Agent-based modelling of alternative futures in the British land use system

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Abstract

Socio-economic scenarios such as the Shared Socioeconomic Pathways (SSPs) have been widely used to analyse global change impacts, but representing their diversity is a challenge for the analytical tools applied to them. Taking Great Britain as an example, we represent a set of stakeholder-elaborated UK-SSP scenarios, linked to climate change scenarios (Representative Concentration Pathways), in a globally-embedded agent-based modelling framework. We find that distinct model components are required to account for divergent behavioural, social and societal conditions in the SSPs, and that these have dramatic impacts on land system outcomes. From strong social networks and environmental sustainability in SSP1 to land consolidation and technological intensification in SSP5, scenario-specific model designs vary widely from one another and from present-day conditions. Changes in social and human capitals can generate impacts larger than those of technological and economic change, and comparable to those of modelled climate change. We develop an open-access, transferrable model framework and provide UK-SSP projections to 2080 at 1km2 resolution, revealing large differences in land management intensities, provision of a range of ecosystem services, and the knowledge and motivations underlying land manager decision-making. These differences suggest the existence of large but underappreciated areas of scenario space, within which novel options for land system sustainability could occur.

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Key Points:

- A national-scale agent-based model is developed to represent paired climatic and socio-economic scenarios in the land system.
- Key scenario characteristics relate to forms of human behavior, interactions and societal preferences.
- Large differences emerge between scenarios in terms of land management intensities, ecosystem service provision and land sparing.

Abstract

Socio-economic scenarios such as the Shared Socioeconomic Pathways (SSPs) have been widely used to analyse global change impacts, but representing their diversity is a challenge for the analytical tools applied to them. Taking Great Britain as an example, we represent a set of stakeholder-elaborated UK-SSP scenarios, linked to climate change scenarios (Representative Concentration Pathways), in a globally-embedded agent-based modelling framework. We find that distinct model components are required to account for divergent behavioural, social and societal conditions in the SSPs, and that these have dramatic impacts on land system outcomes. From strong social networks and environmental sustainability in SSP1 to land consolidation and technological intensification in SSP5, scenario-specific model designs vary widely from one another and from present-day conditions. Changes in social and human capitals can generate impacts larger than those of technological and economic change, and comparable to those of modelled climate change. We develop an open-access, transferrable model framework and provide UK-SSP projections to 2080 at 1km2 resolution, revealing large differences in land management intensities, provision of a range of ecosystem services, and the knowledge and motivations underlying land manager decision-making. These differences suggest the existence of large but underappreciated areas of scenario space, within which novel options for land system sustainability could occur.

1 Introduction

If efforts to mitigate climate change in the coming years are not transformative, then the impacts themselves likely will be. The adoption of effective mitigation and adaptation strategies is therefore essential, and these depend upon thorough knowledge of possible future conditions (Rounsevell et al., 2021). To help generate such knowledge, various sets of scenarios have been developed to provide structures within which analyses can be conducted (Schindler & Hilborn, 2015). Currently, the most widely-used scenario sets for environmental studies are the Representative Concentration Pathways (RCPs) describing alternative greenhouse gas concentration trajectories, and the Shared Socioeconomic Pathways (SSPs) describing alternative socio-economic trajectories (O'Neill et al., 2020).

The RCP-SSP framework has been adopted across disciplines, and a decade's worth of research has built upon it (O'Neill et al., 2020). It has proven particularly useful because it allows various combinations of climatic and socio-economic conditions to be explored, providing coherent storylines of plausible future conditions. RCP-SSP combinations have been defined for numerous contexts from global to local scales, often through participatory processes of stakeholder engagement (e.g. Kebede et al., 2018; Kok et al., 2019; Wear & Prestemon, 2019). Together, these scenarios describe radically different 'worlds' in which societal structures and priorities differ, are subject to different modes of governance, and are constrained by different socio-economic resources.

One of the main uses of these scenario storylines has been in computational modelling. This modelling supports the identification of pathways towards particular outcomes, such as limiting global mean-temperature increases to 1.5°C (Rogelj et al., 2018), or reversing global biodiversity declines (Leclère et al., 2020). Model-based implementations of the RCPs and SSPs have become the de facto basis for anticipatory policy-making at the international level, effectively defining the expected scope of actions and outcomes during the 21st century (O'Neill et al., 2020).

Reliance on computational models for quantitative exploration of future conditions is largely inevitable, but is not without drawbacks. Faced with widely divergent SSPs, it would be appropriate to use similarly divergent modelling approaches to fully explore scenario space (Brown et al., 2021; Polasky et al., 2011). However, large-scale land system models have been relatively convergent in approaches and assumptions (Brown et al., 2017; Gambhir et al., 2019; Haasnoot et al., 2013; Uusitalo et al., 2015). Most rely on cellular automata, econometric or similar models with statistical transition probabilities between broad land use classes based on observed (past) changes (Brown et al., 2017; Verburg et al., 2019). Only a small subset of scenario components have been explored as a result, usually those related to economic or policy change. Aspects of scenarios most neglected in large-scale land system models relate to human behaviour within the land system, ecosystem services provision, representing land use (as opposed to land cover) alternatives across sectors, and explicit links between global and smaller-scale dynamics (Müller et al., 2019; Verburg et al., 2019). As a result, the highly divergent nature of SSP scenarios may be obscured, and important areas of scenario space unexplored (Estoque et al., 2020; Pedde et al., 2019).

Here we take a set of detailed, stakeholder-developed, qualitative and quantitative SSPs for the United Kingdom, and simulate the development of the British land system throughout these scenarios using a flexible agent-based modelling framework driven by national and global scenario storylines. In adapting this framework to each UK-SSP in turn, we highlight the ways in which the scenarios differ from the present day and from one another. We develop a new model application that contains scenario-specific elements and settings, and consider model outputs in the light of the design choices we make and their underlying scenario elements. In doing so we further develop an open-access and transferrable agent-based modelling framework capable of representing paired SSP-RCP scenarios at national to continental scales, and evaluate its application through the comprehensive TRACE protocol (in SI). We also provide new projections to 2080 of the UK-SSPs at 1km2 resolution, accounting for key scenario elements related to human behaviour, ecosystem service valuation and land management intensity. We use our findings to understand potential changes in the British land system in particular, and potential advances in the simulation of SSPs in the land system in general.

1.1 The UK context

The UK makes a particularly appropriate case study for scenario analysis for a number of reasons. First, its land systems span wide ranges of uses, intensities, environmental and climatic conditions, and economic viabilities – from highly productive arable farming in the south-east to marginal and extensive livestock management in the north west. Second, the UK has well-developed data and land system research facilities. Third, land management in the UK faces a particularly uncertain future, with fundamental changes to policy frameworks following the UK's exit from the European Union that are likely to diverge to some extent between the country's four constituent nations. Combined with substantial expected climatic changes and strong remaining links to global markets, these give a notably broad space for scenario exploration. Participatory processes have already been used to explore this space (Holman et al., 2008), most recently with the development of detailed UK-SSP scenarios describing alternative social, economic and political trajectories (CEH, 2021; Harmáčková et al., 2022; Pedde et al., 2021).

Nevertheless, modelling of the British land system under alternate scenarios has been limited. Much of the modelling that has been done has focused on the impacts of climate change (Rounsevell & Reay, 2009), and/or has been sub-national in scale and focused on particular scenario elements, issues or ecosystem services (Cantarello et al., 2011; Holman et al., 2005, 2016). Bateman et al. (2013) developed an integrated environment-economy model covering different ecosystem services, but their optimisation approach involved constraining economic rules and was only applied to a limited set of scenarios. Policy-oriented reports on UK land use futures therefore have been able to draw on only limited evidence from modelling studies, and none that covers a representative range of British land uses and future scenarios (Foresight Land Use Futures Project, 2010). The UK therefore provides a particularly relevant, well-understood and dynamic analogy for many other national contexts, but one for which limited scenario explorations exist. We aimed to develop a detailed, cross-scale and cross-sectoral model that remains sufficiently efficient and user-friendly to be used in participatory processes for UK scenario analyses.

2 Materials and Methods

We make use of two main resources in this study: a set of qualitative and quantitative UK-RCP and UK-SSP scenarios described in detail in Harmáčková et al. (2022), Merkle et al. (2022) and Robinson et al. (2022), and a newly-developed UK land use model described below and in the supporting information. By pairing these scenarios and model, we explore potential future land system change in Great Britain prompted by linked climatic and socio-economic conditions (referred to below as the 'UK-RCP-SSPs'). The model is further embedded within a global modelling framework to account for global change and the UK's international trade under each scenario. Here we describe the general design and calibration of the model before explaining how it was tailored to each of the UK-RCP-SSPs. Full details are contained in a stand-alone methods section and TRACE model evaluation document in the Supporting Information.

2.1 Overview

We develop CRAFTY-GB, a new agent-based model of the British land system based on a broad range of available land system data and operating at 1km2 resolution. The range of the model is restricted to Great Britain rather than the UK as a whole because consistent data were not available for Northern Ireland. CRAFTY-GB is an application of the CRAFTY agent-based modelling framework (Murray-Rust et al., 2014). The core model is therefore the same as in earlier applications of this framework (e.g. to Europe (Brown et al., 2019), Sweden (Blanco et al., 2017) and Brazil (Millington et al., 2021)) while the inputs were tailored to the British context (Fig. 1).

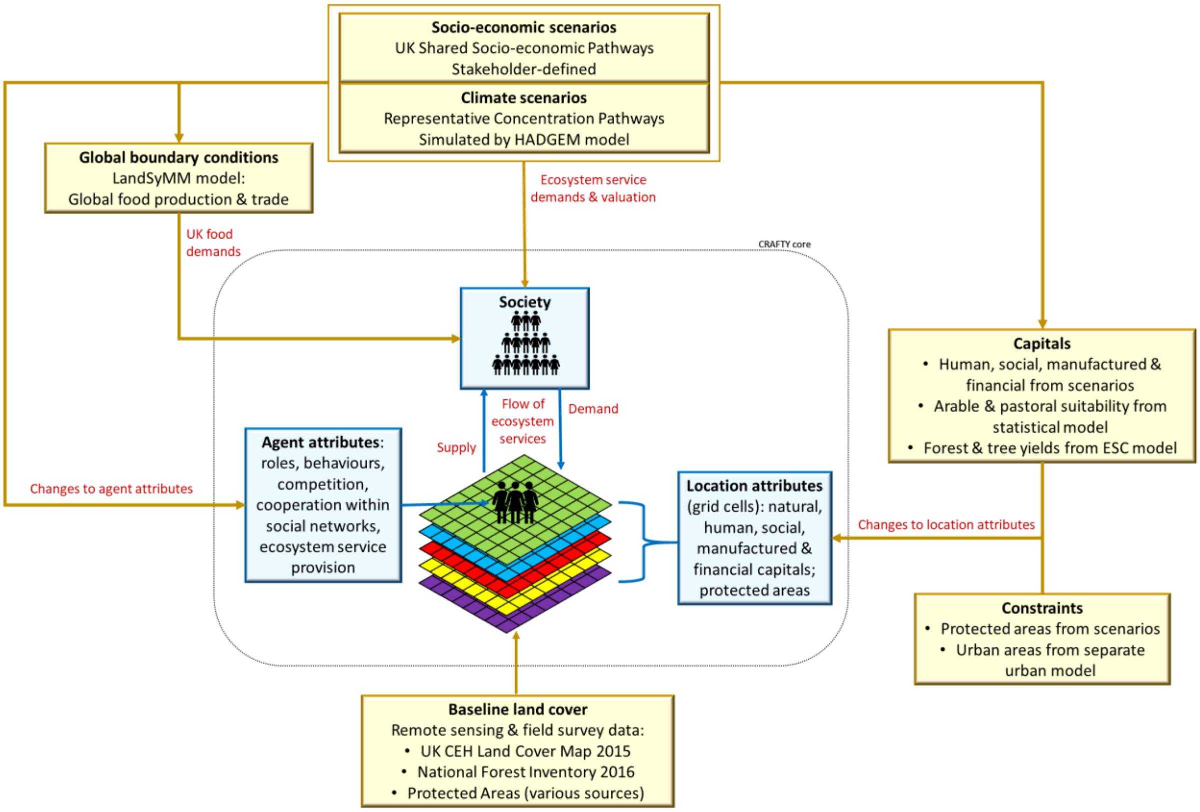

Figure 1.: Schematic diagram of CRAFTY-GB structure and information flows. The blue features belong to the generic core of CRAFTY, and the yellow features are specific to the British model implementation, providing information to the core processes. This external information is derived from observational, modelled and stakeholder-developed data explained in the text. Red labels describe particular information exchanges.

The basis for modelled land use change in CRAFTY-GB is a set of capitals that describe location resources or attributes for each 1km2 cell (Tables S1 – S3). Each cell is also assigned an agent representing a specific form of land management through a modelled process of competition with other agents (Table S4). CRAFTY uses the concept of Agent Functional Types (Arneth et al., 2014) to create simplified typologies of land managers according to their objectives, behaviours, and their forms and intensities of land management. These agents are able to use the capitals to produce services that satisfy societal demands, which are exogenously defined. Agents are initially distributed using baseline land use data, and then engage in a simulated process of competition for cells. This competition is driven by the level of demand for the services that different agents provide, and the relative valuation of each of those services. Competition outcomes vary with the productive and behavioural characteristics of the agents, as well as cooperation between them through modelled social networks.

This basic model circuit is driven by exogenous scenarios that describe scenario-based climatic and socio-economic changes over time. These changes can affect capital values, agent characteristics, societal demand levels, competition processes and policy objectives. The nature and spatio-temporal properties of modelled land use change therefore depend on the interaction of these core model components. In this application, scenarios are also used to calibrate the model parameters and to determine which modelled processes are active, which is a novel aspect of the approach. Below we describe model inputs before going on to scenario implementation.

2.2 Model components

Capitals describing resources or attributes of each individual cell underpin simulated land use change in CRAFTY-GB. Capitals are divided into human, social, manufactured, financial and natural capitals, with natural capital further divided into yields or suitabilities for arable, pastoral and forest land uses or species (Tables S1 & S2). Social, human, financial and manufactured capitals were derived from UK-SSP projections of eight socio-economic indicators from (Merkle et al., 2022) (see Table S2). Forest suitabilities were modelled using the Ecological Site Classification (ESC) yield class model (Forest Research, 2021; Pyatt, 1995), and arable, and improved and semi-natural pastoral suitabilities were modelled statistically (SI section 'Capitals'). Protected areas belonging to 11 different types of national and international designation and to five different private land-owning organisations (NGOs) were included in the model, and varied according to SSP storylines (Table S3, Fig. S1).

Across the modelled landscape, CRAFTY-GB includes a range of agent types designed to capture the main forms of land use in Great Britain, including gradations of intensity and multifunctionality. Agent types were divided between arable land uses (intensive arable for food, intensive arable for fodder, sustainable arable and extensive arable), pastoral land uses (intensive pastoral, extensive pastoral, very extensive pastoral), forest land uses (productive native conifer, productive non-native conifer, productive native broadleaf, productive non-native broadleaf, multifunctional mixed woodland and native woodland for conservation), and combined classes (bioenergy and agroforestry) (Table S4). Variation in ecosystem service provision within these classes allows them to represent a continuous range of forms of land management rather than arbitrarily distinct groups. Variations in decision-making behaviour further allow individual agents and groups of agents to respond differently to modelled changes (SI section 'Behaviour', Table S5). Urban areas were projected in the scenarios by an independent urban model (more details in the SI, and full details in Merkle et al., in review). The initial distribution of land uses was based on a range of data sets described in Table S4.

Each modelled land use was represented as providing a range of provisioning, regulating and cultural ecosystem services and other indicators (e.g. biodiversity, employment) of relevance to the UK-SSP scenarios. These services are defined in Tables S6 and S7. The potential and required provisioning of these services varied according to the UK-RCP-SSP scenarios. Demand levels for foods were derived from the LandSyMM (Land System Modular Model; www.landsymm.earth) global modelling framework running global RCP-SSP scenario combinations (Rabin et al., 2020), as described in SI section 'Services & demand levels'. Non-food demands were taken from the UK-SSP scenarios, and are described in (Merkle et al., 2022).

Demand levels are shown in the results below, and are available along with all model data (see 'data availability' section).

2.3 Scenarios

The SSPs were specified for the UK as described in Pedde et al. (2021), Harmáčková et al. (2022) and Merkle et al. (2022). These substantial extensions of the global SSPs provide detailed narratives and quantifications of social, economic and political developments across the UK until 2100. The narratives integrate national stakeholder knowledge on locally-relevant drivers and indicators with higher level information from the European and global SSPs. These narratives were simplified and converted into model parameterisations (Fig. 2, Table S8). The UK-SSPs were put in a global context through LandSyMM global land system modelling to provide consistency with the broader SSP framework and to account for the UK's international trade. The SSP implementation also utilised the forms of behaviour represented in CRAFTY to capture land management decision-making (Table S6). Of these behaviours, social networks are the only new addition to the CRAFTY framework. These allow agents of the same type to affect one another's competitiveness within defined spatial neighbourhoods, to represent the benefits both of improved local knowledge diffusion and of economies of scale.

The RCPs were specified for the UK as described in the SI (section 'Scenarios') and (Robinson et al., 2022). Climatic conditions were taken from the CHESS-SCAPE future climate data set, which extends the regional climate model (RCM) output in the UK Climate Projections 2018 (UKCP18) (Lowe et al., 2018; Met Office Hadley Centre (MOHC), 2018) by downscaling them from 12km to 1km resolution and producing realisations for three RCPs in addition to RCP8.5. This data set covers several physical climate variables to 2080 at 1 km spatial resolution and time steps ranging from daily to decadal averages. Spatially and temporally explicit values for several climate variables were generated for the UK, including temperature and precipitation, potential evapotranspiration and growing degree days. These variables were then used as inputs to the crop, grassland and forest modelling to produce annual scenario-specific capital values.

RCP-SSP combinations were chosen to: (i) cover a broad range of uncertainty in both emissions (and hence climate) and socio-economic developments; and (ii) include any combination of SSPs and RCPs that is plausible, meaningful and useful. The six combined scenarios we use (RCP2.6-SSP1, RCP4.5-SSP2, RCP4.5-SSP4, RCP6.0-SSP3, RCP8.5-SSP2, RCP8.5-SSP5) cover weak to strong climate change, as well as future societies with high and low challenges to adaptation and mitigation. The selection also allows analysis of the effects of different RCPs within the same SSP (RCPs 4.5 and 8.5 with SSP2), and the effects of different SSPs within the same RCP (SSPs 2 and 4 with RCP4.5; SSPs 2 and 5 with RCP8.5). Furthermore, low adaptation challenges (SSP1/5) and high adaptation challenges (SSP3/4) are confronted with different RCPs.

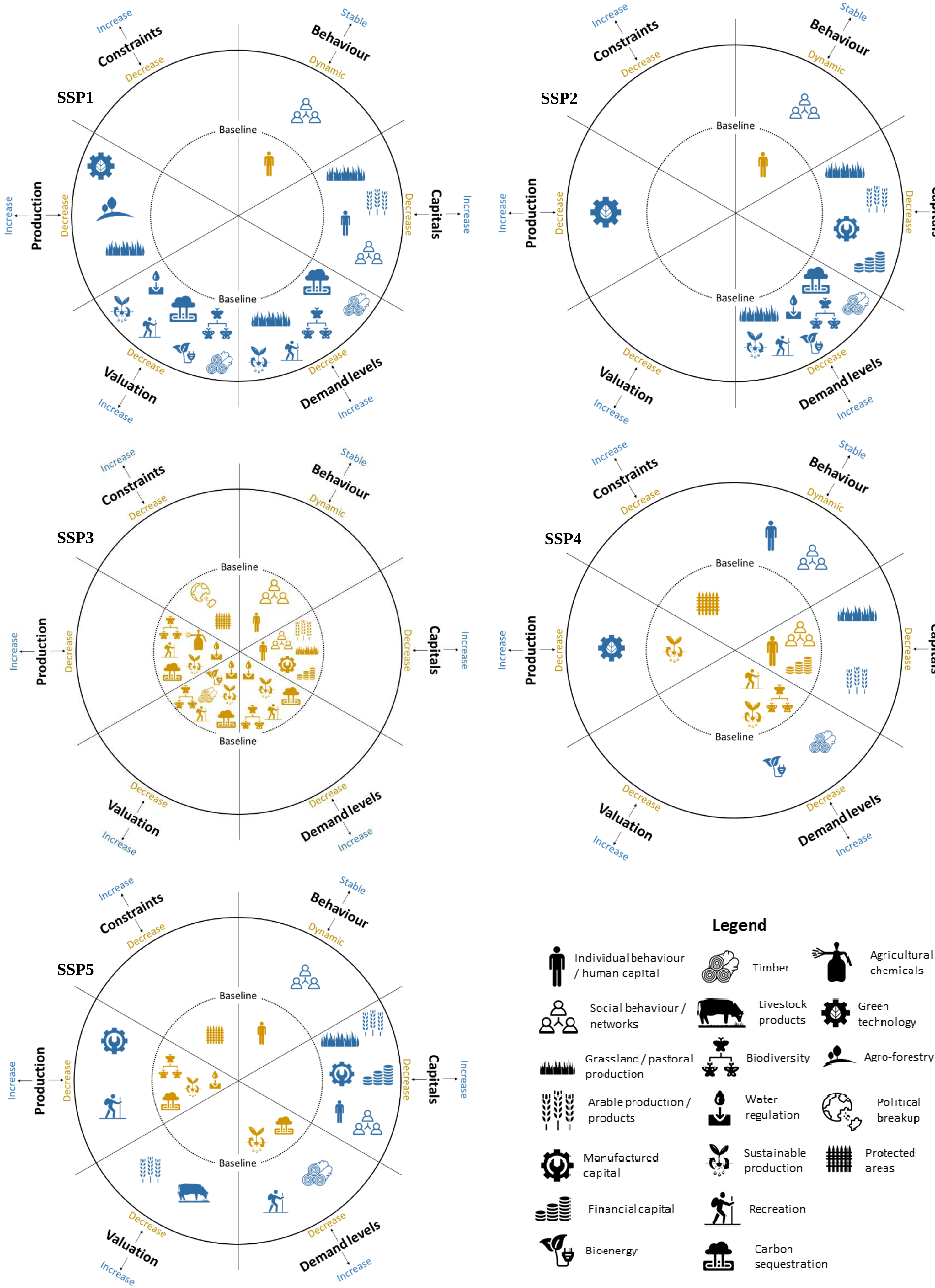
SSP1
Constraints
Increase
Decrease
Behaviour
Stable
Dynamic
Production
Increase
Decrease
Capitals
Decrease
Increase
Valuation
Decrease
Increase
Demand levels
Decrease
Increase
Baseline
Baseline
SSP2
Constraints
Increase
Decrease
Behaviour
Stable
Dynamic
Production
Increase
Decrease
Capitals
Decrease
Increase
Valuation
Decrease
Increase
Demand levels
Decrease
Increase
Baseline
Baseline
SSP3
Constraints
Increase
Decrease
Behaviour
Stable
Dynamic
Production
Increase
Decrease
Capitals
Decrease
Increase
Valuation
Decrease
Increase
Demand levels
Decrease
Increase
Baseline
Baseline
SSP4
Constraints
Increase
Decrease
Behaviour
Stable
Dynamic
Production
Increase
Decrease
Capitals
Decrease
Increase
Valuation
Decrease
Increase
Demand levels
Decrease
Increase
Baseline
Baseline
SSP5
Constraints
Increase
Decrease
Behaviour
Stable
Dynamic
Production
Increase
Decrease
Capitals
Decrease
Increase
Valuation
Decrease
Increase
Demand levels
Decrease
Increase
Baseline
Baseline
Legend
Individual behaviour / human capital
Timber
Agricultural chemicals
Social behaviour / networks
Livestock products
Green technology
Grassland / pastoral production
Biodiversity
Agro-forestry
Arable production / products
Water regulation
Political breakup
Manufactured capital
Sustainable production
Protected areas
Financial capital
Recreation
Bioenergy
Carbon sequestration

Figure 2: Summary of the implementation of the UK-SSPs in CRAFTY GB. Items included here represent main scenario conditions and refer specifically to the CRAFTY-GB implementation, relative to the baseline, and are in addition to the broader scenario storylines. Changes in demand shown here are per capita and do not represent the overall demand changes summarised in Fig. 4. The 'Behaviour' segment in the plots varies between 'stable' and 'dynamic' rather than 'increase' and 'decrease' because behavioural variations are not directional but affect the heterogeneity and temporal dynamism of agent behaviour (see Table S5).

