Ash *(Fraxinus excelsior)* Aspen *(Populus tremula)* Beech *(Fagus sylvatica)* Bilberry *(Vaccinium myrtillus)* Downy oak *(Quercus pubescens)* Pendunculate oak *(Quercus robur)* Hazel *(Corylus avellana)* Hornbeam *(Carpinus betulus)* Silver birch *(Betula pendula)* Small-leaved lime *(Tilia cordata)* White birch *(Betula pubescens)* Brown bear *(Ursus arctos)* Lynx *(Lynx lynx)* Purple emperor butterfly *(Apatura iris)* Roe deer *(Capreolus capreolus)* Wild boar *(Sus scrofa)* Woodcock *(Scolopax rusticola)*	Presence of >10ha of forest within the grid cell. In some scenarios this could include the % of set aside allocated to on-farm woodland.
Wetland	Bog myrtle *(Myrica gale)* Cloudberry *(Rubus chamaemorus)* Common reed *(Phragmites australis)* Crowfoot *(Ranunculus bulbosa)* Cursed buttercup *(Ranunculus scleratus)* Great water parsnip *(Sium latifolium)* Grey willow *(Salix cinerea)* Lesser celandine *(Ranunculus ficaria)* Lesser twayblade *(Listera cordata)* Reed sweetgrass *(Glyceria maxima)* Spring quillwort *(Isoetes echinospora)* White beak-sedge *(Rhynchospora alba)* Beaver *(Castor fiber)* Corncrake *(Crex crex)* Great bittern *(Botaurus stellaris)* Mallard *(Anas platyrhynchus)* Swallowtail butterfly *(Papilio machaon)* Western dappled white butterfly *(Euchloe crameri)*	This is masked using the wetland outputs of the FLOOD and COASTS MODEL: presence of a wetland habitat.

Category	Species included (from IAP2 output)	Habitat Mask
	Yellow-bellied toad *(Bombina variegata)*	
Saltmarsh	Annual seablite *(Suaeda maritima)* Common arrow grass *(Triglochin maritima spp)* Common saltmarsh grass *(Puccinellia maritima)* Common sea-lavender *(Limonium vulgare)* Glasswort *(Salicornia europaea)* Lax-flowered sea-lavender *(Limonium humile)* Saltmarsh flat-sedge *(Blysmus rufus)* Sea purslane *(Atriplex portulacoides)* Sea rush *(Juncus maritimus)* Shrubby seablite *(Suaeda vera)*	This is masked using the wetland outputs of the FLOOD and COASTS MODEL: presence of saltmarsh habitat.
Coastal grazing marsh	Curlew *(Numenius arquata)* Hairy buttercup *(Ranunculus sarduous)* Natterjack toad *(Bufo calamita)* Strawberry clover *(Trifolium fragiferum)* Water crowfoot *(Ranunculus baudotii)* Whooper swan *(Cygnus cygnus)* Black grass *(Juncus geradii)* Red fescue *(Festuca rubra)*	This is masked using the wetland outputs of the FLOOD and COASTS MODEL: presence of coastal grazing marsh habitat
Heathland	Bell heather *(Erica cinerea)* Heather *(Calluna vulgaris)* Cornish heath *(Erica vagans)* Cross-leaved heath *(Erica tetralix)* Dwarf willow *(Salix herbacea)* Hairy greenweed *(Genista pilosa)* Lavender spp *(Lavandula spp)* Oleander *(Nerium oleander)* Pricky Burnet *(Sarcopoterium spinosum)*	This is masked using the presence of either extensive grassland or unmanaged land that is in an area predicted to be climatically suitable for heathland
Pollinators	Alfalfa leafcutter bee *(Megachile rotundata)* Buff-tailed bumble bee *(Bombus terrestris)* Common carder bee *(Bombus pascuorum)* Early bumble bee *(Bombus pratorum)* Early mining bee *(Andrena haemorrhoa)* European orchard bee *(Osmia cornuta)* Garden bumble bee *(Bombus hortorum)* Mining bee *(Andrena carantonica)* Red mason bee *(Osmia rufa)*	It was not possible to allocate these species to one particular habitat. As such they are not currently masked for habitat – thus they reflect only changes in climate.
Charismatic	Apollo butterfly *(Parnassius apollo)* Ibex *(Capra ibex)* Red-breasted goose *(Branta ruficollis)* Two-tailed pasha butterfly *(Charaxes jasius)* Chamois *(Rupicapra rupicapra)* Red deer *(Cervus elaphas)* Capercaillie *(Tetrao urogallus)* Mastic (Pistacia lenticus)	These species were selected to represent European charismatic species. They are not masked variously by habitats within which they are found.

Table B1 Species included in IAP2 modelling and the land use mask used to determine habitat presence/absence.