2.4 Model evaluation

Model evaluation is presented in detail in a TRACE ("TRAnsparent and Comprehensive model Evaludation") model evaluation document in the SI (Augusiak et al., 2014; Ayllón et al., 2021; Grimm et al., 2014; Schmolke et al., 2010), with main components summarised here. The CRAFTY framework has been evaluated using combinations of unit tests, sensitivity and uncertainty analyses, comparisons to empirical data and to the results of other models, full peer-reviewed descriptions of model design and functioning, and full, free access to the model itself including interactive online systems for exploring model outputs (https://landchange.earth/CRAFTY) (e.g. Alexander et al., 2017; Brown et al., 2014, 2018; Holzhauer et al., 2019; Murray-Rust et al., 2014; Synes et al., 2019). The technical implementation of this framework through the CRAFTY-GB model and its application to the UK RCP-SSPs was evaluated through sensitivity analyses as the model was developed, consultations with experts and stakeholders (as described in Merkle et al. (2022)), and finally comparison to existing relevant literature on UK land use projections. We did not check CRAFTY-GB's ability to reproduce historical land use change within the UK as such change has no definite relevance to future changes, and because there is no temporally consistent UK land cover data against which to check modelled change (the UK Land Cover Map data do not allow for comparison of all CRAFTY-GB classes across years, and other inputs are unavailable for matching timepoints).

We carried out further evaluation of the representativeness of CRAFTY-GB agent types. The baseline allocation of agent types was compared against (semi-)independent datasets to check its coverage and interpretation with respect to agricultural and ecological characteristics. These datasets were 1) LCM 2015 (Rowland et al., 2017), to provide a summary of the translation of LCM classes into CRAFTY-GB classes (Table S4), 2) The standardised European EUNIS habitat classification scheme at 100m resolution (European Environment Agency, 2019; Weiss & Banko, 2018), 3) The UK CEH Land Cover Plus: Fertilisers and Pesticides data (Jarvis et al., 2020; Osório et al., 2019). Comparison to these data provides an evaluation of the agent typology and its initial geographic distribution because it reveals the extent to which the ranges of different ecological and agricultural characteristics found in British land systems are captured by the typology as a whole, and the extent to which individual agent types can be interpreted as representing specific characteristics from those ranges. It is not a targeted validation because the agent typology is not designed specifically to achieve these objectives, but it provides a basis from which to better interpret model results. On the basis of these and previous evaluations, we believe the model is appropriate for the purpose for which it is used here.

2.5 Representing levels of management intensity in the model outputs

To improve the interpretability of the results, we developed a land use intensity mapping approach. This involved the assignment of values on a continuous range for each of the arable, and each of the pastoral (except very extensive pastoral) classes across the scenarios. Intensity values were defined as a combination of the use of agricultural inputs (fertilisers, pesticides and machinery), technology, and modelled production levels. For the purposes of illustration these are combined multiplicatively here and used to select colour saturation levels in the map figures. Alternative representations are possible, and it is important to note that our presentation does not distinguish the specific use of technology to reduce the use of chemical inputs, as in UK-SSP1. This method does however make scenarios results more comparable and means that differences in land management intensities among the scenarios are readily apparent.

3 Results

3.1 Agent typology evaluation

Results of the comparison between baseline CRAFTY agent types and independent habitat and management maps suggested that the typology has good coverage, with clear but variable associations between agent types and each of the characteristics included (SI section 'Agent typology evaluation', Figs S4-S9). At a basic level, the baseline mapping reproduced the LCM classes that were the primary data used to locate agents geographically (Fig. S2, Table S4). Forest types were the most inconsistent between the CRAFTY-GB baseline and the LCM data, and comparisons at the sub-grid scale reveal that forest types are generally more associated with heterogeneous landscapes compared to intensive arable and pastoral agents (Figs S4 & S5). The ranges of LCM class coverage within each agent type also reflects the mixed nature of land cover in many of the CRAFTY-GB cells. This mixture is reflected in the capitals and service levels more fully than in the generic agent type labels, but is also further revealed by the EUNIS habitat comparison.

The EUNIS classes were widely distributed between agent types, but with clear associations (Figs S6 – S8). These were generally as expected, for example with grassland habitats strongly associated with pastoral areas, farmland habitats with agricultural areas and so on. Woodland habitats were particularly strongly associated with forested areas in the baseline map, providing some confirmation of their locations and interpretation. Nevertheless, many different specific habitats occurred even within the most intensive agent types at baseline, and these can be expected to persist or even increase in proportion in most scenarios, with the exception of SSPs 4 and 5 where the scenario storylines include consolidation of farms and fields across larger areas, implying loss of secondary habitats.

The quality of all of these habitats is also dependent on usage of chemical inputs and machinery. As expected, chemical inputs were most strongly associated with intensive arable areas (within which sustainable arable agents were randomly distributed at baseline, allowing no distinction in levels of chemical application) (Fig. S9). Once again, the association of productive broadleaf woodlands with agricultural areas was apparent in the elevated levels of chemical inputs within those cells. Farmland and broadleaf woodland habitats can therefore be expected to be most affected by the increased application of agricultural chemicals in SSPs 4 and 5.

3.2 Scenario results

The application of CRAFTY-GB to the UK RCP-SSP scenarios introduced very different driving conditions to the model, which resulted in significant divergence between simulated land use over time (Table 1). Most notably, divergence occurred in terms of intensity of land use. This was partly because intensity was determined by the scenario conditions, and partly because intensity changed as an emergent property of the simulations. For example, the gradual restriction of agricultural pesticides in UK-SSP1 led to a direct reduction in management intensity (when defined partly in terms of chemical inputs), but also an indirect reduction as agents that did not require chemical inputs, and were therefore unaffected by the restriction, became more competitive. Such direct and indirect changes in intensity were substantial in all of the scenarios. Overall, these socio-economic effects were far stronger than climatic effects on land use outcomes.

In UK RCP2.6-SSP1 (low emissions coupled with the Sustainability scenario) the emphasis on sustainable agricultural and forestry production and the delivery of multiple ecosystem services led to an overall lower intensity of land management compared to most other scenarios, despite intensification options being available. Reduced meat demand caused a substantial move away from pastoral management in many areas (Fig. 3). However, as the remaining livestock production focused on grass-fed livestock products (as opposed to domestic or imported feedstocks) and other agricultural land uses became more extensive, the area reduction of agricultural management was limited. Intensity gains were simulated in small areas (Fig. 4), but overall sustainable and extensive management became more widespread. By 2080, sustainable arable management dominated eastern England, while the British uplands were largely given over to extensive pastoral management (Fig. 3). Nevertheless, substantial areas were also covered by natural vegetation (whether unmanaged or managed for conservation) and, in forestry, native conifer and broadleaf species (Fig. S10). This resulted in some large, contiguous areas under either natural vegetation or native tree cover, especially in south-west England, Wales and southern Scotland. Despite the relative increase of extensive, mixed and sustainable land uses, under-supplies of biodiversity, employment, recreation and carbon increased during the simulation, with a slight but persistent over-supply of grass-fed red meat. The UK land system was unable to meet the very high demands for the wide range of ecosystem services in UK-SSP1.

UK-SSP2 (the Middle of the Road socio-economic scenario) was run under two climatic scenarios, RCP4.5 and RCP8.5. Overall, the different climatic conditions had limited effects, being most apparent in slightly larger areas of forest under RCP8.5, within which species were more separated between conifer-dominated forests in the south and broadleaf-dominated in the north, following climatic suitability (Fig. S10). In both cases, forests were more widespread than in UK-SSP1 due to increased demands for afforestation to sequester carbon and produce timber. Non-native species dominated these forests, especially in Scotland and in RCP8.5. As a result, the area of natural vegetation was relatively low outside (substantial) areas under conservation management. These were possible because of intensification of arable agriculture in particular, and a decrease in the demand for grass-fed livestock products that allowed food demands to be met consistently (Fig. 4). This also led to a very large reduction (ca. 60%) in the area of intensive pastoral management (much of which was converted to forestry; Fig. 5), which also became dispersed among other land uses in less productive areas. This was reinforced by a large drop in meat and milk demand over the first decade of the simulation, and concurrent increase in timber demand. The scenario generated very little over-supply, but biodiversity and carbon were slightly under-supplied (at around 90% of demand) by the end of the simulation. Intensive arable agriculture remained concentrated in the south-east, with extensive pastoral in the north-west (Fig. 3).

UK RCP6.0-SSP3 (relatively high emissions coupled with the Regional Rivalry scenario) is a highly dystopian scenario with increasing barriers to trade and widespread social tensions and conflict. Overall, simulated land use was highly extensive (more extensive than in any other scenario or even in the baseline) because capitals and inputs supporting agriculture were lacking in the storyline. This occurred both within land uses (e.g. decreasing intensity of management within 'intensive arable' cells) and between them (e.g. a widespread initial transition from intensive pastoral to extensive arable management) (Figs. 3-5). Nevertheless, this extensive agricultural management occupied large, contiguous areas as growing food for survival becomes the primary demand (Fig. 3). Many forest areas were converted to arable agriculture, with remaining forests dominated by conifers (Fig. S10). As the scope for intensive management decreased during the century, supply levels fell below demands and utilisation of depleted intensification options increased. Nevertheless, food crops were only able to satisfy around 60% of demand at some points, with employment levels even lower (Fig. 4). In areas where intensification options were most limited due to low levels of multiple capitals (much of Scotland and Wales, where independence from England also meant that demands had to be satisfied domestically), multifunctional alternatives such as agroforestry and sustainable arable production emerged as competitive ways of maintaining some food production.

UK RCP4.5-SSP4 (medium emissions coupled with the Inequality scenario) is dominated by a business and political elite who take over much of the British land system and invest in large-scale industrial agriculture. This produced a substantially more intensive land system than SSPs 1-3, which was especially pronounced in increasing arable extent and intensity (Fig 5). A decrease in the relative demand for grass-fed livestock products led to a reduction in intensive pastoral production from around 2050, but meat and milk were still highly over-supplied at some points in time as demand levels fluctuated (with milk supply at more than 150% of demand early and in the middle of the century) (Fig. 4). Conversely, intensive arable production increased as pastoral decreased, as did bioenergy, which was ultimately grown across the country in marginal agricultural areas (Fig. 3). This left little room for forest management, but large areas of abandonment and conservation management did emerge in some upland areas, partly due to demand for recreation by the rich elite in the scenario. Within forests, non-native conifers dominated, being used to satisfy timber demand. Large land holdings had a competitive advantage, and land use became particularly homogeneous in productive areas, implying further degradation of habitats.

UK RCP8.5-SSP5 (high emissions coupled with the Fossil Fuel Development scenario) was the most intensive land use scenario, with massive urban expansion and agricultural intensification as demand levels increased due to a substantial rise in the UK population and a shift to highly individualistic and consumptive lifestyles. Protected areas were removed as concern for the environment was low. Declining social capital made marginal production vulnerable to change, while strong local networks allowed consolidation of dominant land uses. Nevertheless, there was a substantial amount of sustainable arable agriculture and conservation, because these provided multiple low-priority ecosystem services in single cells. Limited forest area was concentrated in southern and north-west England, the Welsh borders, and north-west Scotland, with native broadleaf and conifer species dominating outside Scotland (Fig. S10). The pastoral land area was almost maintained in this scenario due to very high demands for livestock products (Fig. 5). Despite some urban expansion into productive land and extensification of unproductive land, overall land use intensity increased dramatically (Fig. 4). Food supply increased too, but not enough to satisfy demands for grass-fed red meat. There was a general shortfall in supply of intangible services, supporting the existence of sustainable and conservation management to supply several of these within the intensive landscapes. Land abandonment in the uplands was an emergent response to intensification elsewhere, but this was consistent with the scenario storyline of upland rewilding to deliver recreation benefits.

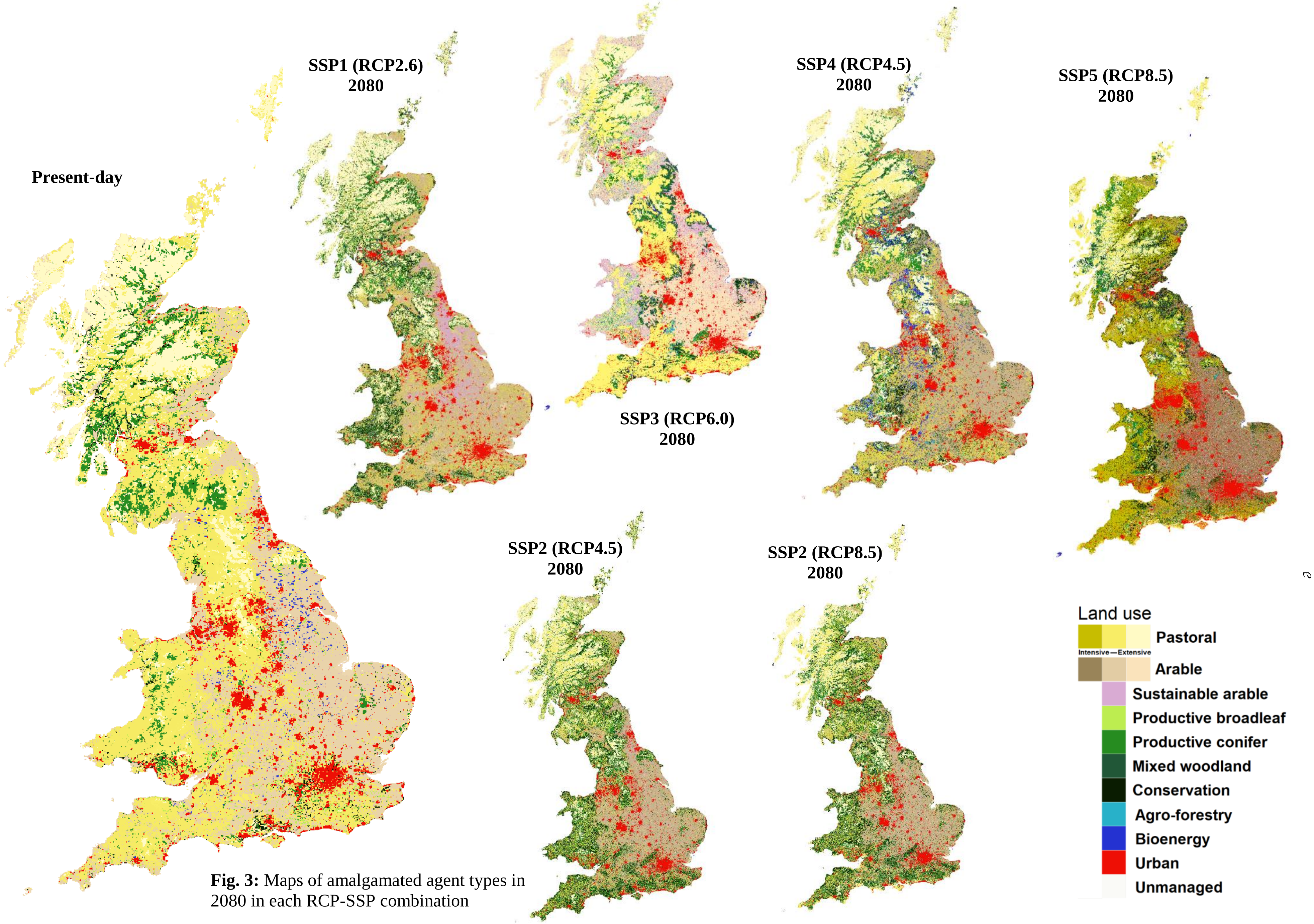

Fig. 3: Maps of amalgamated agent types in 2080 in each RCP-SSP combination

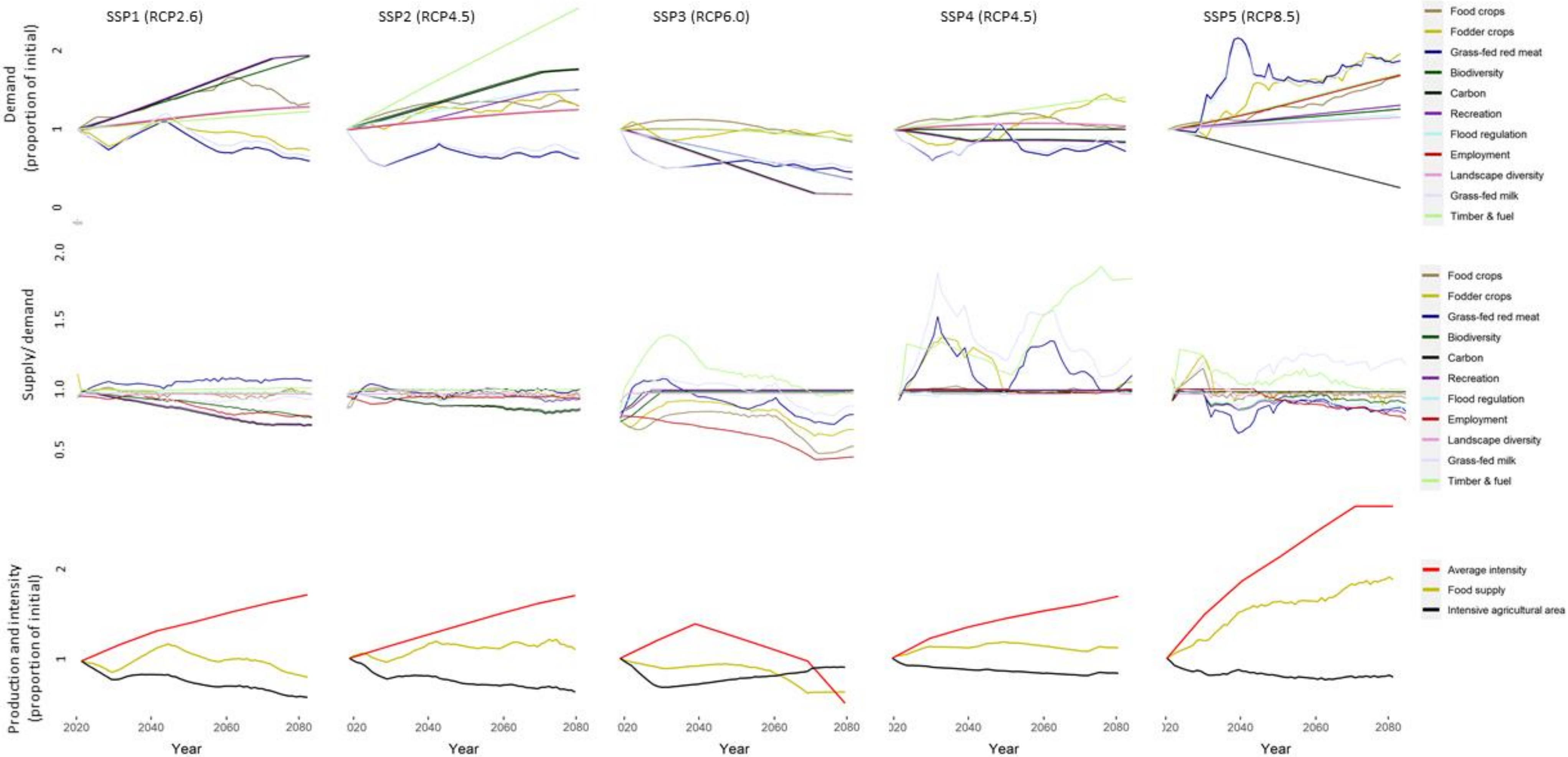

Fig. 4: Demand levels, supply as proportion of demand, and land use intensity, food supply and intensive area throughout each SSP scenario (RCP8.5-SSP2 results were very similar to those shown for RCP4.5-SSP2, and can be found in Fig. S11).

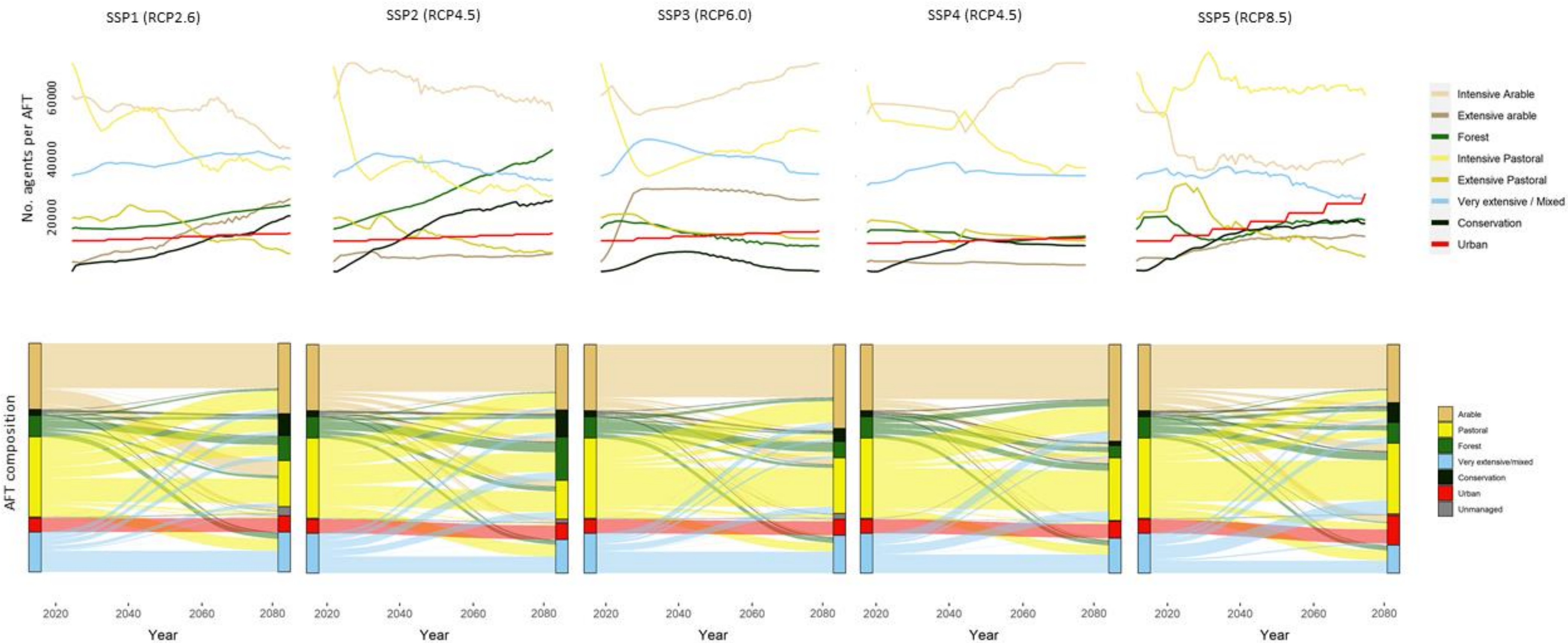

Fig. 5: Agent Functional Type (AFT) dynamics throughout each SSP scenario: numbers of agents within amalgamated AFTs (top) and transitions between broad land use types (bottom). RCP8.5-SSP2 results were very similar to those shown for RCP4.5-SSP2, and can be found in Fig. S11.

Scenario	Description	Distinguishing features in CRAFTY-GB	Main outcomes
SSP1 - Sustainability	UK-SSP1 shows the UK transitioning to a fully functional circular economy as society quickly becomes more egalitarian leading to healthier lifestyles, improved well-being, sustainable use of natural resources, and more stable and fair international relations. It represents a sustainable and co-operative society with a low carbon economy and high capacity to adapt to climate change.	Novel forms of sustainable agriculture with strong societal support	Decreasing area of intensive agriculture, greater multifunctionality of agricultural land
		Low demand levels for livestock products, but preference for grass-fed production	Move away from livestock production and decrease in pastoral area, limited by relatively low-efficiency of pastoral production
		Preference for native tree species in forestry	Substantial shift towards native species in forests, depending on suitabilities
SSP2 – Middle of the Road	UK-SSP2 is a world in which strong public-private partnerships enable moderate economic growth but inequalities persist. It represents a highly regulated society that continues to rely on fossil fuels, but with gradual increases in renewable energy resulting in intermediate adaptation and mitigation challenges.	Established forms of agriculture with potential for intensification	Intensification and increasing efficiency of agriculture, leading to intensive area declines
		Increasing demand for timber and forest-based carbon sequestration	Large increase in forest area, dominated by non-native tree species
		Low demand for grass-fed livestock products	Large decrease in intensive pasture area, most livestock production feed-based
SSP3 – Regional rivalry	The dystopian scenario, UK-SSP3, shows how increasing social and economic barriers may trigger international tensions, nationalisation in key economic sectors, job losses and, eventually a highly fragmented society with the UK breaking apart. It represents a society where rivalry between regions and barriers to trade entrench reliance on fossil fuels and limit capacity to adapt to climate change.	Large decreases in most capitals	Extensification of production as inputs become unavailable, shortfalls in supply and increasing area with maximum possible intensity
		Trade barriers reduce food imports. Decreasing demand for most other services	Food production dominates land uses, with other ecosystem services being by-products of enforced low-intensity management
		Very weak social networks	Heterogeneous and frequent changes in land use, suboptimal exploitation of available capitals
		Political breakup of the UK	Divergence in land system trajectories between England, Wales and Scotland, with least intensive production methods being only feasible options in smaller nations
SSP4 - Inequality	UK-SSP4 shows how a society dominated by business and political elites may lead to increasing inequalities by curtailing welfare policies and excluding the majority of a disengaged population. The business and political elite facilitate low carbon economies but large differences in income across segments of UK society limits the adaptive capacity of the masses.	Economies of scale in agriculture	Large, homogeneous areas of agriculture emerge, representing large farms with large fields
		High demand for recreation among economic elites	Conservation/recreation management in upland areas, loss of marginal land uses
		Low demand for grass-fed livestock products	Decline in pasture, livestock production using crop-based feed
		High demand for bioenergy	Expansion of bioenergy on arable land in many areas; overall increase in arable area & intensity, at expense of forest areas
SSP5 – Fossil-fuelled development	UK-SSP5 shows the UK transitioning to a highly individualistic society where the majority become wealthier through the exploitation of natural resources combined with high economic growth. It represents a technologically advanced world with a strong economy that is heavily dependent on fossil fuels, but with a high capacity to adapt to the impacts of climate change.	Increasing demands for urban areas and food production	High pressure on land area and strong competition between land uses
		Increasing intensification options	Very high levels of intensification in agriculture supporting large increases in production
		Removal of Protected Areas and low demands for related ecosystem services	Expansion of productive land uses into natural areas, with consequent abandonment in upland and marginal areas not under protection.

Table 1: Descriptions of each UK-SSP, the main drivers that distinguish each within CRAFTY-GB, and the results of those drivers observed in the model outputs.

4 Discussion

This study targets the gap between detailed stakeholder-developed SSP storylines and their representations in computational models. We attempt to extend scenario modelling using flexible model structures and parameterisations that are not limited to the single pathway established by historical land use change (Fig. 2, Table 1). This is not a predictive exercise, but an exploration of possible consequences of alternate futures as envisioned in detail by a group of policy-makers and other stakeholders (Harmáčková et al., 2022; Merkle et al., 2022; Pedde et al., 2021). While some aspects of the scenarios remain unrepresented in the model, the substantial scenario-specific modifications we made confirmed some elements of the scenario storylines (e.g. upland land abandonment in UK-SSP5), challenged others (e.g. the provision of high-levels of many ecosystem services in UK-SSP1), and revealed further emergent differences not previously anticipated (e.g. extensification of agriculture as a response to altered competition dynamics in UK-SSPs 1 and 5).

The level of land use intensity was the most notable variation between scenario outcomes, in terms of levels of agricultural inputs and levels of ecosystem service outputs. In UK-SSP1 we found deliberate extensification (land sharing) leading to some environmental benefits of the kind envisioned in the scenario storyline, but still with less success in meeting ecosystem service demands than some other more intensive (land sparing) scenarios. In the land sparing scenarios (UK-SSPs 4 and 5), environmental benefits were indirect and, from the point of view of the agents represented in the model, a by-product of their primary activity. In UK-SSP3 such benefits occurred because strong intensification was not possible given the lack of agricultural inputs (manufactured, chemical, financial and social), but in UK-SSP5 they occurred because intensification freed up land that could be managed multifunctionally, or abandoned to rewilding. At the same time, substantial increases in farm sizes and agricultural chemical application implies that environmental quality on farmland declined substantially in UK-SSPs 4 and 5.

These changes occurred within a consistent global framework that provided at least some coherence between the internal and external drivers of British land system change. For instance, the scenarios took account of global population projections and resultant trade shifts, meaning that development in Great Britain remains within appropriate global boundary conditions. When implemented in this way, the UK-SSPs had far more substantial effects on land system outcomes than the climatic UK-RCP scenarios (see also e.g. Brown et al., 2019; Kriegler et al., 2017; Molotoks et al., 2021; Wiebe et al., 2015). Nevertheless, the absence of extreme events from RCP8.5 in particular (because the spatial and temporal resolution of the climate modelling limits representation of such events) does imply that very large climatic impacts may be missing (Kopp et al., 2016; Otto et al., 2020). Furthermore, there was no simulated impact of land degradation on agricultural productivity, potentially arising from climatic extremes, or the high intensity of use envisaged within the UK-SSP5 storyline. National changes can also be seen in their global context, for instance in terms of extremely high import levels in UK-SSP5, and for some commodities in UK-SSPs 1 and 2, suggesting indirect land use change abroad as an externality of either land sparing or land sharing domestically (Fuchs et al., 2020).

Some of these findings are broadly consistent with the comparable study of (Bateman et al., 2013), who found that including ecosystem services in modelling based on economic valuations led to very different balances among service provision. We find a similar importance of the valuation of ecosystem services, and a similar importance of considering spatial and temporal variations in ecosystem service provision levels. In developing a full UK RCP-SSP scenario implementation we also find, however, that policy options and the associated room for manoeuvre are limited by other factors, including the level of international trade, societal tolerance for intensive methods of production, the rate at which land managers become aware of, and adopt, new technologies or practices, and the levels of supporting capitals available to land managers. Two of these, human and social capital, vary enormously across the scenarios, but are usually absent from scenario modelling. Pedde et al. (2019) showed that they are nevertheless essential for major policy targets such as the Paris climate agreement, quite possibly more so than the far-more-studied technological and economic factors. We also concur with earlier studies that concluded that social factors can be more important than climate policy in achieving societal objectives (Liu et al., 2020), because they determine the realised impacts of those policies.

Other findings relate to further necessary development. This model, and land use models in general, will have greater utility as they become more closely aligned with biodiversity outcomes, in particular by more fully assessing the role of land management in driving either declines or recovery in terrestrial biodiversity (Leclère et al., 2020; Rounsevell et al., 2018; Urban et al., 2021). More realistic assessment of land-based climate change mitigation is also a priority (Estoque et al., 2020). Both of these will also require improved modelling of forest (and forestry) dynamics, and especially the links between tree species growth, management practices and decisions, and competition within the broader land system (Blanco et al., 2017; Brown et al., 2017; Shifley et al., 2017; Vulturius et al., 2017). Together with the development of urban areas, forest management is very sensitive to socio-economic conditions in the SSPs, and in turn has strong implications for the extent of climate change mitigation (Bukovsky et al., 2021).

While we propose that these extensions of scenario modelling improve the realism and utility of model outputs, we also acknowledge that they increase uncertainty (revealed uncertainty at least, as the same uncertainty can be said to be hidden in models that do not account for these factors). It has been argued (e.g. by Rosen, 2021) that the SSPs have not been useful for climate mitigation policy analysis because they are implemented differently in different models, leading to a lack of agreement about what different SSPs actually imply. Rosen (2021) suggests a reduction in the number and variance of models used, to develop canonical representations of the SSPs. We disagree with that argument. Instead, we suggest that models should be further developed to capture the key elements of SSP scenarios that have been previously neglected – social change, non-economic values of ecosystem services, variations in land use intensity and competition between forms of management. Even then, we suggest that more diversity in models and modelling approaches is needed to properly explore the rich and complex storylines of stakeholder-developed scenarios. The application of multi-model ensembles to explore future scenario space is an especially promising option. Rather than being a recipe for confusion, we view this as a way to gradually build up an improved understanding of potential futures and, crucially, to support the development of genuinely robust policy pathways towards societal objectives.

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Open Research

All output data and model code are freely available through https://landchange.earth/CRAFTY and https://doi.org/10.17605/OSF.IO/CY8WE.

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AGU PUBLICATIONS

Earth's Future

Supporting Information for

Agent-based modelling of alternative futures in the British land use system

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Additional Supporting Information (Files uploaded separately)

TRACE (”TRAnsparent and Comprehensive model Evaludation”) document uploaded separately to preserve its independent formatting.

Introduction

This Supporting Information document provides more details on the methods and results of the CRAFTY-GB implementation. The text builds on and extends the main paper.

Methods

Model components

CAPITALS

Capitals are divided into human, social, manufactured, financial and natural capitals, with natural capital further divided into yields or suitabilities for arable, pastoral and forest land uses or species (Tables S1 & S2). Social, human, financial and manufactured capitals were derived from UK-SSP projections of eight socio-economic indicators from Merkle et al. (2022) (Table S1). Natural capitals were created in two distinct steps. Forest suitabilities were modelled using the Ecological Site Classification (ESC) model originally developed by (Pyatt, 1995) and since used frequently in forestry modelling for the UK (Forest Research, 2021). This model uses data on accumulated temperature, continentality, wind risk, moisture deficit, soil moisture regime, and soil nutrient regime to predict biophysical suitability and associated potential yield class (timber growth) for a range of tree species. In the scenarios, these data were derived from UK-specific RCPs (Robinson et al. 2022).

To project land suitability for arable and pastoral land a General Additive Model (GAM; (Hastie & Tibshirani, 1990) was produced to link land cover classes from Land Cover Map 2015 (Rowland et al., 2017) to UK-RCP covariates. Land Cover target class 3 (arable) and 4 (improved Grassland) were used as the training maps for arable and improved grassland, respectively, whilst semi-natural grassland was trained on LCM target classes 5-7, 9 and 10 (neutral, calcareous and acid grassland; heather; and heather grassland). UK-RCP derived bioclimatic variables for growing degree days (GDD), minimum and maximum temperature, and soil moisture deficit (SMD) and surplus (SMS) were used as covariates, following Pearson et al., ((Pearson et al., 2004). Urban areas were masked out in advance of model training. The baseline map of arable suitability was further processed to take into consideration changes in agricultural yields through time as modelled by the IMPRESSIONS European integrated assessment model (Harrison et al., 2019) and these augmented arable layers were used as a capital layer within the CRAFTY-UK modelling. The two grassland suitability maps were used directly as capital layers within the CRAFTY-UK modelling.

Capital	Indicator Variables	Linear Rescaling Thresholds				
		Very Low [0 ; 0.2]	**Low [0.2 ; 0.4]**	**Medium [0.4 ; 0.6]**	**High [0.6 ; 0.8]**	**Very High [0.8 ; 1]**
Social	Income quintile ratio (S80/S20)	60 ; 25	25 ; 10	10 ; 5	5 ; 2	2 ; 1
	Proportion of people who agree to “people around here are willing to help their neighbours”	0 ; 30	30 ; 50	50 ; 70	70 ; 90	90 ; 100
Human	Life expectancy at birth	30 ; 50	50 ; 60	60 ; 70	70 ; 80	80 ; 110
	Proportion of people aged 25 – 64 with tertiary education	0 ; 10	10 ; 20	20 ; 30	30 ; 45	45 ; 80
Financial	Household Income per capita [EUR PPS]	0 ; 5	5 ; 10	10 ; 25	25 ; 50	50 ; 80
	Proportion of people who agree to “I can save any amount of my income”	0 ; 20	20 ; 30	30 ; 40	40 ; 50	50 ; 100
Manufactured	Gross Fixed Capital Formation per Area [mEUR/km^2]	0 ; 0.75	0.75 ; 1.25	1.25 ; 3	3 ; 10	10 ; 500
	Average of total speed-weighted road length [Speed-weighted km/km^2]	0 ; 0.1	0.1 ; 0.2	0.2 ; 0.3	0.3 ; 1	1 ; 4

Table S1: Description of socio-economic capitals. For each of the capitals, individual values per area and time slice were formed as means between two indicator variables interpolated between decadal values, and subsequently normalised to [0,1]. Full details of the indicator variables underlying the socio-economic capitals are given in Merkle et al. (2022). Natural capital, split into 11 suitabilities, is described in Table S2.

Suitability	Explanation	Source/reference
Arable suitability	GAM-projected arable suitability index (0 to 1) based on relationship between bioclimatic covariates and LCM target class 3, modified by changes in arable yields from IMPRESSIONS integrated model.	GAMs (Hastie and Tibshirani, 1990) LCM 2015 (Rowland et al., 2017) IMPRESSIONS IAP (Harrison et al., 2019) Biophysical covariates Pearson et al., (2002). See capitals section for full description.
Improved grassland suitability	GAM-projected semi-natural grassland suitability (0-1 index) based on relationship between bioclimatic covariates and LCM target class 4.	
Semi-natural grassland suitability	GAM-projected semi-natural grassland suitability (0-1 index) based on relationship between bioclimatic covariates and LCM target classes 5-7,9 and 10.	
Natural: Short Rotation Coppice (SRC) suitability	ESC modelling: Willow yield	ESC (Forest Research, 2021)
Natural: Agro-forestry tree suitability	ESC modelling: Sycamore yield	
Natural: Non-native conifer suitability	ESC modelling: Sitka spruce yield	
Natural: Non-native broadleaf suitability	ESC modelling: Beech yield	
Natural: Native conifer suitability	ESC modelling: Scots pine yield	
Natural: Native broadleaf suitability	ESC modelling: Sessile Oak yield	
Natural: Native broadleaf suitability	ESC modelling: Silver Birch yield	
Natural: General tree species suitability	ESC modelling: Combination of all other yields	

Table S2: Description of Suitabilities comprising natural capital. All are normalised to a [0,1] scale at baseline and are linked to empirical production values through supply normalisation (described below). Abbreviations are as follows: GAM - General additive model; LCM – Land Cover Map: IAP – Integrated Assessment Platform; ESC – Ecological Site Classification.

PROTECTED AREAS

Protected areas belonging to 11 different types of national and international designation and to 5 different private land-owning organisations (NGOs) were included in the model (Table S3, Fig. S1). Each protected area was first categorised into IUCN Protected Area Management Categories according to the existing categorisation of the (IUCN National Committee United Kingdom, 2012) or, where no existing categorisation was found, according to landowners' stated objectives. Two broad levels of protected area emerged from this classification: IUCN category IV and V areas where many forms of land use are found (all of the officially designated protected areas in the UK), and IUCN category II areas where land use is more tightly controlled (most of the NGO-owned protected areas). We therefore adopted two forms of constraint within the protected areas, with all land use except the most intensive being permitted in the first group, and no land use change except to the most extensive or conservation management permitted in the second. We also prevented land use change on areas classified as water, bare rock, coastal sediment and marsh in the baseline land use map. Institutions were used to enforce land use protections, and were represented as having complete power and knowledge with which to do so.

Type of protected area	IUCN category	Data source	Effect in CRAFTY-GB
International			
Biosphere Reserves	IV	(UNESCO, 2017)	Not intensive
Ramsar site	IV	(JNCC, 2020)	
Special Area of Conservation (SAC)	IV		
Special Protection Area (SPA)	IV		
National			
Area of Outstanding Natural Beauty (AONB)	V	(Natural England, 2020a; Natural Resources Wales, 2021a)	Not intensive
Site of Special Scientific Interest (SSSI)	IV	(Natural England, 2021c; Natural Resources Wales, 2020; SNH, 2020)	
Heritage Coast (HC)	V	(Natural England, 2017; Natural Resources Wales, 2017a)	
Local Nature Reserve (LNR)	IV	(Natural England, 2021a; Natural Resources Wales, 2018; Scottish Government, 2020a)	
National Nature Reserve (NNR)	IV	(Natural England, 2021b; Natural Resources Wales, 2021b; Scottish Government, 2020b)	
National Park (NP)	V	(Natural England, 2020c; Natural Resources Wales, 2017b; Scottish Government, 2021a, 2021b)	
National Scenic Area (NSA)	V	(Scottish Government, 2021c)	
NGOs			
John Muir Trust (JMT)	II	JMT, personal communication	No Change
National Trust / National Trust for Scotland (NT/NTS)	V	(National Trust, 2021; National Trust for Scotland, 2015)	
RSPB	II	(RSPB, 2021)	
Scottish Wildlife Trust	II	(Scottish Wildlife Trust, 2016)	
Other NGO	II	Trees for Life, personal communication	

Table S3: Types of protected area included in the model, their equivalent IUCN ranking (taken from (IUCN National Committee United Kingdom, 2012) or determined based on management objectives), data sources and the modelled constraint each type of protected area places on land use change.

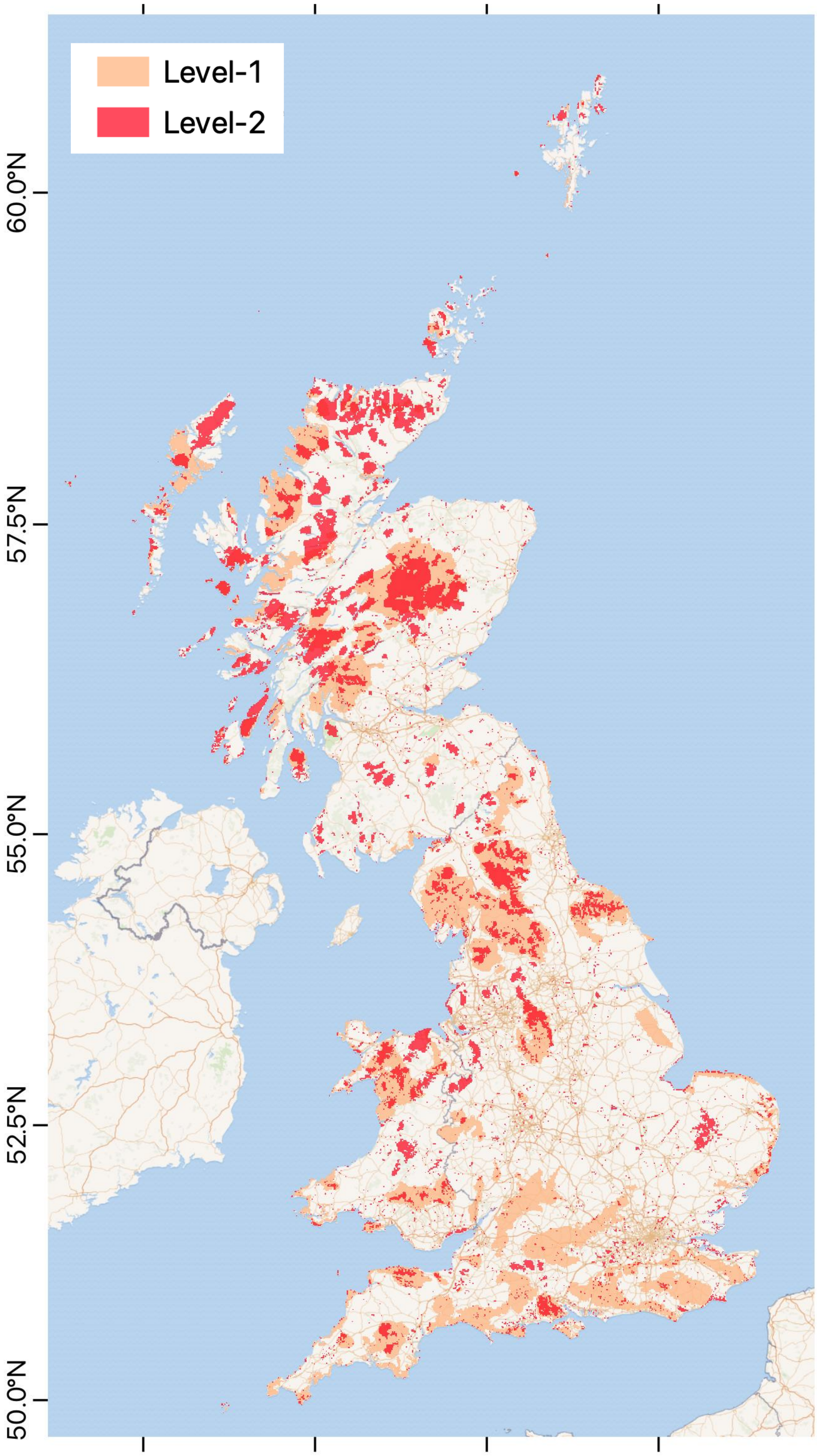


Fig. S1: Protected areas applied in CRAFTY-GB. The map is projected using OSGB1936 / British National Grid coordinate reference system (EPSG: 27700). The background map is provided by Wikimedia (https://maps.wikimedia.org/)

LAND USES (AGENT TYPES)

CRAFTY-GB includes a range of agent types designed to capture the main forms of land use in Great Britain, including gradations of intensity and multi-functionality. Agent types were divided between arable land uses (intensive arable for food, intensive arable for fodder, sustainable arable and extensive arable), pastoral land uses (intensive pastoral, extensive pastoral, very extensive pastoral), forest land uses (productive native conifer, productive non-native conifer, productive native broadleaf, productive non-native broadleaf, multifunctional mixed woodland and native woodland for conservation), and combined classes (bioenergy and agroforestry) (Table S4). Variation in ecosystem service provision within these classes allows them to represent a continuous range of forms of land management rather than arbitrarily distinct groups.

Allocation of the initial distribution of land uses was based on the 2015 Land Cover Map (LCM2015) produced by the (UK Centre for Ecology & Hydrology, 2016) (Rowland et al., 2017) and the National Forest Inventory (NFI) 2010-2015 (Forestry Commission, 2021). Further datasets were used to define the extent and location of specific land uses, and full details are given in Table S4. Urban areas were derived from land cover data at the baseline (LCM 2015) and then projected in the scenarios by an independent urban model (described in detail in Merkle et al., in review). This model created 1km gridded urban surface projections through a newly developed urban allocation algorithm based on a neighbourhood density function, SSP-specific sprawl parameter settings, and SSP-specific land exclusions of protected areas and flood risk areas. Land not otherwise used was modelled as unmanaged.
In some cases, input data were incomplete and had to be further processed before being used. This was true of some coastal areas and islands (particularly estuaries and the Shetland isles). Data gaps in Shetland were filled using a simple regression model using topographic variables (i.e. elevation, slope, and aspect) trained upon the data of the nearest Orkney island. Gaps in coastal areas were filled using nearest-neighbour values. We also used 5x5 moving average interpolation to smooth hard boundaries between administrative units in the capitals. Finally, where scenario input data for 2020 were not consistent with baseline data, those data series were normalised by the equivalent baseline values.

Land use (agent)	Notes	Initial allocation
Intensive arable (food)	Farmers managing intensively for crop production for food.	Allocated to LCM2015 aggregate class 'Arable'. Food and fodder types distributed randomly within that according to (modelled) baseline demand levels to provide the required amount of each
Intensive arable (fodder)	Farmers managing intensively for crop production for livestock fodder, ultimately producing meat and milk.	
Sustainable arable	Farmers managing organically or otherwise less intensively for crop production for food	Allocated to LCM2015 aggregate class 'Arable' to give an area coverage equal to the 2015 area of organic arable in the UK (as reported by (DEFRA, 2016a), with specific cells chosen spatially randomly
Extensive arable	Farmers managing with few inputs for limited crop production for food; equivalent to subsistence production where capitals are very low	Allocated to the LCM2015 aggregate class 'Arable' cells within the lowest 10% of modelled suitability for arable crops
Intensive pastoral	Farmers managing intensively for livestock	LCM2015 Improved grassland
Extensive pastoral	Farmers managing extensively for livestock on semi-natural grassland	LCM2015 Semi-natural grassland
Very extensive pastoral	Minimal management involving some grazing	LCM2015 Mountain, heath, bog and LCM2015 Semi-natural grassland (Fen Marsh Swamp)
Bioenergy	Dedicated production of Short Rotation Coppice / Miscanthus	Assigned to LCM2015 aggregate class 'Arable' to cover the 2015 extent of arable bioenergy land (DEFRA, 2016b), assigned to locations of Energy Crops Scheme (Tranche 2) agreements 2013-2015 (Natural England, 2020b)
Agroforestry	Farmers practicing silvo-pastoral or silvo-arable forms of agroforestry, combining trees with either grazing or crops, for timber, crop and livestock production.	NFI 'low-density' class when otherwise unassigned.
Productive non-native conifer	Production-focused forest managers with non-native conifer plantations. Primary objective is softwood timber production.	LCM2015 Coniferous woodland class, sub-divided by NFI Conifer class, located where modelled suitability is higher for non-native than for native species
Productive non-native broadleaf	Production focused forest managers with non-native broadleaf plantations. (Not currently common, but felt to have potential importance in the future). Primary objective is hardwood timber production.	LCM2015 Broadleaf woodland, sub-divided by NFI broadleaf class, located where modelled suitability is higher for non-native than for native species
Productive native conifer	Production focused forest managers with native conifer plantations. Primary objective is softwood timber production.	LCM2015 Coniferous woodland, sub-divided by NFI Conifer class, located where modelled suitability is higher for native than for non-native species
Productive native broadleaf	Production focused forest managers with native broadleaf plantations. Primary objective is hardwood timber production.	LCM2015 Broadleaf woodland, sub-divided by NFI broadleaf class, located where modelled suitability is higher for native than for non-native species.
Multifunctional mixed woodland	Forest managers with mixed woodlands and multiple objectives practising low-intensity management	LCM2015 Broadleaf or Coniferous woodland, subdivided by NFI mixed classes
Native woodland (conservation)	Conservation focused forest managers. Primary objective is to conserve biodiversity.	LCM2015 Broadleaf or coniferous woodland, excluding NFI classes indicating active management or no forest cover, and located where modelled broadleaf suitability is within the lowest 50% or modelled conifer suitability is within the lowest 10%
Urban	Urban and industrial areas	Modelled separately
Unmanaged	Represents areas with minimal to no management, often where biophysical conditions preclude significant productivity e.g. high montane or deep peat areas	Unassigned cells

Table S4: Allocation of initial distribution of land uses. Levels of intensity are assigned discretely in terms of agent types, but modelled continuously across these types according to availability and usage of agricultural inputs and production levels. The resulting allocation is shown in Fig. S2

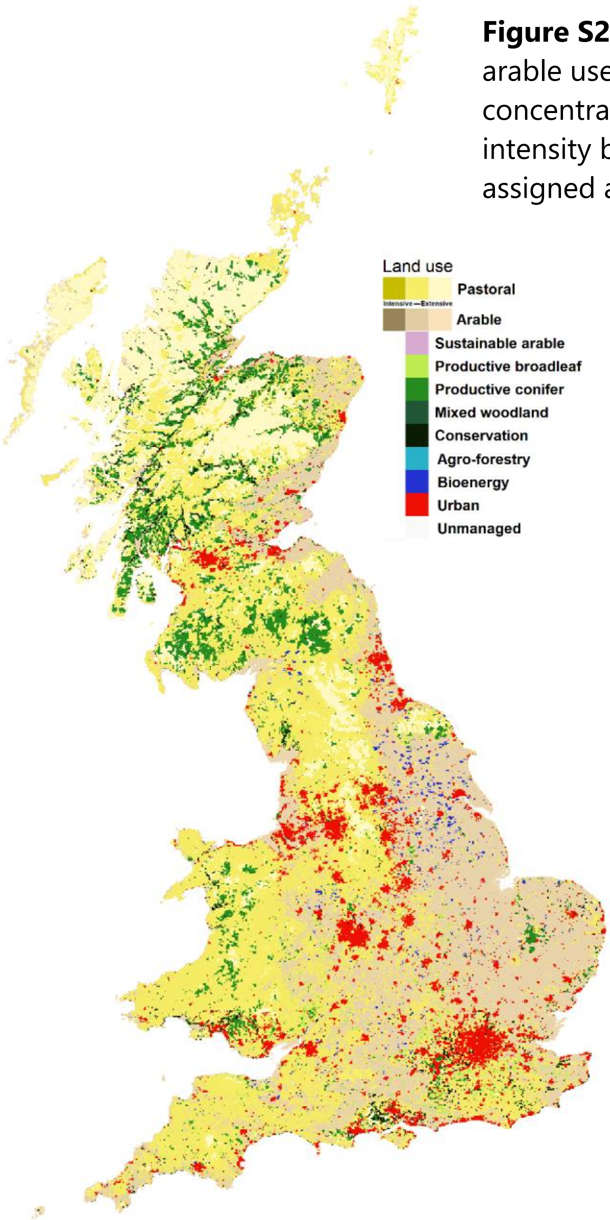


Figure S2: Simplified baseline allocation of land uses. Pastoral and arable uses are presented on coloured intensity gradients, and are concentrated towards the extensive end of the gradient because intensity becomes greater in some scenarios (intensity values are assigned as described in the text).

BEHAVIOURS

CRAFTY-GB is designed to represent many forms of behaviour relating to land management decision-making through a small number of generic parameters, described in Table S5.

Parameterised behaviour	Description	Interpretation
Capital sensitivities	Quantification of agent dependence on each capital for the production of a service. Variation at individual and typological levels.	Represents agent abilities to utilise capitals (e.g. through particular production methods), reliance on supporting capitals (e.g. social support systems) and access to personal resources (e.g. additional labour).
Productive abilities	The maximum potential service production an agent can achieve under perfect capital conditions. Variation at individual and typological levels.	Represents the ability and willingness of agents to provide ecosystem services, including potential decisions about trade-offs between services made on the basis of agent preferences.
Search ability	Comprising three parameters: the number of search iterations an agent type can undertake per timestep, the number of cells considered for competition during each search iteration, and the order (random or ranked) in which those cells are competed for. Variation at typological level.	Represents the ability and willingness of agents to seek new land to manage, and their knowledge about the potential productivity of that land.
Abandonment threshold	Minimum benefit level an agent will accept before abandoning land. Variation at individual and typological levels.	Represents agents' dedication to their land use in the absence of more beneficial alternatives. Can incorporate risk aversion, 'traditionalist' attitudes, cultural norms etc.
Competition threshold	Maximum relative competitive disadvantage in benefit values that an agent will tolerate before relinquishing land to another land use agent. Variation at individual and typological levels.	Represents agents' dedication to their land use under competition from more beneficial alternatives. Can incorporate similar factors as the abandonment threshold, as well as opportunity costs and more specific aversions to other land uses.
Social networks	An additional component of the model, representing social links between agents of each type located within a defined circular neighbourhood of one another. Settings control neighbourhood radius, other parameters that effects act upon, and magnitudes of those effects.	Represents social support or norms, knowledge diffusion, economies of scale or any other spatially-mediated interaction between agents

Table S5: Behavioural effects included in CRAFTY-GB

Of these behaviours, social networks are the only new addition to the CRAFTY framework, and function as follows. Agent types each have a defined neighbourhood within which influences can occur. Neighbourhoods have a default 20 km radius, based on evidence that a neighbourhood of this size best captures diffusion effects in the uptake of land management options and policies in the UK (Brown et al., 2018). Within each neighbourhood, the density of agents of the same type is calculated at each timestep, and this density is used to rescale other parameter values. Here, density affects the competitiveness of agents, with increasing competitiveness when density is high to represent the benefits both of improved local knowledge diffusion and of economies of scale. The magnitude of this effect and the size of the social neighbourhood are varied in the scenarios as described in the main text (and below).

SERVICES & DEMAND LEVELS

A range of provisioning, regulating and cultural ecosystem services and other indicators (e.g. biodiversity, employment) of relevance to the UK-SSP scenarios were modelled. These services are defined in Table S6, and their provision by different agent types based on capital levels is presented in Table S7. In this implementation, the relative calibration of service provision is approximate and largely assumption-based, though informed by empirical or modelled evidence where possible.

Services	**Details**
Food crops	Crops for human consumption
Fodder crops	Crops for consumption by ruminant and monogastric livestock
Grass-fed meat	Red meat produced in pastoral systems
Grass-fed milk	Milk produced in pastoral systems
Bioenergy fuel	Bioenergy crops; short rotation coppice & miscanthus
Softwood	Softwood (conifer) timber
Hardwood	Hardwood (broadleaf) timber
Biodiversity	Biological diversity
Landscape diversity	Diversity of landscape elements
Carbon sequestration	Quantity of carbon sequestered (above & below ground)
Recreation	Recreation potential
Flood Regulation	Land ability to store water
Employment	Potential for employment associated with land management
Sustainable production	Abstract service providing sustainability in agriculture

Table S6: Goods and services modelled in CRAFTY-GB. The ability of agents to produce these services given certain capital values is presented in Table S7.

In modelling production of crops and livestock products, we assume divisions between crop production for direct human consumption, crop production for livestock consumption, and grass-fed livestock production. We assume that pastoralist agents produce grass-fed milk (intensive pastoral only) and red meat, while 'arable for fodder' agents effectively produce crop-fed red and white meat, and milk. Monogastrics are gramivores, so are fed only from cropland. Evidence for production levels includes an existing application of the CRAFTY framework to Scotland (Burton et al., in prep), and literature evidence on ecosystem services provision in different land use types (Burton et al., 2018; Rolo et al., 2021).

Table S7: Capital sensitivities and service production levels of each modelled land use (agent type). Capital sensitivities determine how reliant each form of land use is on certain characteristics of the land system (as defined in the Capitals section), and service production levels determine the relative quantity of each service produced when capitals are not limiting. Scales here are approximate and relative within each capital, and are subject to small amounts of variation across scenarios; these are described further in the Scenarios section and complete absolute values are given in the relevant production files (see data availability section). Urban and unmanaged land uses are not actively modelled and do not use capitals or produce services. Abbreviations are as follows: Capitals H=human capital; S=social capital; M=manufactured capital; F=financial capital; Ar=arable suitability; IG=intensive grassland suitability; SNG=semi-natural grassland suitability; Bi=bioenergy suitability; AF=agro-forestry suitability; NNC= non-native conifer suitability; NC=native conifer suitability; NNB=non-native broadleaf suitability; NB=native broadleaf suitability; Tr=tree suitability. Services Food=food crops; Fodder=fodder crops; GF meat=grass-fed meat; GF milk=grass-fed milk; Fuel=bioenergy fuel; SW= softwood; HW=hardwood; BD=biodiversity; LD=landscape diversity; C=carbon sequestration; Rec=recreation; Fl. reg.=flood regulation; Emp= employment; SusP=sustainable production.

Land use (agent)	Sensitivity to capitals														Production of services													
	H	S	M	F	Ar	IG	SNG	Bi	AF	NNC	NNB	NC	NB	Tr	Food	Fodder	GF meat	GF milk	Fuel	SW	HW	BD	LD	C	Rec	Fl. reg.	Emp	SusP
Intensive arable (food)																												
Intensive arable (fodder)																												
Sustainable arable																												
Extensive arable																												
Intensive pastoral																												
Extensive pastoral																												
Very extensive pastoral																												
Bioenergy																												
Agroforestry																												
Productive non-native conifer																												
Productive non-native broadleaf																												
Productive native conifer																												
Productive native broadleaf																												
Multifunctional mixed woodland																												
Native woodland (conservation)																												
Urban																												
Unmanaged																												

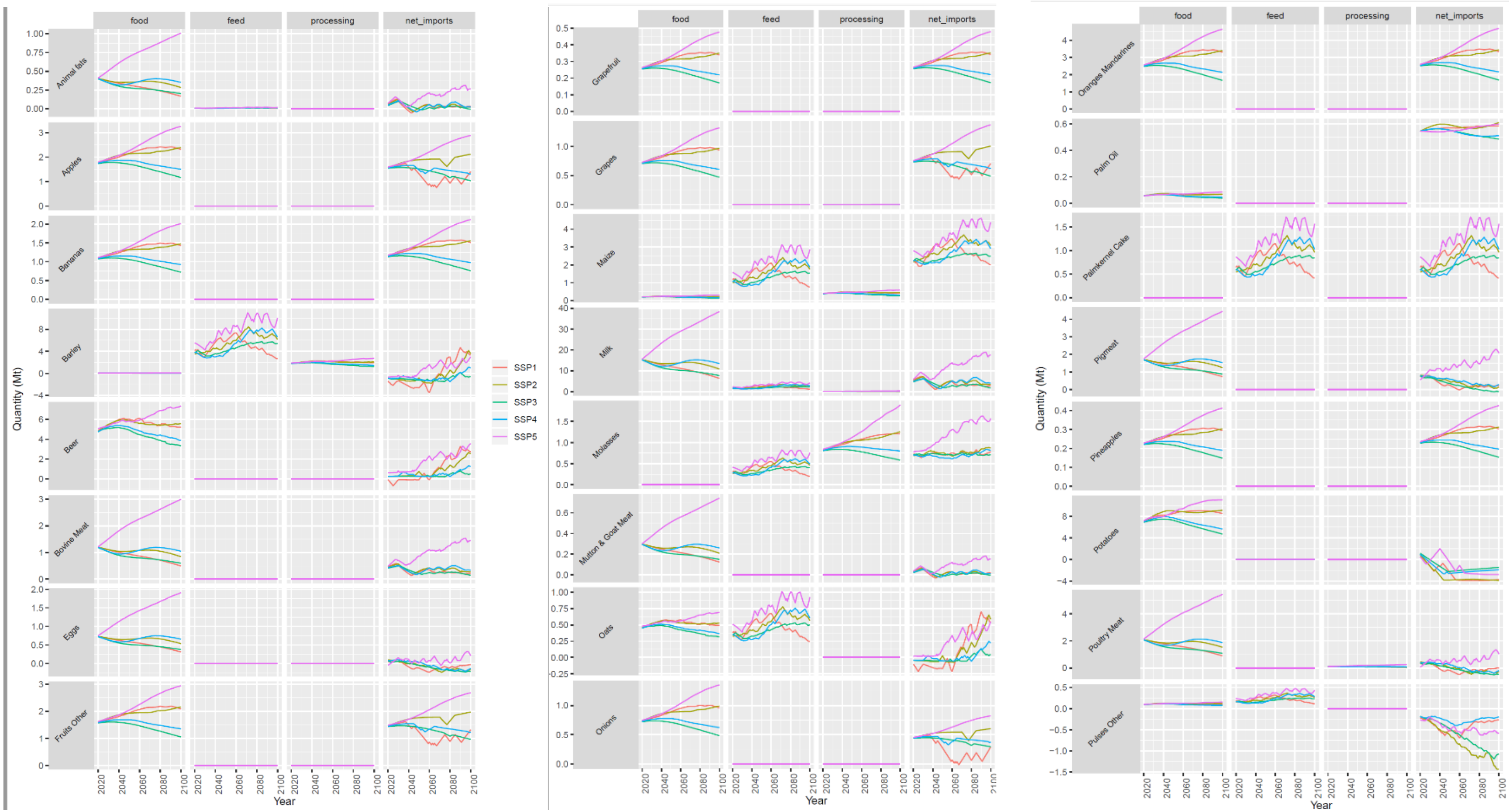
Approximate relative value

0 — **1**

Non-food demands were taken from the stakeholder-defined scenarios, and are described in (Merkle et al. 2022). Demand levels for foods were derived from the LandSyMM (Land System Modular Model; www.landsymm.earth) global modelling framework (Rabin et al., 2020). Within LandSyMM, the dynamic global vegetation model LPJ-GUESS simulates physiological, demographic, and disturbance processes for a variety of plant functional types (Smith et al., 2014) , while the land use model PLUM simulates land use and management based on global trade and cell-level (0.5◦) productivity (Alexander et al., 2018). Food demand was calculated from scenario projections of country-level population and gross domestic product (GDP), using the historical relationship of per capita GDP to consumption of each of six crop types – C3 cereals, C4 cereals, rice, oil crops, pulses, and starchy roots – plus ruminant and monogastric livestock. Separate demand levels were calculated for food crops for human consumption and for feed for monogastric livestock and ruminant livestock not raised on pasture. Both types of demand account for crops used for processing, seed stocks, and for losses sustained during the production process. Demands were also adjusted to take account of imports and exports, as calculated by PLUM. Demand levels broken down by food type are shown in Fig. S3.

In the case of CRAFTY-GB, the total food production of the UK simulated by LandSyMM was taken as the national demand (i.e. aggregated from the 0.5° grid that LandSyMM uses). Because the simulated LandSyMM baseline (representing the year 2020) is not based on land cover data, while the baseline land allocation of CRAFTY-GB is, all LandSyMM demands were normalised relative to their 2020 values, giving a continuous series of annual changes in demand levels as proportions of 2020 demand.

First the domestic production of feed and food crops was calculated. Food crops scale with the production of agents in CRAFTY, from a baseline quantity of 35.65Mt of crops (an average of 771 tonnes for each of the 46,252 purely arable agents in CRAFTY-GB at the baseline, including subsequent losses, processing and seeds etc.). Feed crops were converted to livestock products through product-specific Feed Conversion Ratios taken from (Alexander et al., 2016). Monogastrics are fed exclusively on these feed crops (including those imported), meaning that the demands for Mt of pork, poultry and eggs could be immediately converted into demands for Mt of feed crops. Ruminant livestock (according to demands for Beef, Mutton, Goat and milk) were similarly converted, and the remaining available feed crops were assigned proportionally to them. Leftover demand for these livestock products was converted to a pasture demand by scaling from the baseline, and for comparison by using an additional pasture food conversion ratio.



food
feed
processing
net_imports
Animal fats
Apples
Bananas
Barley
Beer
Bovine Meat
Eggs
Fruits Other
Grapefruit
Grapes
Maize
Milk
Molasses
Mutton & Goat Meat
Oats
Onions
Oranges Mandarines
Palm Oil
Palmkernel Cake
Pigmeat
Pineapples
Potatoes
Poultry Meat
Pulses Other
SSP1
SSP2
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2020
2040
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2100

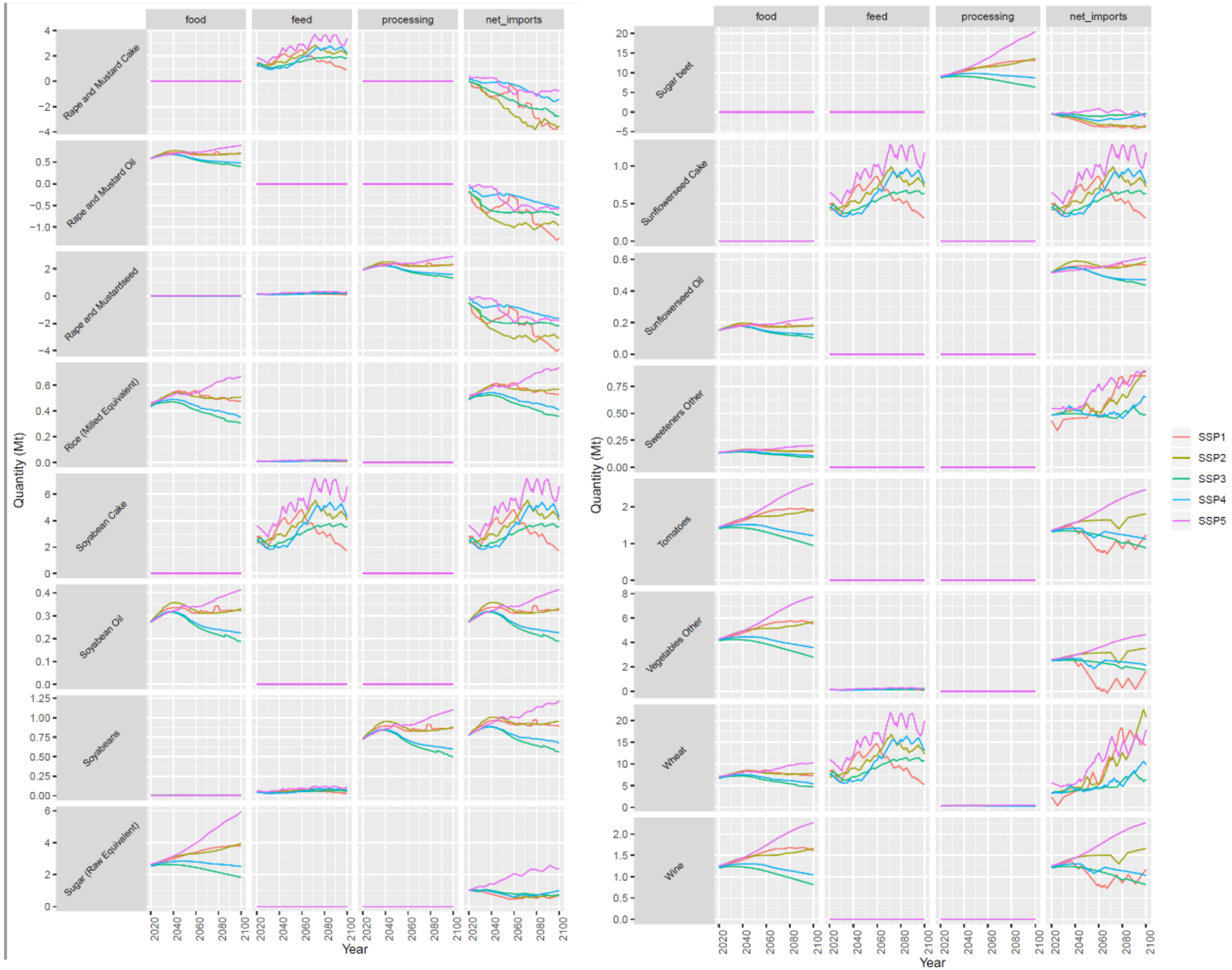


Figure S3: Food commodity demand levels supplied by the PLUM model as part of LandSyMM, prior to conversion for use in CRAFTY-GB

Scenarios

We use combinations of the Representative Concentration Pathways (RCP) climate scenarios (van Vuuren et al., 2011) and Shared Socioeconomic Pathways (SSP) socio-economic scenarios (O'Neill et al. 2017). A combined set of these scenarios was specified for the British context through a combination of stakeholder engagement and computational or statistical modelling.

The SSPs were specified for the UK as described in Pedde et al. (2021), Harmáčková et al. (2022) and Merkle et al. (2022). These substantial extensions of the global SSPs provide detailed narratives of social, economic and political developments across the UK until 2100. The narratives integrate national stakeholder knowledge on locally-relevant drivers and indicators with higher level information from the European and global SSPs. These narratives were simplified and converted into model parameterisations (Fig. 2, Table S8). SSPs were put in a global context through LandSyMM global land system modelling to provide consistency with the broader SSP framework and to account for the UK's international trade.

The SSP implementation also utilised the forms of behaviour represented in CRAFTY to capture land management decision-making (Table S5). Of these behaviours, social networks are the only new addition to the CRAFTY framework. These allow agents of the same type to affect one another's competitiveness within defined spatial neighbourhoods, to represent the benefits both of improved local knowledge diffusion and of economies of scale, and are described above (SI section 'BEHAVIOURS').

Climatic conditions are taken from the CHESS-SCAPE data set, which provides several climate variables at 1 km2 spatial resolution and several temporal resolutions, from daily to decadal. CHESS-SCAPE is derived from the 12 km2 resolution UKCP18 regional predictions for the UK. UKCP18 regional predictions were obtained by running a perturbed parameter ensemble of a regional climate model (RCM), nested within a global climate model (GCM) for RCP8.5 (Murphy et al., 2018). CHESS-SCAPE was derived from this regional data set by: (i) downscaling from 12 km2 to 1 km2 using a modified version of the CHESS methodology (Emma L. Robinson, Blyth, Clark, Finch, et al. 2017); (ii) bias-correcting to observed historical climate using the CHESS-met dataset (Emma L. Robinson, Blyth, Clark, Comyn-Platt, et al. 2017); and (iii) time-shifting and pattern scaling to provide RCPs 2.6, 4.5 and 6.0, using members of the CMIP5 ensemble to define target trajectories of global temperature change (Taylor et al., 2012). Full details can be found in (Robinson et al. 2022). The highest temporal resolution of CHESS-SCAPE is daily. From these were calculated 20-year mean-monthly climatologies, at a 10-year time-step, giving spatially and temporally explicit values for several climate variables for the UK, including temperature and precipitation. The climate variables were used to calculate Penman-Monteith potential evapotranspiration with interception correction (PETI), following the method of Robinson et al. (2017). This is potential evapotranspiration calculated for a short grass, with a correction applied on rain days to account for the greater efficiency of evaporation of water from the canopy surface before it can reach the soil. The air temperature was used to calculate growing degree days (GDD), which is a count of the number of days for which mean air temperature was greater than 5℃. The air temperature, precipitation, PETI and GDD were then used as inputs to the crop, grassland and forest modelling to produce annual scenario-specific capital values.

RCP-SSP combinations were chosen to: (i) cover a broad range of uncertainty in both emissions (and hence climate) and socio-economic developments; and (ii) include any combination of SSPs and RCPs that is plausible, meaningful and useful. The six combined scenarios we use (RCP2.6-SSP1, RCP4.5-SSP2, RCP4.5-SSP4, RCP6.0-SSP3, RCP8.5-SSP2, RCP8.5-SSP5) cover weak to strong climate change, as well as future societies with high and low challenges to adaptation and mitigation. The selection also allows analysis of the effects of different RCPs within the same SSP (RCPs 4.5 and 8.5 with SSP2), and the effects of different SSPs within the same RCP (SSPs 2 and 4 with RCP4.5; SSPs 2 and 5 with RCP8.5). Furthermore, low adaptation challenges (SSP1/5) and high adaptation challenges (SSP3/4) are confronted with different RCPs.
The model components and inputs described above were used to produce coherent representations of the UK-RCP-SSPs. These representations are summarised in Fig. 2 and in Table S8.

Scenario	**Description**	**Implementation**					
		Behaviour	Capitals	Demand levels	Valuation	Production	Other
SSP1 - Sustainability	UK-SSP1 shows the UK transitioning to a fully functional circular economy as society quickly becomes more egalitarian leading to healthier lifestyles, improved well-being, sustainable use of natural resources, and more stable and fair international relations. It represents a sustainable and co-operative society with a low carbon economy and high capacity to adapt to climate change.	*Social networks add up to 10% to agent competitiveness* *Agents more likely to change or abandon land use, except for very extensive management consistent with conservation*	*Arable and intensive grassland productiviti es +20% by 2070* *Social capital increases*	*At least 60% of ruminant products from grass-fed systems* *Higher demand for sustainable food* *Higher per capita demands for timber, biodiversity, carbon, recreation* *Higher demand for sustainable agriculture*	*Benefit values for non-food services x1.5*	*Grass-fed meat & milk productivity +10%* *Agro-forestry agents +10% productivity of main services* *Sustainable/extensive production levels benefit more from increases in manufactured capital* *Extensive & multifunctional agents have less dependence on financial capital (-20%)*	
SSP2 – Middle of the Road	UK-SSP2 is a world in which strong public-private partnerships enable moderate economic growth but inequalities persist. It represents a highly regulated society that continues to rely on fossil fuels, but with gradual increases in renewable energy resulting in intermediate adaptation and mitigation challenges.	*Agents more likely to change or abandon land use* *Social networks add up to 4% to competitiveness*	*Arable & intensive grass productiviti es +20% by 2070*	*Increased per capita demands for timber (+40%), carbon (+40%), bioenergy (+20%), water regulation (+20%) & recreation (+20%) and sustainable ag. Products (+50%)* *Min. 50% of ruminant products from grass-fed systems*		*Sustainable/extensive production levels benefit more from increases in manufactured capital*	
SSP3 – Regional rivalry	The dystopian scenario, UK-SSP3, shows how increasing social and economic barriers may trigger international tensions, nationalisation in key economic sectors, job losses and, eventually a highly fragmented society with the UK breaking apart. It represents a society where rivalry between regions and barriers to trade entrench reliance on fossil fuels and limit capacity to adapt to climate change.	*Individual-level randomness in agent characteristics* *Social networks operate over smaller (5km) radius, with smaller (max +2%) effect on competitiveness*	*Arable & intensive grass suitabilities -20% by 2100*	*Demand for sustainable ag, biodiversity, carbon, l diversity -80%*	*Food productio n benefit 5x non-food*	*Heavy reliance on manufactured capital to follow input availability (agricultural products) Services can only be supplied within-nation; no trade between parts of UK (demands scaled by population)* *Intensive agents produce -50% secondary services* *Biodiversity lower production all (-50%)*	*PAs removed*

SSP4 - Inequality	UK-SSP4 shows how a society dominated by business and political elites may lead to increasing inequalities by curtailing welfare policies and excluding the majority of a disengaged population. The business and political elite facilitate low carbon economies but large differences in income across segments of UK society limits the adaptive capacity of the masses.	*Intensive agents less likely to give up or give in* *Social networks add up to 10% to competitiveness*	*Arable & intensive grass suitability values +20% by 2070*	*Fuel (bioenergy), timber demands 200% by 2070* *Recreation & biodiversity -20% by 2040, static thereafter* *Sustainable ag demand -50%*	*All services have lower benefit due to lack of ability to pay (-50%)*	*Extensive agents produce less due to lack of support (-10%)* *Greater reliance on (benefit from) manufactured capital in forestry (+20%)*	*PAs removed in 2050*
SSP5 – Fossil-fuelled development	UK-SSP5 shows the UK transitioning to a highly individualistic society where the majority become wealthier through the exploitation of natural resources combined with high economic growth. It represents a technologically advanced world with a strong economy that is heavily dependent on fossil fuels, but with a high capacity to adapt to the impacts of climate change.	*Social networks add up to 10% to competitiveness* *thresholds allow more change*	*Arable & intensive grass suitability values +40% by 2070*	*Recreation demand +20%* *Sustainable ag demand -80%*	*Food production benefit 3x non-food*	*Intensive production more reliant on manufactured capital (+20%)* *Recreation not reliant on infrastructure (manufactured capital)* *Lower levels of secondary services in intensive agriculture (-10%)*	*PAs removed*

Table S8: Descriptions and summary of the implementation of the UK-SSPs

INTENSITY REPRESENTATION

To improve the interpretability of the results, we developed a land use intensity mapping approach. This involved the assignment of values on a continuous range for each of the arable, and each of the pastoral (except very extensive pastoral) classes across the scenarios. Intensity values were defined as a combination of the use of agricultural inputs (fertilisers, pesticides and machinery), technology, and modelled production levels. For the purposes of illustration these are combined multiplicatively here and used to select colour saturation levels in the map figures.
Alternative representations are possible, and it is important to note that our presentation does not distinguish the specific use of technology to reduce the use of chemical inputs, as in UK-SSP1. This method does however make scenarios results more comparable and means that differences in land management intensities among the scenarios are readily apparent.

Results

Agent typology evaluation

This section describes the comparison of the CRAFTY-GB agent typology with different (semi-) independent datasets on land cover (LCM 2015), habitat characteristics (EUNIS habitats), and agricultural intensity (UK CEH Land Cover Plus: Fertilisers and Pesticides data). All comparisons were made between the baseline AFT map (1km² spatial resolution) and maps of the respective datasets at their native resolution.

LCM 2015

The first comparison was between the baseline AFT map (1km²) and the LCM 2015 fractional land cover (1km²) to check the consistency of the baseline AFT allocation as described in Table S4. Full results of the comparison are shown in Figure S4, with a summary provided in Figure S5.

As the LCM 2015 dominant land cover map was the main source for the baseline AFT allocation there is generally a good agreement between AFTs and LCM land-cover classes, although with large variations across individual grid cells (Fig S5). Intensive agricultural AFTs show the highest fractions of arable land or improved grassland with only small contributions from woodlands and other classes, indicating a good representation of rather homogeneous agricultural landscapes within these AFTs. In contrast extensive agricultural AFTs are often associated with a mixture of agricultural and different semi-natural LCM classes (Fig S4). The AFT 'Sustainable arable' has been allocated randomly within the agricultural cells in the baseline, therefore not showing substantial differences to the intensive types. Broadleaved forest types are usually associated with a substantial amount of arable land and improved grasslands, but less mixed with conifer classes, indicating a clear distinction between the forest types in the allocation. However, broadleaved woodlands seem to represent more heterogeneous landscapes compared to coniferous woodlands. As expected, the most heterogeneous landscapes (with regard to land-cover composition) were found in multifunctional and native woodland agents. The agroforestry AFT does not have an equivalent in the LCM 2015 data and is mostly associated with LCM water classes, indication some room for improvement.

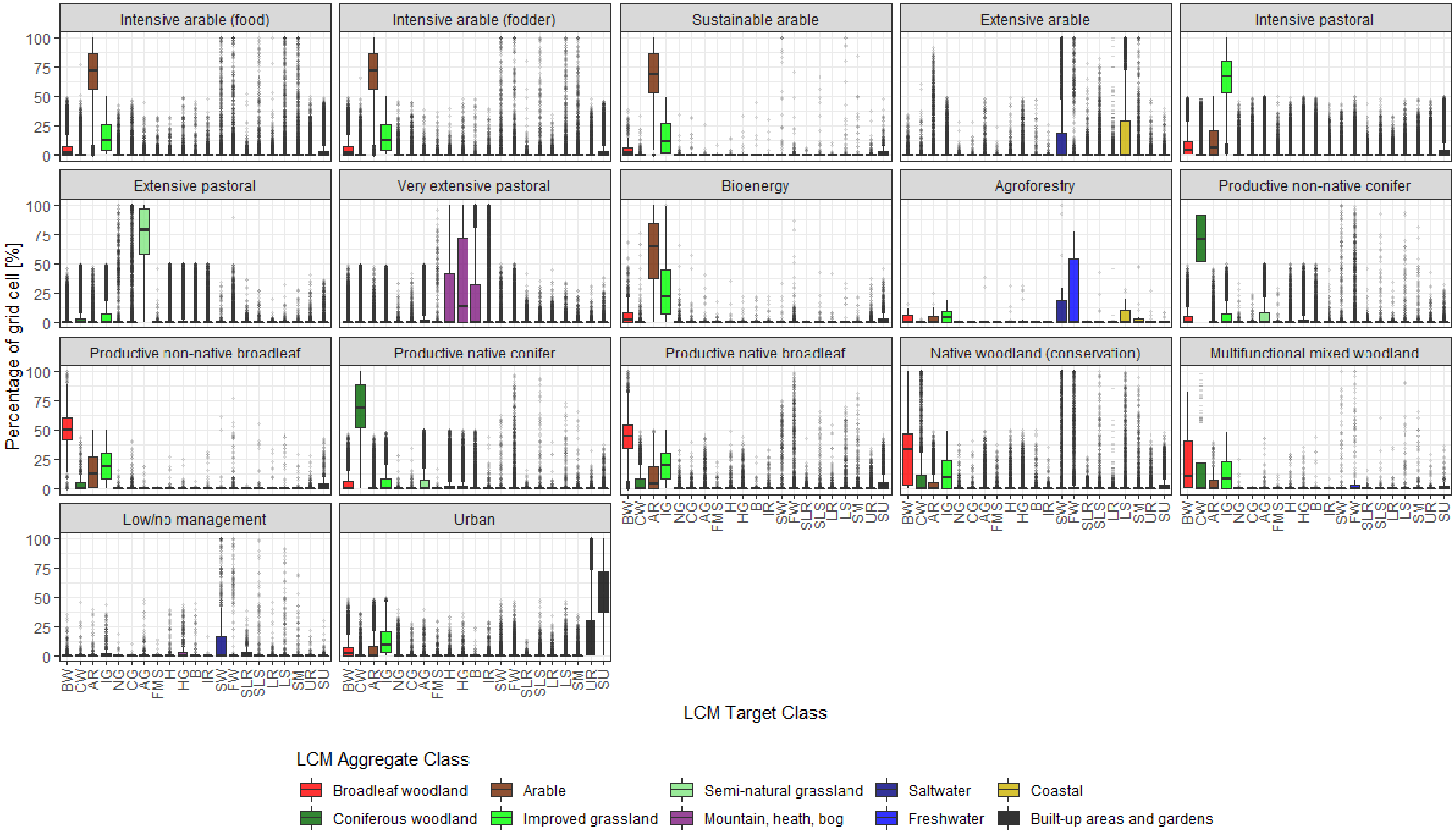


Figure S4: Sub-grid scale distribution of LCM classes within CRAFTY-GB agents. LCM classes as follows: **BW** Broadleafed woodland. **CW** Coniferous woodland. **AR** Arable and horticulture. **IG** Improved grassland. **NG** Neutral grassland. **CG** Calcareous grassland. **AG** Acid grassland. **FMS** Fen, marsh, and swamp. **H** Heather. **HG** Heather grassland. **B** Bog. **IR** Inland rock. **SW** Saltwater. **FW** Freshwater. **SLR** Supra-littoral rock. **SLS** Supra-littoral sediment. **LR** Littoral rock. **LS** Littoral sediment. **SM** Saltmarsh. **UR** Urban. **SU** Suburban

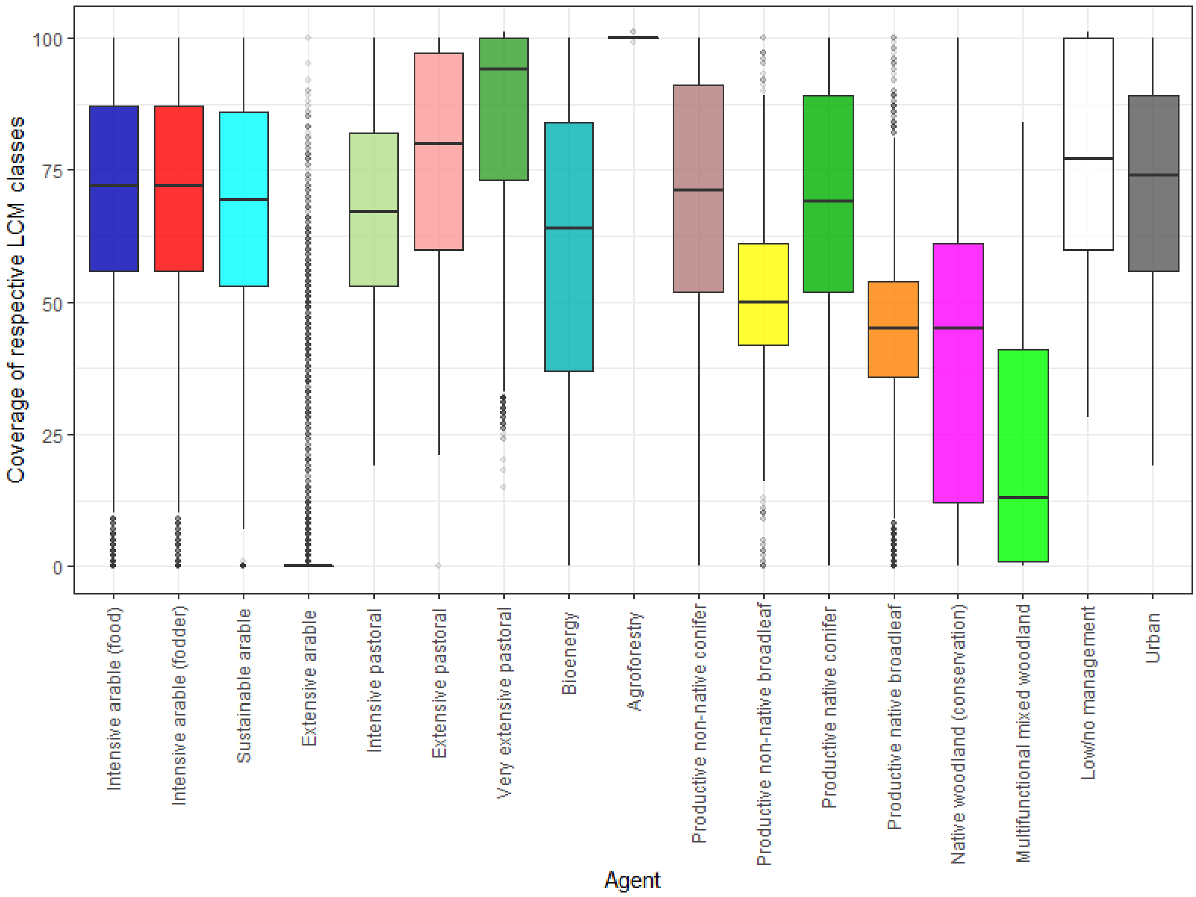


Figure S5: Sub-grid scale distribution of the LCM classes that correspond to CRAFTY-GB agents according to Table S4 (not accounting for additional data that has been used for allocation). For example, for agent 'Intensive arable (food)' fractions of LCM 'Arable' have been considered. As 'Agroforestry' has no equivalent in the LCM data, all classes were considered corresponding classes, explaining the 100% match. Lower (median) percentages indicate more heterogeneous landscapes, as higher percentages of 'non-matching' LCM classes can be found in the respective grid cells.

EUNIS habitats

The second comparison was between the baseline AFT map (1km resolution) and the EUNIS Habitat Map (100m resolution) representing ecosystem types across Europe (European Environment Agency, 2019). In this comparison, the distribution of EUNIS habitat types within each CRAFTY-GB cell was recorded. Because they are derived from different sources, these two maps were not expected to align closely. Nevertheless, the comparison was intended to characterise CRAFT-GB agents with regard to provision of habitat diversity and illustrate the scope for translation between the two.

Results showed good agreement between classes in each dataset, but with large variation within types. This can reflect heterogeneity within 1km cells, mismatches between the datasets used, as well as variation within AFTs that would be apparent in service levels but not in their labels. Figure S6 shows an example comparison between the CRAFTY-GB agent type 'Intensive arable (food)' and the EUNIS classes, revealing a clear association with arable habitats, but also the less frequent presence of several other habitat types within those cells. Full results are shown in Figure S7 and summarised in Figure S8.

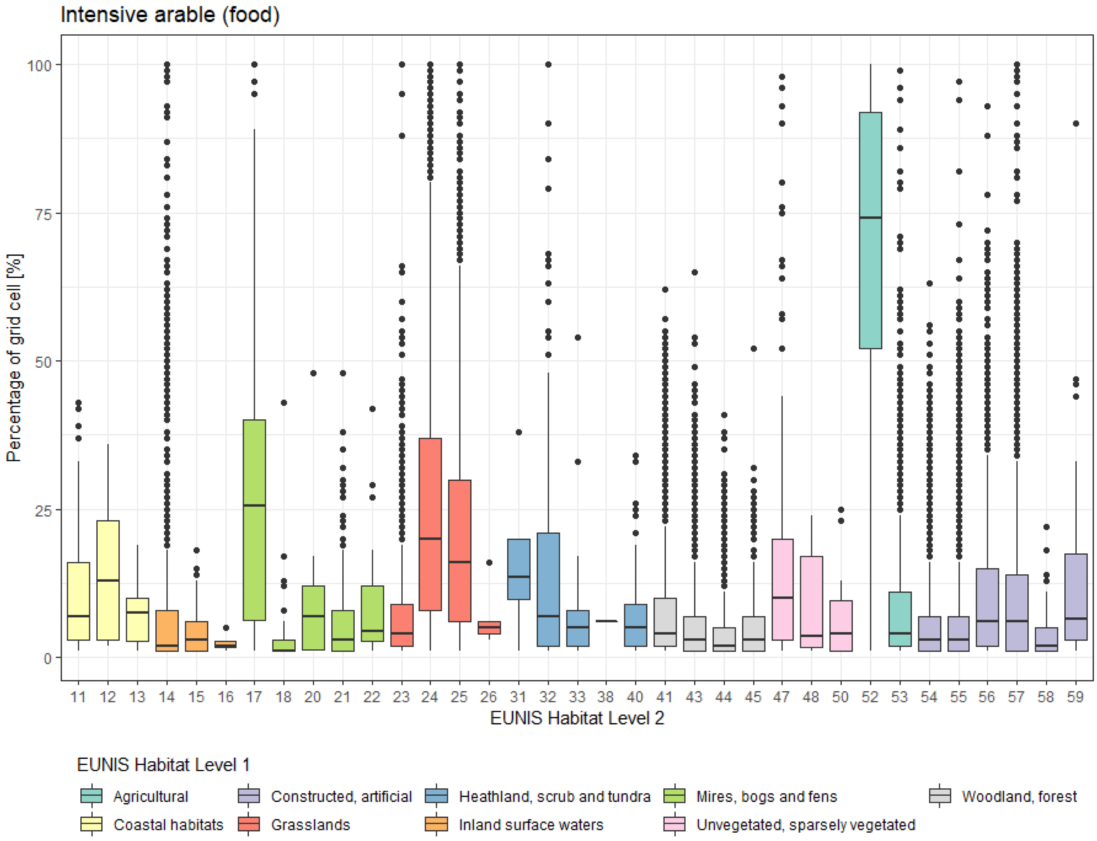


Figure S6: The distribution of EUNIS habitat types within the CRAFTY-GB 'intensive arable (food)' class. Habitat identities are explained in Table S9.

Figure S7: The distribution of EUNIS habitat types within the CRAFTY-GB agents. Habitat identities are explained in Table S9.

Figure S8: The distribution of broad EUNIS habitat types within the CRAFTY-GB agents.

ID	EUNIS Level 2	EUNS Level 1
11	Coastal dunes and sandy shores	
12	Coastal shingle	Coastal habitats
13	Rock cliffs, ledges and shores, including the supralittoral	
14	Surface standing waters	
15	Surface running waters	Inland surface waters
16	Littoral zone of inland surface waterbodies	
17	Raised and blanket bogs	
18	Valley mires, poor fens and transition mires	
20	Base-rich fens and calcareous spring mires	Mires, bogs and fens
21	Sedge and reedbeds, normally without free-standing water	
22	Inland saline and brackish marshes and reedbeds	
23	Dry grasslands	
24	Mesic grasslands	Grasslands
25	Seasonally wet and wet grasslands	
26	Alpine and subalpine grasslands	
31	Arctic, alpine and subalpine scrub	
32	Temperate and mediterranean-montane scrub	
33	Temperate shrub heathland	Heathland, scrub and tundra
38	Riverine and fen scrubs	
40	Shrub plantations	
41	Broadleaved deciduous woodland	
43	Coniferous woodland	
44	Mixed deciduous and coniferous woodland	Woodland, forest
45	Lines of trees, small anthropogenic woodlands, recently felled woodland, early-stage woodland and coppice	
47	Screes	
48	Inland cliffs, rock pavements and outcrops	Unvegetated, sparsely vegetated
50	Miscellaneous inland habitats with very sparse or no vegetation	
52	Arable land and market gardens	Agricultural
53	Cultivated areas of gardens and parks	
54	Buildings of cities, towns and villages	
55	Low density buildings	
56	Extractive industrial sites	Constructed, artificial
57	Transport networks and other constructed hard-surfaced areas	
58	Highly artificial man-made waters and associated structures	
59	Waste deposits	

Table S9: EUNIS habitat identities.

CEH Pesticides and Fertilisers

The third comparison of the baseline AFT map was to the 'CEH Land Cover® Plus: Pesticides v2.0' and 'CEH Land Cover® Plus: Fertilisers 2010-2015 (England)' datasets. These datasets report annual application intensity per km^2 grid cell of 162 ingredients for pesticides and nitrogen (N), phosphorus (P), and potassium (K) for fertilisers. Both datasets are gridded products based on the interpolation of survey data to crop type data (Jarvis et al. 2020; Osório et al. 2019). The sum of all 162 ingredients per grid cell was used as an indicator for pesticide application intensity. Both this indicator and the fertiliser data were min-max normalized to 0-1 in order to display comparable measures in Fig. S9. Although there is again a large variation of intensity levels within individual cells assigned to an AFT, which represents to some extent real-world variability (and is depicted in CRAFTY-GB by variable levels of capitals and services), average intensity levels of the individual AFTs show up as expected.

Intensive agricultural AFTs show the highest application intensities of both pesticides and fertilisers, while the application is substantially lower in extensive AFTs (both arable and pastoral). Due to the random allocation of 'Sustainable Arable' within cropland in the baseline map, there is no distinction to the intensive agricultural AFTs at this initial timepoint. Broadleaf woodland AFTs show higher rates of pesticides and fertilisers compared to coniferous woodland AFTS, most probably due to the higher association of broadleaf systems with intensive arable land (as discussed above).

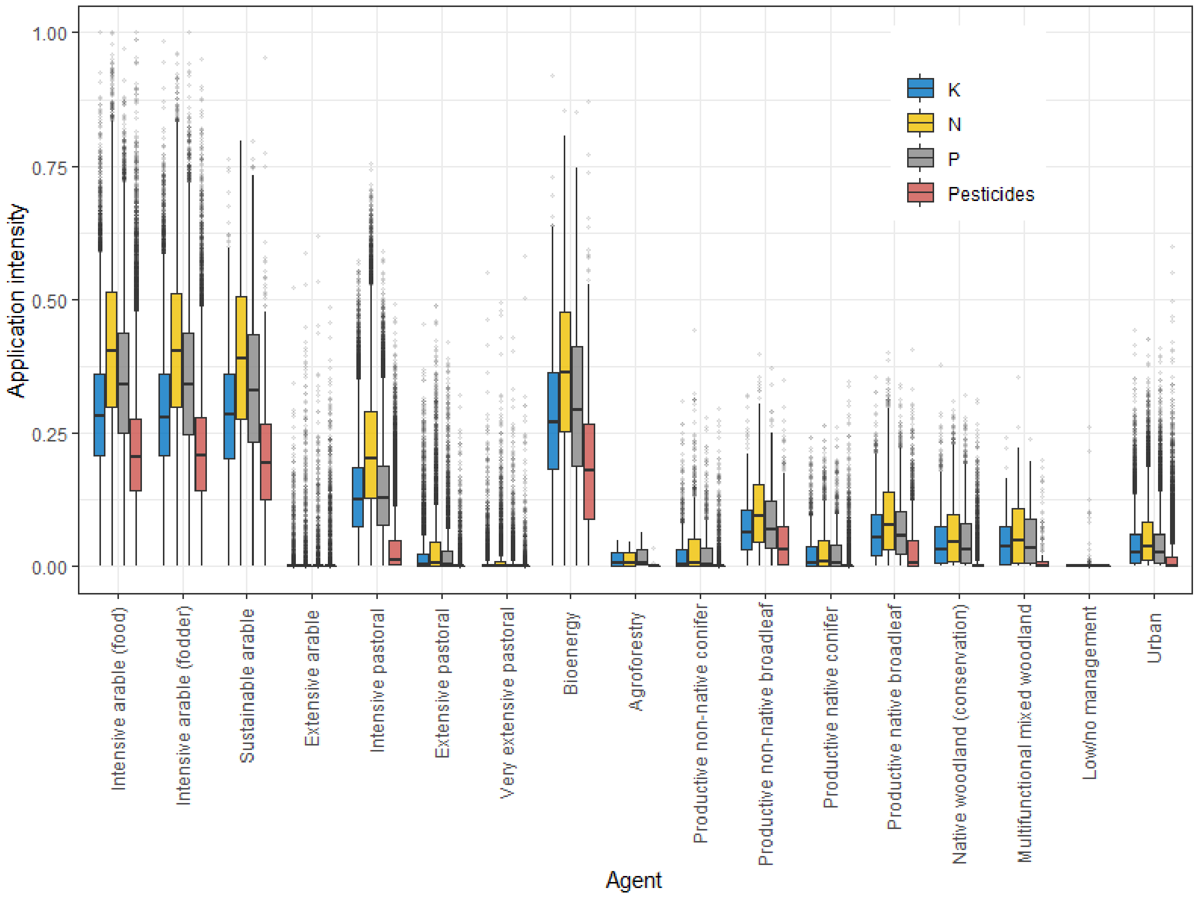


Figure S9: Associations between CRAFTY-GB agent types and application of fertilisers and pesticides as described in independent baseline data.

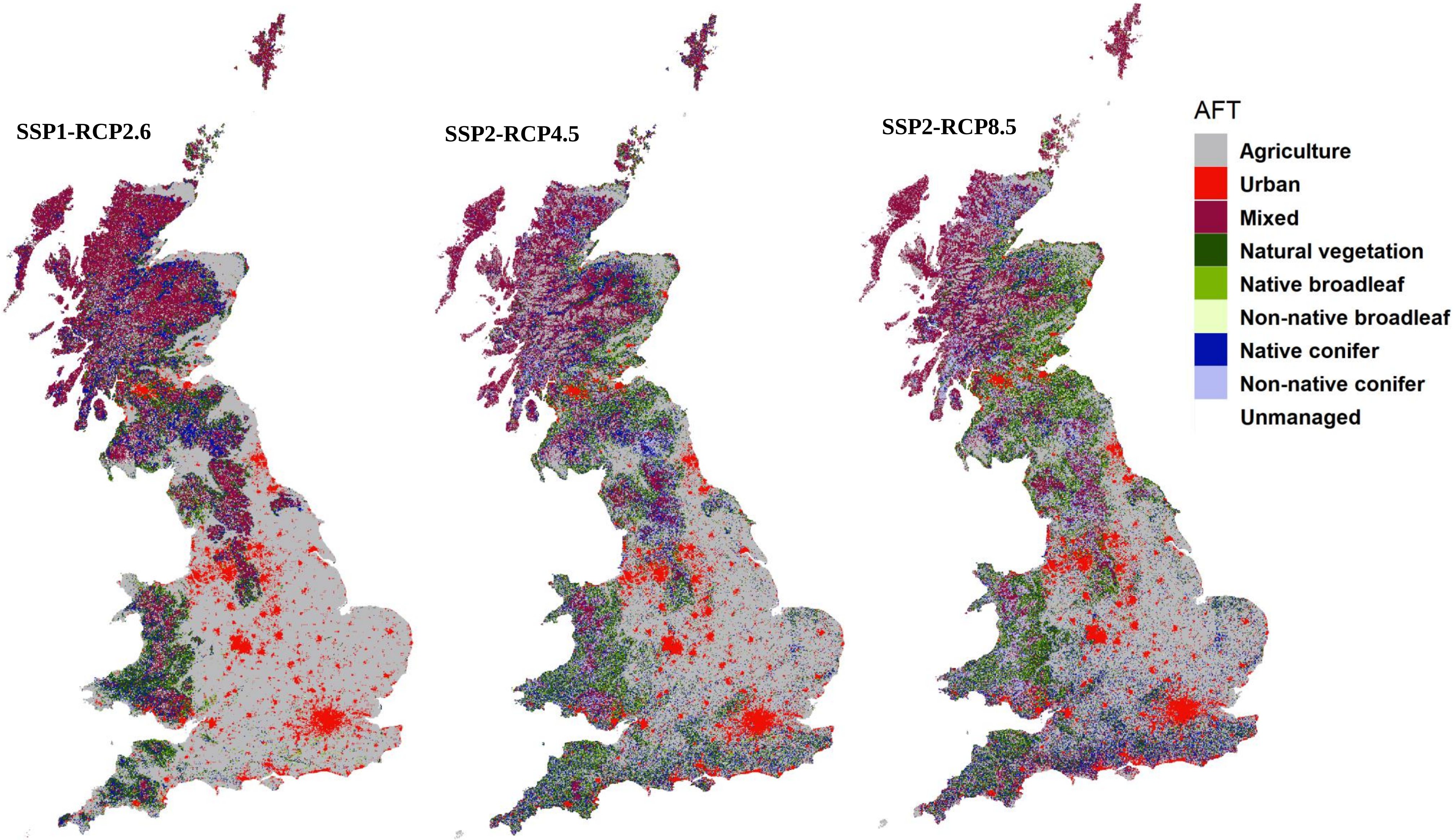
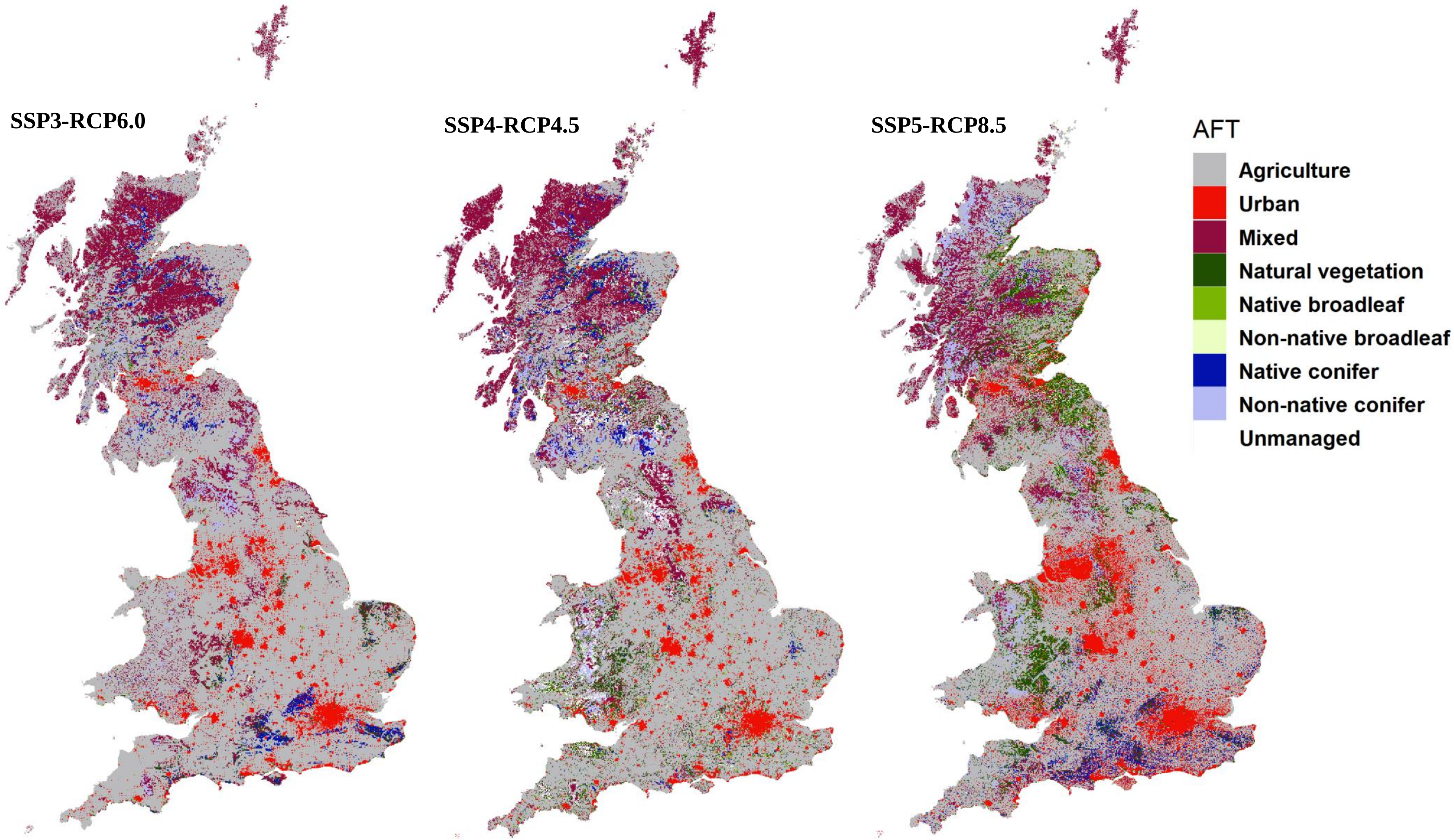
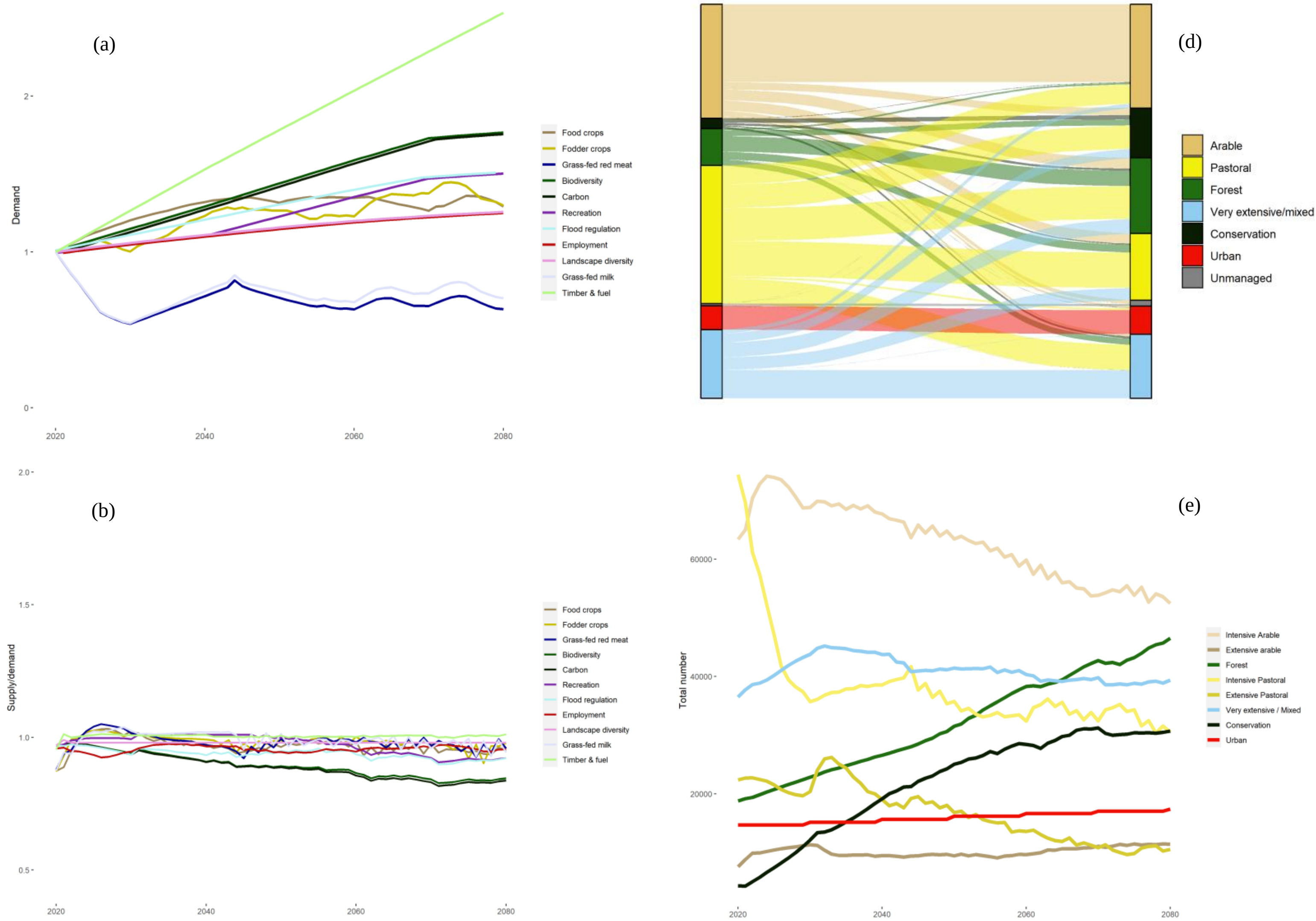


Fig. S10: Mapped results for the year 2080 in each scenario focusing on forest vegetation types. The mapped categories represent the dominant type within each cell. 'Mixed' contains forest and non-forest vegetation and land uses.


SSP3-RCP6.0
SSP4-RCP4.5
SSP5-RCP8.5
AFT
Agriculture
Urban
Mixed
Natural vegetation
Native broadleaf
Non-native broadleaf
Native conifer
Non-native conifer
Unmanaged



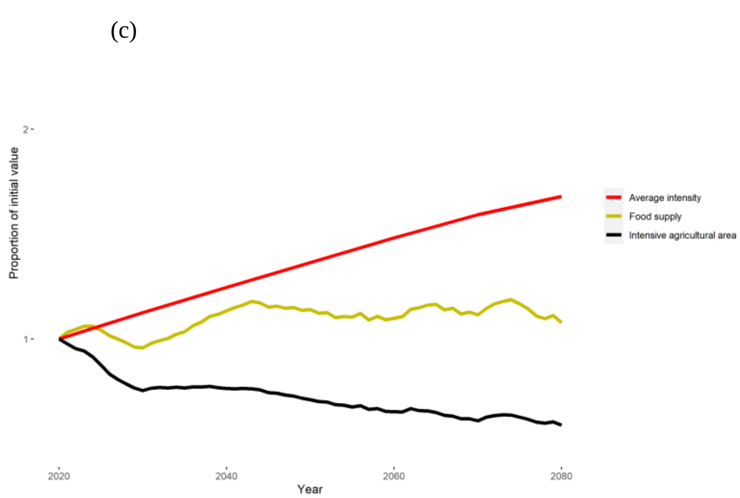


Fig. S11: Demand levels (a), supply as proportion of demand (b), land use intensity, food supply and intensive area (c), numbers of agents within amalgamated AFTs (d) and transitions between broad land use types (e) throughout SSP2-RCP 8.5 results.

TRACE document

This is a TRACE document ("TRAnsparent and Comprehensive model Evaludation") which provides supporting evidence that our model presented in:

> Brown et al. (in review), Agent-based modelling of alternative futures in the British land use system,

was thoughtfully designed, correctly implemented, thoroughly tested, well understood, and appropriately used for its intended purpose.

The rationale of this document follows:

> Schmolke A, Thorbek P, DeAngelis DL, Grimm V. 2010. Ecological modelling supporting environmental decision making: a strategy for the future. *Trends in Ecology and Evolution* 25: 479-486.

and uses the updated standard terminology and document structure in:

> Grimm V, Augusiak J, Focks A, Frank B, Gabsi F, Johnston ASA, Kułakowska K, Liu C, Martin BT, Meli M, Radchuk V, Schmolke A, Thorbek P, Railsback SF. 2014. Towards better modelling and decision support: documenting model development, testing, and analysis using TRACE. *Ecological Modelling*

and

> Augusiak J, Van den Brink PJ, Grimm V. 2014. Merging validation and evaluation of ecological models to 'evaludation': a review of terminology and a practical approach. *Ecological Modelling*.

Contents

1 Problem formulation

This TRACE element provides supporting information on: The decision-making context in which the model will be used; the types of model clients or stakeholders addressed; a precise specification of the question(s) that should be answered with the model, including a specification of necessary model outputs; and a statement of the domain of applicability of the model, including the extent of acceptable extrapolations.

Summary:

***CRAFTY-GB* is a model of the British land system (including Great Britain but excluding Northern Ireland), with the following primary and subsidiary objectives:**

- **To allow exploration of British land system change under a wide range of climatic and socio-economic scenarios, by representing:**
    - **Different sectors within the land system, including agriculture, forestry, urban, conservation and other major forms of management;**
    - **Different intensities of management within these systems;**
    - **A diverse, scenario-consistent set of socio-economic conditions affecting land management;**
    - **Human decision-making at individual and social levels within the land system, in terms of management and demands for different food types and ecosystem services;**
    - **Ecosystem service provision across a range of regulating, provisioning and cultural services**.

CRAFTY-GB is an agent-based model of the British land system based on a broad range of available land system data and operating at 1km^2 resolution. The model is an application of the CRAFTY agent-based modelling framework (Murray-Rust et al. 2014). It is intended for use in exploring land use change under divergent climatic and socio-economic scenarios. It is primarily intended for use by scientific researchers working on issues connected with future land use change. The model is not predictive and is not intended or able to reveal likely outcomes of particular interventions, and so is not for direct use in policy formulation. It can, however, provide broad contextual information to support policy decisions, particularly with respect to interactions between land use sectors and objectives and the effects of human decision-making within the land system.

The questions that the model is intended to answer are:

- How might the British land system develop under specified climatic and socio-economic scenario conditions?
- How might human decision-making affect outcomes within those scenarios?
- To what extent do outcomes depend on these climatic, socio-economic and behavioural conditions?
- How does the British land system affect, and how is it affected by, international food production?
- How are different ecosystem services and different land system objectives affected by simulated outcomes?

In order to answer these questions, the model produces a range of outcomes. Key amongst these are:

- Maps and timelines of land use/management, land cover, and ecosystem service provision
- Supply levels and associated valuations for all simulated ecosystem services

The domain of applicability is Great Britain, and modelling can be conducted for any temporal extent during which necessary input data are available (currently 2020-2080) – CRAFTY-GB itself involves no extrapolations beyond these data. Therefore, the model represents an open-ended 'virtual laboratory' in which simulation experiments can be run on the basis of suitable input data and the assumptions and design features of the model.

2 Model description

This TRACE element provides supporting information on: The model. Provide a detailed written model description. For individual/agent-based and other simulation models, the ODD protocol is recommended as standard format. For complex submodels it should include concise explanations of the underlying rationale. Model users should learn what the model is, how it works, and what guided its design.

Summary:

An ODD protocol for the CRAFTY-GB model is presented below.

Introduction: technical overview

CRAFTY-GB is an application of the CRAFTY agent-based modelling framework (Murray-Rust et al. 2014), which is an Open Source framework built on reusable software components, and is an independent piece of software written in Java. Interactions between components (agents, cells, regions etc.) is specified using interfaces that enable users to create their own configuration of model components. For example, the agent interface specifies that agents have a unique ID, have a current competitiveness and, among other things, belong to a certain Agent Functional Type (AFT; Arneth, Brown, and Rounsevell 2014). As with other model components, a user may implement new agent types as long as they fulfil the contract of the interface.

To remove the need for high-level programming among model users, the CRAFTY framework and CRAFTY-GB itself can be configured and setup to run through the use of XML files. This is a form of declarative specification – the XML files declare which objects should take part in a simulation, and they are then passed over to a scheduling system. Each XML file defines one or more entities within the simulation, and will typically include other files for subcomponents. Model configuration is based on the principles below:

- A Scenario file encodes overall parameters of the simulation – the number of time steps (years) over which it will run, an ID for the simulation, the means of accessing input data and the required outputs (such as videos, images and tables).
- A World file defines the regions that comprise the simulated world.
- Each Region file specifies:
    - The coordinates and capital levels of the cells in the Region, typically using a CSV or ASCII raster file

- The Allocation, Competition and Demand models used within the region, often using CSV files to specify time-varying quantities (e.g. changes in capitals and demand)
- A set of agents and their properties, making use of CSV files as necessary.
- Various land use raster data to protect or overload externally modelled land use changes such as urbanisation and protected areas.

In each of these cases, the files also specify the Java classes to be used along with their parameters, allowing users to incorporate their own code in the model.

In contrast to the declarative approach taken to configuration, CRAFTY (and hence CRAFTY-GB) uses a fixed schedule that encodes the flow of operations. To further enhance transparency of model behaviour, CRAFTY includes numeric and graphic displays for model variables. Spatially explicit outputs are also made available and include agent type, capital levels, competitiveness scores and supply of services. Any of these displays can be used to create animations of the model's behaviour over time.

1. Purpose

CRAFTY-GB is an application of the 'Competition for Resources between Agent Functional Types' (CRAFTY) model framework, which was designed to allow land use changes to be modelled across large spatial extents. **The specific purpose of CRAFTY-GB is to allow exploration of British land system change under a wide range of climatic and socio-economic scenarios**, as outlined in Section 1 (Problem Formulation) above. The model allows the adoption of different land uses, variations in the intensity of land uses, diversification into multifunctional land uses, land abandonment and competition for land.

2. Entities, state variables, and scales

Spatial units CRAFTY-GB is based on a grid of *cells* at 1km^2 resolution. Each cell has defined levels of a range of *capitals*, which describe the availability of particular social, environmental or economic resources. Cells can be grouped into independent or semi-independent *regions*, but these are not applied in the default setup. A non-spatial population is assumed to exist and to generate demands for *services*, such as food, timber and access to nature. These demands are defined exogenously. Each cell may be managed by a single land use *agent.*

Agents Land managers are explicitly represented as agents in CRAFTY-GB (institutional agents can exist as well, and are described in Holzhauer, Brown, and Rounsevell 2019). Land management agents have functional and behavioural components to describe their forms of land management and decision-making. Agents are able to leverage the *capitals* available in a *cell* to provide a range of *services*. Each agent has a production function that maps capital levels onto service provision levels (see Sub-section **Error! Reference source not found.**, Production). An agent's *competitiveness* according to a given level of service provision can be calculated based on societal demands, supply levels and marginal benefit functions that define the economic and non-economic value of service production given the supply-demand difference at that point in the simulation.

Agents have several attributes that directly affect land use change, the two most fundamental being abandonment (*"giving up"*) and competition (*"giving-in"*) thresholds. If an agent's competitiveness falls below their giving up threshold, which defines the minimum return an agent is willing to accept from a cell, it abandons the cell, which then becomes available to other agents. If an agent that does not currently own a cell has a competitiveness greater than an incumbent agent's, and if the difference is larger than the incumbent's giving-in threshold, the incumbent relinquishes its cell to the competitor – having been, in effect, 'bought out'. An agent searching for land can therefore only take over unmanaged (abandoned) cells, or those on which it can outcompete the existing agent. These processes are mediated by an abandonment probability that determines the likelihood of an agent abandoning their cell at any particular timestep, and search abilities that determine the number and order of cells that are searched for competition at each timestep (Table 1).

Agents are drawn from a typology that defines general characteristics of agents, and which is based on the Agent Functional Types (AFT) approach (see sub-section 4). As well as defining extant agents, the typology allows for new agents to be created, and for the comparison of productivity, benefit and other characteristics of "typical" agents of the type. These "Potential Agents" are used within the allocation process to represent agents who are attempting to find some land to manage, or to analyse the optimum type of agent to manage a given cell. Finally, individual agents of a given type need not be identical – all of the agent's characteristics can be drawn from user-definable distributions to provide within-type heterogeneity. See Table 1 for a complete list of agent variables.

Table 1: Variables of agents

Variable	***Description***
Typological variables (allowing for random individual level variation)	
Competition (giving-in) threshold	If a competing agent's competitiveness is greater than the incumbent agent's by a value larger than the giving-in threshold then the incumbent agent relinquishes that cell to the competitor.
Abandonment (giving-up) threshold	If an agent's competitiveness falls below its giving-up threshold (defines the minimum return an agent is willing to accept from a cell) it needs to abandon its cell(s) (with giving-up probability).
Abandonment (giving-up) probability	Probability for giving up in case the agent's competitiveness falls below the giving-up threshold
Optimal production	Amount of produced service in case of optimal conditions (all relevant capitals maximised)
Capital sensitivities	Sensitivities of production to capital values
Production model	Component responsible for calculation of service provision
Search ability	Comprising three parameters: the number of search iterations an agent type can undertake per timestep, the number of cells considered for competition during each search iteration, and the order (random or ranked) in which those cells are competed for.
Social networks	Comprising two parameters: the size and the effect of neighbourhoods within which agents of the same type benefit one another's capital, production or competitiveness levels.
Individual variables (do not exist at typological level)	
Competitiveness	Denotes the agent's current competitiveness value (calculated in-model)

Environment. CRAFTY-GB represents the British land system. Within this land system, heterogeneity is represented by capitals (economic, social, financial, manufactured, human and natural) that describe the locational attributes of each cell.

Scales. CRAFTY-GB covers the British land system at 1 km resolution. A time step in CRAFTY-GB represents a year by default, but this is not fixed and can vary to match the timescale of land use change decisions.

3. Process overview and scheduling

At each modelled timestep, the level of service production achieved by an agent is given a benefit value via a function that relates production levels to unmet demand. Agents compete for land based on these benefit values, and this competition is affected by individual or typological behaviour, as defined above. Table 2 gives an overview of the CRAFTY-GB simulation schedule.

Table 2. Basic simulation schedule for CRAFTY-GB.

Timestep
1. Read in masks that constrain land use changes in this timestep (e.g. Urban mask) **2.** For each agent ∈ Agents a. Update competitiveness based on residual demand b. **If competitiveness < giving-up threshold, draw random number on [0,1] and compare against giving-up probability. If lower, abandon cell** **3.** For each region ∈ Regions **allocate-land:** a. Allocate most competitive agent type to unoccupied cells, if consistent with giving-up threshold and masks b. For each agent type *t* ∈ Agent Types, undertake *n* search iterations of *m* cells c. For every searched cell, calculate *t*'s competitiveness d. **If *t's* competitiveness > (cell owner's competitiveness + cell owner's giving-in threshold), and if permitted by masking rules, owner relinquishes cell** e. Agent of type *t* takes cell over, with parameters drawn randomly from typological ranges, if used. **4.** For each agent ∈ Agents Update supply of services produced **5.** (For each region ∈ Regions Update supply and unmet demand)

Figure 1 shows the flow of operation within each tick (or timestep). Each timestep starts by updating the decision-making context for land use agents – the levels of demand, capitals and any restrictions related for example to protected areas. Updates are made to the levels of demand across each region, and levels of capitals within each cell. These are loaded from external files, either as direct values or as functions to be sampled from on a yearly basis. Next, the land use agents respond and adapt to this altered context:

- First, each agent updates its level of supply, based on current capital levels. The total supply of each service is then calculated.
- Next, each agent's competitiveness is calculated on the basis of the difference between total supply and demand, and the valuation per unit unmet demand of each service.
- Any agents who give up are removed from the model.
- The active allocation procedure now runs, allowing new agents to take over unmanaged land and allowing other land transitions to take place.

Once all of the land use agents have been updated, final accounting is carried out, such as calculating total supply and demand, creating output files, displaying model state and creating videos.

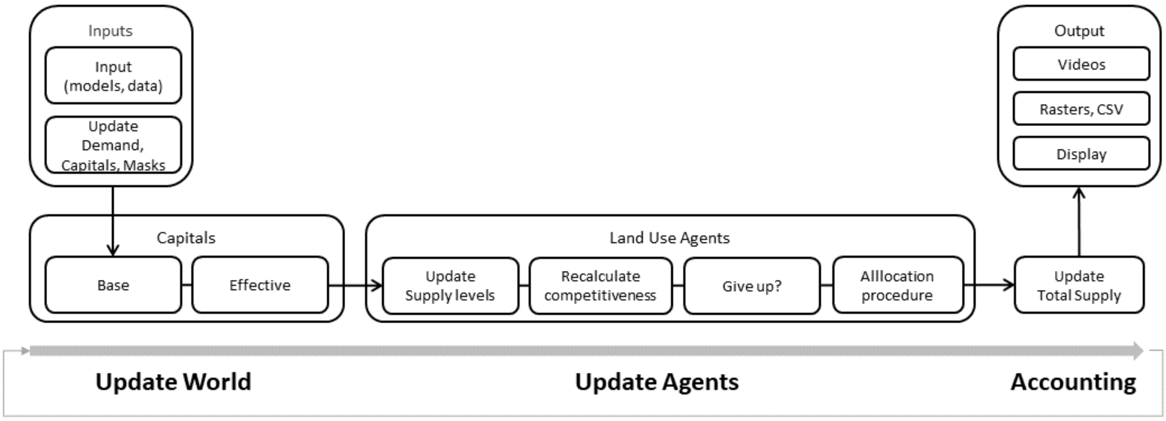


Figure 1. CRAFTY-GB flow diagram. This represents a single timestep for a single region.

4. Design concepts

Basic principles. The concept of Agent Functional Types is used to group land-use agents by their productive and decision-making characteristics. This typology is intended to allow generalisations of the attributes (traits) of individual actors in order to simplify model development and application, and to provide a transparent representation of agent decisional processes and behaviour. The AFT concept derives from a direct analogy with the use of Plant Functional Types (PFTs) in Dynamic Vegetation Models (Arneth, Brown, and Rounsevell 2014).

CRAFTY-GB inherits a number of design criteria from the CRAFTY framework on which it is based. These are:

1) The model must be able to run at 1km^2 resolution across national extent. This requirement holds for runtime costs, complexity, and the availability of data to parameterise and calibrate the model.
2) The model should take into account a wide range of societal demands for ecosystem services, including those that have no direct financial value.
3) The model must be able to represent multifunctional land use, and be responsive to the trade-offs between provision of various services.
4) The model should be able to represent the diversity of human behaviour that determines land management.
5) The model should be easy to refine and extend. This includes incorporating different data on services, capitals, land uses and agents, as well as adding complexity and variation to individual agents.

In CRAFTY-GB, these are extended to cover the purposes set out in Section 1 of this TRACE document.

The decision making submodel (see sub-section **Error! Reference source not found.**) acknowledges the existence of different modes of decision making like habits, heuristics and rule-based behaviour, and deliberative decision making. Decision are triggered by certain environmental or individual conditions or changes thereof which are checked every time step of the simulation. Table 3 provides an overview of the main assumptions that guided the

CRAFTY framework development, and which therefore underpin the operation of CRAFTY-GB.

Table 3: Design assumptions made in CRAFTY-GB

Model assumption	**Details**	**Justification**
Potential productivity of land can be represented by a range of capitals	Capitals representing natural productivity (for any good or service such as a specific food or timber crop) and any anthropogenic effects on productivity (such as availability of finance or infrastructure) can be used as a basis for the description of ecosystem services.	Well-established method of characterising and modelling land systems (Boumans et al. 2002; Scoones 1998; Harrison et al. 2013; Pedde et al. 2019).
Production of services by land managers can be described by a function dependent upon access to capitals and productive abilities.	The ability of land managers to produce services is dependent on the underlying productivity and attributes of the land, expressed via capitals (above) and their individual or typological productive ability, which may depend upon a number of personal characteristics and behavioural factors. (The form of the production function is not set, but a Cobb-Douglas function is used by default).	An established method that allows for production levels to vary according to context and agent characteristics (Douglas 1976; Fulginiti and Perrin 1998; Martin and Mitra 2001).
The competitiveness of land managers depends upon demand for specific services.	Pre-determined demands exist for ecosystem goods and services, and land managers compete to satisfy these demands (where not satisfied by imports). Land managers are more competitive when they can produce greater (total) quantities of services for which there is unmet demand.	Demands for services are known to be expressed via the economic value of service production, and, in the absence of behavioural factors, land use is driven primarily by economics. Partly, decisions are made on grounds of non-monetary (or indirectly monetary) demands – e.g. for green space - and CRAFTY is designed to be capable of handling these, where they can be parameterised. No fixed assumption about the relationship between unmet (residual) demand and utility values (competitiveness) is made.
Land managers can be classified into Agent Functional Types according to their behaviours and functions.	The management practices and behaviours of land managers allows them to be classified into a typology analogous to the Plant Functional Types used in Dynamic Global Vegetation Models, increasing modelling efficiency.	The use of types increases computational efficiency by providing a description of land management and human behaviour at a level of abstraction that decreases the need for empirical parameterisation but retains the characteristics most important to large-scale land use change (Arneth, Brown, & Rounsevell, 2014).
Three mechanisms of land use change.	Land use (or ownership) changes when agents abandon land, take over unmanaged land, or take over managed land from the current owner.	Analogous to main forms of land use change in the real world.
Each cell is managed by a single agent	Multiple ownership of cells is not supported	The scale of application is not defined and so can be set to the appropriate scale of land holdings in any particular case (the minimum size of holding that is of

		interest to the modeller). Agents may be permitted to manage multiple cells. In CRAFTY-GB, a 1 km^2 resolution is selected as representative of typical British land holdings.
Agents have a fixed set of potential actions	The set of potential actions an agent may select in decision making processes and perform afterwards needs to be defined and assigned beforehand.	The evolution of potential actions during the time span of simulation can be emulated by defining them beforehand and by their dependence on evolving capital and demand levels, which can in turn be affected by other model components.
Wide range of land-use relevant behaviour can be represented by 'giving-in' and 'giving-up' thresholds	Range of personal characteristics and behaviours known to affect land use decisions can be often abstracted in two values giving (relative) willingness of land managers to change land use or abandon land. Believed to be a necessary simplification for large-scale land use models that adequately mimics observed behaviour but can be 'overwritten' by more specific decisions (see sections Agents and Submodels, Decision Making).	Known that numerous factors affect personal decision-making (e.g. Siebert, Toogood, and Knierim 2006; Gorton et al. 2008; Brown et al. 2020; Bartkowski and Bartke 2018) - too many to model or parameterise. Several studies have suggested that, for modelling purposes, a wide range of behaviours are reducible to a small number of dimensions similar to those used here (Berger 2001; Polhill, Gotts, and Law 2001; Siebert, Toogood, and Knierim 2006; Gorton et al. 2008; Murray-Rust et al. 2011).
Knowledge and social influence flows over geographical social networks.	Land managers are connected via proximity-dependent social ties that transport information, norms and practices.	Adoption of management practices depends on horizontal spatial ties to institutions and organisations (Brown et al. 2020; Bartkowski and Bartke 2018; Brown, Alexander, and Rounsevell 2018).
Demand for urban land is not subject to competition with other land uses	Urban land is allocated externally to the model and acts as a mask for land use change within CRAFTY.	As a relatively small but essential land cover, urban land is likely to take precedence and is not currently modellable in the CRAFTY framework
Protected Areas can be represented as spatial constraints on the intensity of land management	Protected Areas are classified into two levels and used to constrain land use transitions between levels of intensity.	No fixed rules for land use change exist in most British protected areas but limits on intensification are consistent with objectives for environmental protection

Emergence. Emergent effects that could be observed as outcomes of experiments using CRAFTY-GB are spatially explicit changes to land ownership and management, the intensification of land uses, including mono- or multi-functional land uses, changes in productivities and yields of different land uses, and total supply levels.

Adaptation. Individual agents in CRAFTY-GB do not adapt their rules during a simulation run. However, the agent population adapts to changing conditions, and individual variation allows for adaptation in behavioural characteristics within types. Social interaction allows for indirect adaptation through alteration of capital values, allowing land management decisions to evolve and affect one another over time and space.

Learning. Agents can learn from neighbours to whom they are associated in social networks. This learning takes the form of improvements in capitals (e.g. representing knowledge), production or competitiveness, and is scaled by the degree of social networking.

Fitness. Agents' survival in the system depends upon their *competitiveness*, which is determined by an agent's ability to contribute to services for which unmet demands exist.

Prediction. CRAFTY-GB allows for contingent, explorative prediction only – i.e. it provides realisations of outcomes given the set of input conditions and model design. It does not represent an attempt to predict real-world outcomes, although model results can speak to what these real-world outcomes might be, when properly interpreted.

Sensing. Agents in CRAFTY-GB are aware of current demand levels and the production levels required if they are to avoid giving up their cells. They use the capital levels (attributes of a cell) to produce supply of services based on their respective production functions. Potential agents are aware of a defined number of abandoned/vacant cells that they may occupy depending upon their competitiveness. Agents are aware of the competitiveness of other agents in a region and may relinquish their cells to agents that are more competitive. Social networks allow agents to implicitly become aware of advantageous management practices used by their neighbours.

Interaction. Direct interactions occur between new ('potential') and existing agents that compete for cell ownership. Interactions also occur within social networks, allowing changes to production conditions to be shared.

Stochasticity. Agents can have individual variation in giving-up and giving-in threshold parameters, levels of service production, and the importance of each capital to service provision (each agent will have the same values throughout its lifetime, however). The allocation model includes stochasticity (representing agent-heterogeneity) as new agents consider only a limited number of cells on the grid, and the identity of these cells depends upon the random number seed being used. When giving-up probabilities are non-zero, there is stochasticity in giving-up events because the threshold is checked against a randomly drawn value.

Collectives. Two types of 'passive' agent collectives exist during a course of a simulation run. First is the list of agents that possess land parcels (cells) in a simulated landscape (grid), which can be global or regional in nature (covering the entire modelled land surface or some portion of it). Second is the list of potential agents that enter the system to takeover cells from existing agents (if possible) or occupy a vacant or abandoned cell on the grid. 'Active' collectives are those formed through social networks of neighbouring agents, defined by geographical proximity.

Observation. CRAFTY-GB can provide a range of observations and displays to help understand the model behaviour. Each of the submodels has a display, which is either numeric or graphical, showing curves for variables of note. A range of spatially explicit outputs is also available; these include maps of agent types, capital levels, competitiveness scores and supply of services. Any of these displays can be used to create videos of the model's behaviour over time. Output of a number of simulation data is possible in CSV or raster files. Table 4 gives an overview.

Table 4: CRAFTY output matrix

Data	CSV	Raster	Agg.CSV	GUI	Video
Agent ID	✓	-	-	×	-
LandUseIndex	✓	✓	✓	✓	✓
Capital levels	✓	✓	×	✓	✓
Service Demand	-	-	✓	✓	✓
Service Supply	✓	✓	✓	✓	✓
Productivity	✓	✓	×	✓	✓
Service Product.	✓	×	×	✓	×
Competitiveness	✓	✓	×	✓	✓
Giving In Thresh.	✓	×	×	✓	×
Volatility	×	✓	×	×	×
TakeOvers	×	-	✓	×	×
Performed Actions	✓	✓	×	×	×

5. Initialization

Initialisation proceeds through a set of interlinked XML and CSV files to allow the model's configuration by non-programmers. XML files define basic simulation parameters and provide properties for the initialisation of model components coded as Java objects, while CSV files provide data when there are many values required. The approach is highly flexible and extendable.

CRAFTY-GB initialises by reading the Scenario.xml file and follows the links therein to the configuration of outputs and the world configuration, which in turn contains links to regions and these to their model components like agent types, the competition model being used, or the allocation model. A cell.csv file includes the coordinates and capital levels of the cells in a region, the initial allocation of agents on these cells, and agent properties that are applied when these agents are initialised. Figure 2 gives an overview of a standard setting of XML and CSV files.

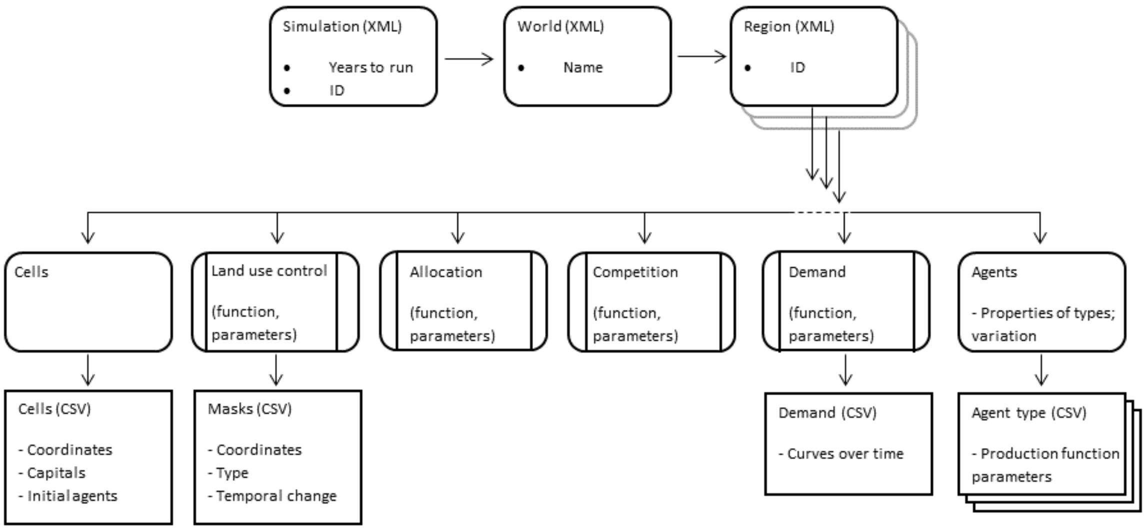


Figure 2: Overview of model configuration, showing relationships between files and what each file provides.

6. Input data

Capital levels.

Capitals are divided into human, social, manufactured, financial and natural capitals, with natural capital further divided into yields or suitabilities for arable, pastoral and forest land uses or species. For CRAFTY-GB, social, human, financial and manufactured capitals were derived from UK-SSP projections of eight socio-economic indicators from (Merkle et al. 2022) (Table 5). Natural capitals were created in two distinct steps. Forest suitabilities were modelled using the Ecological Site Classification (ESC) model originally developed by (Pyatt, 1995) and since used frequently in forestry modelling for the UK (Forest Research 2021). This model uses data on accumulated temperature, continentality, wind risk, moisture deficit, soil moisture regime, and soil nutrient regime to predict biophysical suitability and associated potential yield class (timber growth) for a range of tree species. In the scenarios, these data were derived from UK-specific RCPs (Robinson et al. 2022) (Table 6).

To project land suitability for arable and pastoral land a General Additive Model (GAM; Hastie & Tibshirani, 1990) was produced to link land cover classes from Land Cover Map 2015 (Rowland et al., 2017) to UK-RCP covariates. Land Cover target class 3 (arable) and 4 (improved Grassland) were used as the training maps for arable and improved grassland, respectively, whilst semi-natural grassland was trained on LCM target classes 5-7, 9 and 10 (neutral, calcareous and acid grassland; heather; and heather grassland). UK-RCP-derived bioclimatic variables for growing degree days (GDD), minimum and maximum temperature, and soil moisture deficit (SMD) and surplus (SMS) were used as covariates, following Pearson et al. (2004). Urban areas were masked out in advance of model training. The baseline map of arable suitability was further processed to take into consideration changes in agricultural yields through time as modelled by the IMPRESSIONS European integrated assessment model (Harrison et al., 2019) and these augmented arable layers were used as a capital layer within CRAFTY-GB. The two grassland suitability maps were used directly as capital layers within CRAFTY-GB.

Table 5: Description of socio-economic capitals. For each of the capitals, individual values per area and time slice were formed as means between two indicator variables and subsequently normalised to [0,1]. Values between decades were interpolated. Full details of the indicator variables underlying the socio-economic capitals are given in (Merkle et al. 2022). Natural capital, split into 11 suitabilities, is described in 6.

Capital	Indicator Variables	Linear Rescaling Thresholds				
		Very Low [0 ; 0.2]	**Low [0.2 ; 0.4]**	**Medium [0.4 ; 0.6]**	**High [0.6 ; 0.8]**	**Very High [0.8 ; 1]**
Social	Income quintile ratio (S80/S20)	60 ; 25	25 ; 10	10 ; 5	5 ; 2	2 ; 1
	Proportion of people who agree to "people around here are willing to help their neighbours"	0 ; 30	30 ; 50	50 ; 70	70 ; 90	90 ; 100
Human	Life expectancy at birth	30 ; 50	50 ; 60	60 ; 70	70 ; 80	80 ; 110
	Proportion of people aged 25 – 64 with tertiary education	0 ; 10	10 ; 20	20 ; 30	30 ; 45	45 ; 80
Financial	Household Income per capita [EUR PPS]	0 ; 5	5 ; 10	10 ; 25	25 ; 50	50 ; 80
	Proportion of people who agree to "I can save any amount of my income"	0 ; 20	20 ; 30	30 ; 40	40 ; 50	50 ; 100
Manufactured	Gross Fixed Capital Formation per Area [mEUR/km^2]	0 ; 0.75	0.75 ; 1.25	1.25 ; 3	3 ; 10	10 ; 500
	Average of total speed-weighted road length [Speed-weighted km/km^2]	0 ; 0.1	0.1 ; 0.2	0.2 ; 0.3	0.3 ; 1	1 ; 4

Table 6: Description of suitabilities comprising natural capital. All are normalised to a [0,1] scale at baseline and are linked to empirical production values through supply normalisation (described below). Abbreviations are as follows: GAM - General additive model; LCM – Land Cover Map: IAP – Integrated Assessment Platform; ESC – Ecological Site Classification.

Suitability	Explanation	Source/reference
Arable suitability	GAM-projected arable suitability index (0 to 1) based on relationship between bioclimatic covariates and LCM target class 3, modified by changes in arable yields from IMPRESSIONS integrated model.	GAMs (Hastie and Tibshirani, 1990) LCM 2015 (Rowland et al., 2017) IMPRESSIONS IAP (Harrison et al., 2019) Biophysical covariates Pearson et al. (2002).
Improved grassland suitability	GAM-projected semi-natural grassland suitability (0-1 index) based on relationship between bioclimatic covariates and LCM target class 4.	
Semi-natural grassland suitability	GAM-projected semi-natural grassland suitability (0-1 index) based on relationship between bioclimatic covariates and LCM target classes 5-7,9 and 10.	
Natural: Short Rotation Coppice (SRC) suitability	ESC modelling: Willow yield	ESC (Forest Research 2021)
Natural: Agro-forestry tree suitability	ESC modelling: Sycamore yield	
Natural: Non-native conifer suitability	ESC modelling: Sitka spruce yield	
Natural: Non-native broadleaf suitability	ESC modelling: Beech yield	
Natural: Native conifer suitability	ESC modelling: Scots pine yield	
Natural: Native broadleaf suitability	ESC modelling: Sessile Oak yield	
Natural: Native broadleaf suitability	ESC modelling: Silver Birch yield	
Natural: General tree species suitability	ESC modelling: Combination of all other yields	

Protected areas

Protected areas belonging to 11 different types of national and international designation and to 5 different private land-owning organisations (NGOs) were included in the model (Table 7). Each protected area was first categorised into IUCN Protected Area Management Categories according to the existing categorisation of the IUCN National Committee United Kingdom (2012) or, where no existing categorisation was found, according to landowners' stated objectives. Two broad levels of protected area emerged from this classification: IUCN category IV and V areas where many forms of land use are found (all of the officially designated protected areas in the UK), and IUCN category II areas where land use is more tightly controlled (most of the NGO-owned protected areas). We therefore adopted two forms of constraint within the protected areas, with all land use except the most intensive being permitted in the first group, and no land use change except to the most extensive or conservation management permitted in the second. We also prevented land use change on areas classified as water, bare rock, coastal sediment and marsh in the baseline land use map. Institutions were used to enforce land use protections, and were represented as having complete power and knowledge.

Table 7: Types of protected area included in the model, their equivalent IUCN ranking (taken from IUCN National Committee United Kingdom (2012) or determined based on management objectives), data sources and the modelled constraint each type of protected area places on land use change.

Type of protected area	IUCN category	Data source	Effect in CRAFTY-GB
International			
Biosphere Reserves	IV	(UNESCO 2017)	Not intensive
Ramsar site	IV	(JNCC 2020)	
Special Area of Conservation (SAC)	IV		
Special Protection Area (SPA)	IV		
National			
Area of Outstanding Natural Beauty (AONB)	V	(Natural England, 2020a; Natural Resources Wales, 2021a)	Not intensive
Site of Special Scientific Interest (SSSI)	IV	(Natural England, 2021c; Natural Resources Wales, 2020; SNH, 2020)	
Heritage Coast (HC)	V	(Natural England, 2017; Natural Resources Wales, 2017a)	
Local Nature Reserve (LNR)	IV	(Natural England, 2021a; Natural Resources Wales, 2018; Scottish Government, 2020a)	
National Nature Reserve (NNR)	IV	(Natural England, 2021b; Natural Resources Wales, 2021b; Scottish Government, 2020b)	
National Park (NP)	V	(Natural England, 2020c; Natural Resources Wales, 2017b; Scottish Government, 2021a, 2021b)	
National Scenic Area (NSA)	V	(Scottish Government, 2021c)	
NGOs			
John Muir Trust (JMT)	II	JMT, personal communication	No Change
National Trust / National Trust for Scotland (NT/NTS)	V	(National Trust, 2021; National Trust for Scotland, 2015)	
RSPB	II	(RSPB, 2021)	
Scottish Wildlife Trust	II	(Scottish Wildlife Trust, 2016)	
Other NGO	II	Trees for Life, personal communication	

Land uses (agent types).

CRAFTY-GB includes a range of agent types designed to capture the main forms of land use in Great Britain, including gradations of intensity and multi-functionality. Agent types were divided between arable land uses (intensive arable for food, intensive arable for fodder, sustainable arable and extensive arable), pastoral land uses (intensive pastoral, extensive pastoral, very extensive pastoral), forest land uses (productive native conifer, productive non-native conifer, productive native broadleaf, productive non-native broadleaf, multifunctional mixed woodland and native woodland for conservation), and combined classes (bioenergy and agroforestry) (Table 8). Variation in ecosystem service provision within these classes allows them to represent a continuous range of forms of land management rather than arbitrarily distinct groups.

Allocation of the initial distribution of land uses was based on the 2015 Land Cover Map (LCM2015) produced by the UK Centre for Ecology & Hydrology (2016) (Rowland et al., 2017) and the National Forest Inventory (NFI) 2010-2015 (Forestry Commission 2021). Further datasets were used to define the extent and location of specific land uses, and full details are given in Table 8. Urban areas were derived from land cover data at the baseline (LCM 2015) and then projected in the scenarios by an independent urban model (described in detail in Merkle et al., in review). This model created 1km gridded urban surface projections through a newly developed urban allocation algorithm based on a neighbourhood density function, SSP-specific sprawl parameter settings, and SSP-specific land exclusions of protected areas and flood risk areas. Land not otherwise used was modelled as unmanaged.

In some cases, input data were incomplete and had to be further processed before being used. This was true of some coastal areas and islands (particularly estuaries and the Shetland isles). Data gaps in Shetland were filled using a regression model using topographic variables (i.e. elevation, slope, and aspect) trained upon the data of the nearest Orkney island. Gaps in coastal areas were filled using nearest-neighbour values. We also used 5x5 moving average interpolation to smooth hard boundaries between administrative units in the capitals. Finally, where scenario input data for 2020 were not consistent with baseline data, those data series were normalised by the equivalent baseline values.

Table 8: Allocation of initial distribution of land uses. Levels of intensity are assigned discretely in terms of agent types, but modelled continuously across these types according to availability and usage of agricultural inputs and production levels.

Land use (agent)	**Notes**	**Initial allocation**
Intensive arable (food)	Farmers managing intensively for crop production for food.	Allocated to LCM2015 aggregate class 'Arable'. Food and fodder types distributed randomly within that according to (modelled) baseline demand levels to provide the required amount of each
Intensive arable (fodder)	Farmers managing intensively for crop production for livestock fodder, ultimately producing meat and milk.	
Sustainable arable	Farmers managing organically or otherwise less intensively for crop production for food	Allocated to LCM2015 aggregate class 'Arable' to give an area coverage equal to the 2015 area of organic arable in the UK (as reported by (DEFRA 2016a), with specific cells chosen spatially randomly
Extensive arable	Farmers managing with few inputs for limited crop production for food; equivalent to subsistence production where capitals are very low	Allocated to the LCM2015 aggregate class 'Arable' cells within the lowest 10% of modelled suitability for arable crops
Intensive pastoral	Farmers managing intensively for livestock	LCM2015 Improved grassland
Extensive pastoral	Farmers managing extensively for livestock on semi-natural grassland	LCM2015 Semi-natural grassland
Very extensive pastoral	Minimal management involving some grazing	LCM2015 Mountain, heath, bog and LCM2015 Semi-natural grassland (Fen Marsh Swamp)
Bioenergy	Dedicated production of Short Rotation Coppice / Miscanthus	Assigned to LCM2015 aggregate class 'Arable' to cover the 2015 extent of arable bioenergy land (DEFRA 2016b), assigned to locations of Energy Crops Scheme (Tranche 2) agreements 2013-2015 (Natural England 2020b)
Agroforestry	Farmers practicing silvo-pastoral or silvo-arable forms of agroforestry, combining trees with either grazing or crops, for timber, crop and livestock production.	NFI 'low-density' class when otherwise unassigned.
Productive non-native conifer	Production-focused forest managers with non-native conifer plantations. Primary objective is softwood timber production.	LCM2015 Coniferous woodland class, sub-divided by NFI Conifer class, located where modelled suitability is higher for non-native than for native species
Productive non-native broadleaf	Production focused forest managers with non-native broadleaf plantations. (Not currently common, but felt to have potential importance in the future). Primary objective is hardwood timber production.	LCM2015 Broadleaf woodland, sub-divided by NFI broadleaf class, located where modelled suitability is higher for non-native than for native species
Productive native conifer	Production focused forest managers with native conifer plantations. Primary objective is softwood timber production.	LCM2015 Coniferous woodland, sub-divided by NFI Conifer class, located where modelled suitability is higher for native than for non-native species
Productive native broadleaf	Production focused forest managers with native broadleaf plantations. Primary objective is hardwood timber production.	LCM2015 Broadleaf woodland, sub-divided by NFI broadleaf class, located where modelled suitability is higher for native than for non-native species.
Multifunctional mixed woodland	Forest managers with mixed woodlands and multiple objectives practising low-intensity management	LCM2015 Broadleaf or Coniferous woodland, subdivided by NFI mixed classes
Native woodland (conservation)	Conservation focused forest managers. Primary objective is to conserve biodiversity.	LCM2015 Broadleaf or coniferous woodland, excluding NFI classes indicating active management or no forest cover, and located where modelled broadleaf suitability is within the lowest 50% or modelled conifer suitability is within the lowest 10%
Urban	Urban and industrial areas	Modelled separately
Unmanaged	Represents areas with minimal to no management, often where biophysical conditions preclude significant productivity e.g. high montane or deep peat areas	Unassigned cells

Services and demand levels.

A range of provisioning, regulating and cultural ecosystem services and other indicators (e.g. biodiversity, employment) of relevance to the UK-SSP scenarios were modelled. These services are defined in Table 9, and their provision by different agent types based on capital levels is given in Brown et al. (2022). In this implementation, the relative calibration of service provision is approximate and largely assumption-based, though informed by empirical or modelled evidence where possible.

Table 9: Goods and services modelled in CRAFTY-GB.

Services	**Details**
Food crops	Crops for human consumption
Fodder crops	Crops for consumption by ruminant and monogastric livestock
Grass-fed meat	Red meat produced in pastoral systems
Grass-fed milk	Milk produced in pastoral systems
Bioenergy fuel	Bioenergy crops; short rotation coppice & miscanthus
Softwood	Softwood (conifer) timber
Hardwood	Hardwood (broadleaf) timber
Biodiversity	Biological diversity
Landscape diversity	Diversity of landscape elements
Carbon sequestration	Quantity of carbon sequestered (above & below ground)
Recreation	Recreation potential
Flood Regulation	Land ability to store water
Employment	Potential for employment associated with land management
Sustainable production	Abstract service providing sustainability in agriculture

In modelling production of crops and livestock products, we assume divisions between crop production for direct human consumption, crop production for livestock consumption, and grass-fed livestock production. We assume that pastoralist agents produce grass-fed milk (intensive pastoral only) and red meat, while 'arable for fodder' agents effectively produce crop-fed red and white meat, and milk. Monogastrics are gramivores, so are fed only from cropland. Evidence for production levels includes an existing application of the CRAFTY framework to Scotland (Burton et al., in prep), and literature evidence on ecosystem services provision in different land use types (Burton et al., 2018; Rolo et al., 2021).

Non-food demands were taken from the stakeholder-defined scenarios, and are described in (Merkle et al. 2022). Demand levels for foods were derived from the LandSyMM (Land System Modular Model; www.landsymm.earth) global modelling framework (Rabin et al., 2020). Within LandSyMM, the dynamic global vegetation model LPJ-GUESS simulates physiological, demographic, and disturbance processes for a variety of plant functional types (Smith et al., 2014), while the land use model PLUM simulates land use and management based on global trade and cell-level (0.5°) productivity (Alexander et al., 2018). Food demand was calculated from scenario projections of country-level population and gross domestic product (GDP), using the historical relationship of per capita GDP to consumption of each of six crop types – C3 cereals, C4 cereals, rice, oil crops, pulses, and starchy roots – plus ruminant and monogastric livestock. Separate demand levels were calculated for food crops for human consumption and for feed for monogastric livestock and ruminant livestock not raised on pasture. Both types of demand account for crops used for processing, seed stocks, and for losses sustained during the production process. Demands were also adjusted to take account of imports and exports, as calculated by PLUM.

In the case of CRAFTY-GB, the total food production of the UK simulated by LandSyMM was taken as the national demand (i.e. aggregated from the 0.5° grid that LandSyMM uses). Because the simulated LandSyMM baseline (representing the year 2020) is not based on land cover data, while the baseline land allocation of CRAFTY-GB is, all LandSyMM demands were normalised relative to their 2020 values, giving a continuous series of annual changes in demand levels as proportions of 2020 demand.

First the domestic production of feed and food crops was calculated. Food crops scale with the production of agents in CRAFTY, from a baseline quantity of 35.65 Mt of crops (an average of 771 tonnes for each of the 46,252 purely arable agents in CRAFTY-GB at the baseline, including subsequent losses, processing and seeds etc.). Feed crops were converted to livestock products through product-specific Feed Conversion Ratios taken from (Alexander et al., 2016). Monogastrics are fed exclusively on these feed crops (including those imported), meaning that the demands for Mt of pork, poultry and eggs could be immediately converted into demands for Mt of feed crops. Ruminant livestock (according to demands for Beef, Mutton, Goat and milk) were similarly converted, and the remaining available feed crops were assigned proportionally to them. Leftover demand for these livestock products was converted to a pasture demand by scaling from the baseline, and for comparison by using an additional pasture food conversion ratio.

Services and demand levels

We use combinations of the Representative Concentration Pathways (RCP) climate scenarios (van Vuuren et al., 2011) and Shared Socioeconomic Pathways (SSP) socio-economic scenarios (O'Neill et al. 2017). A combined set of these scenarios was specified for the British context through a combination of stakeholder engagement and computational or statistical modelling.

The SSPs were specified for the UK as described in Pedde et al. (2021), (Harmáčková et al. 2022) and (Merkle et al. 2022). These substantial extensions of the global SSPs provide detailed narratives of social, economic and political developments across the UK until 2100. The narratives integrate national stakeholder knowledge on locally-relevant drivers and indicators with higher level information from the European and global SSPs. These narratives were simplified and converted into model parameterisations, and SSPs were put in a global context through LandSyMM global land system modelling to provide consistency with the broader SSP framework and to account for the UK's international trade.

Climatic conditions are taken from the CHESS-SCAPE data set, which provides several climate variables at 1 km^2 spatial resolution and several temporal resolutions, from daily to decadal. CHESS-SCAPE is derived from the 12 km^2 resolution UKCP18 regional predictions for the UK. UKCP18 regional predictions were obtained by running a perturbed parameter ensemble of a regional climate model (RCM), nested within a global climate model (GCM) for RCP8.5 (Murphy et al., 2018). CHESS-SCAPE was derived from this regional data set by: (i) downscaling from 12 km^2 to 1 km^2 using a modified version of the CHESS methodology (Emma L. Robinson, Blyth, Clark, Finch, et al. 2017); (ii) bias-correcting to observed historical climate using the CHESS-met dataset (Emma L. Robinson, Blyth, Clark, Comyn-Platt, et al. 2017); and (iii) time-shifting and pattern scaling to provide RCPs 2.6, 4.5 and 6.0, using members of the CMIP5 ensemble to define target trajectories of global temperature change (Taylor et al., 2012). Full details can be found in (E. L. Robinson et al. 2022). The highest temporal resolution of CHESS-SCAPE is daily. From these were calculated 20-year mean-monthly climatologies, at a 10-year time-step, giving spatially and temporally explicit values for several climate variables for the UK, including temperature and precipitation. The climate variables were used to calculate Penman-Monteith potential evapotranspiration with interception correction (PETI), following the method of Robinson et al. (2017). This is potential evapotranspiration calculated for a short grass, with a correction applied on rain days to account for the greater efficiency of evaporation of water from the canopy surface before it can reach the soil. The air temperature was used to calculate growing degree days (GDD), which is a count of the number of days for which mean air temperature was greater than 5°C. The air temperature, precipitation, PETI and GDD were then used as inputs to the crop, grassland and forest modelling to produce annual scenario-specific capital values.

7. Submodels

Allocation Model. Land ownership within CRAFTY-GB changes according to three different mechanisms, which simulate both individual and collective aspects of land use dynamics. Firstly, agents may leave the model owing to a competitiveness score that falls below an agent's giving-up threshold. Secondly, when land is unmanaged, due to abandonment or lack of managers, it can be taken over by a newly created agent. By default, the set of potential agents is evaluated to determine their competitiveness score on each unmanaged cell ($c_{a,i}$). The agents are sampled such that the probability of an agent of type a attempting to take over a cell scales with its competitiveness on a cell with 'perfect' capital levels; $P(a) \propto {c_{a,i}}^{\gamma}$, where γ=0 gives a random selection and $\gamma \rightarrow \infty$ tends towards optimal selection. For more general land use transitions, an allocation procedure runs between existing and potential agents to determine ownership changes. This can include direct competition, where incoming agents attempt to take over existing cells; such an attempt succeeds where new agent has a competitiveness on the cell greater than or equal to the existing agent's competitiveness plus giving in threshold: $c_{new} \geq c_{curr} + giving\_up_{curr}$. Different allocation models are possible, however, and can be used to explore the relationships between human behaviour and local or global optimality. Once an agent is located, we assume it does not change location, due to the large costs involved.

Production function. Each agent has a production function, which maps capital levels onto service provision:

(1) $$P_S = F_A(C_i)$$

There is no limitation on the form of this function, but here a Cobb-Douglas style function is used to combine optimal production levels (o_s) with dependence on each capital to give service productivity:

(2) $$p_s = o_s \prod_C {c_i}^{\lambda_c} \;;$$

where λ_c is a weighting factor specific to capital c.

Population, Services, Demand and Utility. We assume that there is a population present in any given region with a level of demand for services D. At the same time, there is a supply of these services from within the region, and the difference between the two is the residual (or unmet) demand, R. The marginal utility of production (i.e., the utility attributed to the production of one additional unit of a service) is a function of this residual demand:

(3) $$m_s = u_s(r_s);$$

where m_s is the marginal utility, u_s is a function that describes the utility of production, and r_s is the residual demand, for service s. The form of the function u_s is linear by default. For a given bundle of service provision, an agents' competitiveness (or utility) is given by:

(4) $$U_S = \sum_S p_s m_s$$

3 Data evaluation

This TRACE element provides supporting information on: The quality and sources of numerical and qualitative data used to parameterize the model, both directly and inversely via calibration, and of the observed patterns that were used to design the overall model structure. This critical evaluation will allow model users to assess the scope and the uncertainty of the data and knowledge on which the model is based.

Summary:

CRAFTY-GB makes use of a range of datasets from different sources. These are summarized here, along with pre-existing evaluation exercises of those datasets. Model development did not involve any additional evaluation of data, and only a small amount of calibration to data (as described below). Model structure was based on a conceptual design (see Section 4) rather than patterns in data.

Data used in CRAFTY-GB are summarized in Table 10, along with their sources and any known evaluation exercises. In most cases, these data formed direct input to the model. Some calibration to data was carried out by running the model without any baseline land use data (i.e. from an empty map) and comparing the resultant numbers and distributions of agents with those contained in the baseline land use data (as in Brown, Seo, and Rounsevell 2019). This comparison was used to check the parameterization of agent types, with some adjustments made to ensure that parameters were not unrealistic in their effects. No agreement target was used because real-world land use patterns are long-term products of numerous factors and processes not contained in the model, but movement towards observed land use distributions was interpreted as improvement. Four rounds of this calibration exercise were carried out, before the modelling team agreed that parameter values had no obvious inconsistencies with the data.

Table 10: Input data for CRAFTY-GB, their sources and details of evaluation. Input data that are purely assumption-based are not described here.

Data type	Data coverage	Specific variables	Source	Evaluation
CAPITALS	Social capital	Income quintile ratio (S80/S20)	OECD, 2011	Data subject to detailed evaluation by OECD and EU member states (UK in this case) (EUROSTAT 2013; OECD 2013)
		Proportion of people who agree to "people around here are willing to help their neighbours"	UKHLS, 2015	Data subject to detailed evaluation described in (Lynn and Knies 2016)
	Human capital	Life expectancy at birth	ONS, 2018	Data subject to detailed evaluation described in (ONS 2017)
		Proportion of people aged 25 – 64 with tertiary education	Eurostat, 2019	Data subject to standardised EUROSTAT evaluation procedures (EUROSTAT 2018, 2022)
	Financial capital	Household Income per capita [EUR PPS]	ONS, 2017	Data subject to detailed evaluation described in (ONS 2022)
		Proportion of people who agree to "I can save any amount of my income"	UKHLS, 2017	Data subject to detailed evaluation described in (Lynn and Knies 2016)
	Manufactured capital	Gross Fixed Capital Formation per Area [mEUR/km^2]	Eurostat, 2017	Data subject to standardised EUROSTAT evaluation procedures (EUROSTAT 2018, 2022)
		Average of total speed-weighted road length [Speed-weighted km/km^2]	GRIP, 2015	Data subject to validation as described in (Meijer et al. 2018)
	Natural capitals	Arable suitability	Developed for this model; method described in Brown et al. (2022)	Statistical evaluation as described in Brown et al. (2022)
		Improved grassland suitability	Developed for this model; method described in Brown et al. (2022)	Statistical evaluation as described in Brown et al. (2022)
		Semi-natural grassland suitability	Developed for this model; method described in Brown et al. (2022)	Statistical evaluation as described in Brown et al. (2022)
		Tree species suitabilities	ESC (Forest Research 2021)	No single evaluation or validation protocol; piecemeal evaluation and improvement over 20 years of model usage (Forest Research 2021; Pyatt 1995)
LAND COVER	UK land cover	Land cover classes, locations	(UK Centre for Ecology & Hydrology 2016)	Validated as described by UK Centre for Ecology & Hydrology (2016)
	National Forest Inventory	Forest classes, locations	(Forestry Commission 2021)	Validated primarily through on-the-ground surveys, as described by Forestry Commission (2021)
	Crop type areas	Total area of organic crops, total area of arable bioenergy	(DEFRA 2016a, 2016b)	Largely survey-based, evaluated as described in by DEFRA (2016a, 2016b)
	Energy crop locations	Locations of Energy Crops Scheme (Tranche 2) agreements 2013-2015	Natural England (2020b)	Based on direct records of scheme uptake locations
PROTECTED AREAS	Protected area locations	Biosphere Reserves	(UNESCO 2017)	All Protected Area data are direct records of area boundaries (shapefiles) and therefore were not evaluated
		Ramsar site, Special Area of Conservation (SAC), Special Protection Area (SPA)	(JNCC 2020)	
		Area of Outstanding Natural Beauty (AONB)	(Natural England, 2020a; Natural Resources Wales, 2021a)	
		Site of Special Scientific Interest (SSSI)	(Natural England, 2021c; Natural Resources Wales, 2020; SNH, 2020)	
		Heritage Coast (HC)	(Natural England, 2017; Natural Resources Wales, 2017a)	

		Local Nature Reserve (LNR)	(Natural England, 2021a; Natural Resources Wales, 2018; Scottish Government, 2020a)	
		National Nature Reserve (NNR)	(Natural England, 2021b; Natural Resources Wales, 2021b; Scottish Government, 2020b)	
		National Park (NP)	(Natural England, 2020c; Natural Resources Wales, 2017b; Scottish Government, 2021a, 2021b)	
		National Scenic Area (NSA)	(Scottish Government, 2021c)	
		John Muir Trust (JMT)	JMT, personal communication	
		National Trust / National Trust for Scotland (NT/NTS)	(National Trust, 2021; National Trust for Scotland, 2015)	
		RSPB	(RSPB, 2021)	
		Scottish Wildlife Trust	(Scottish Wildlife Trust, 2016)	
		Other NGO	Trees for Life, personal communication	
BEHAVIOURS	Social network extent	Radius of influence between agents	Brown et al. (Calum Brown, Alexander, and Rounsevell 2018)	Based on values generated and evaluated in the analysis of Brown et al. (Brown, Alexander, and Rounsevell 2018)
PRODUCTION & DEMAND LEVELS	Food production	Crop production	Derived from the LandSymm global model (Rabin et al. 2020)	Extensively evaluated as described in (Rabin et al. 2020; Alexander et al. 2018)
		Livestock production	Derived from the LandSymm global model (Rabin et al. 2020) and feed conversion ratios of (Alexander et al. 2016)	Extensively evaluated as described in (Rabin et al. 2020; Alexander et al. 2018, 2016)
	Ecosystem service provision	Timber & fuel production	Dependent on natural capitals, as described above	Evaluation as described under natural capitals in this table
		Biodiversity, carbon, recreation, flood regulation & employment provision	Qualitatively based on literature findings	No direct evaluation, but comparison and interpretation of literature values (e.g. Burton et al. 2018; Rolo et al. 2021)
	Food demands	Crop & livestock product demands	Derived from the LandSymm global model (Rabin et al. 2020) and feed conversion ratios of (Alexander et al. 2016)	Extensively evaluated as described in (Rabin et al. 2020; Alexander et al. 2018, 2016)
SCENARIOS	All scenario-dependent model inputs	Capital levels, behaviours, production and demand levels, ecosystem service valuations	Stakeholder-derived, as described in Pedde et al. (2021), (Harmáčková et al. 2022) and (Merkle et al. 2022)	Participatory stakeholder evaluation; see Pedde et al. (2021), (Harmáčková et al. 2022) and (Merkle et al. 2022)

4 Conceptual model evaluation

This TRACE element provides supporting information on: The simplifying assumptions underlying a model's design, both with regard to empirical knowledge and general, basic principles. This critical evaluation allows model users to understand that model design was not ad hoc but based on carefully scrutinized considerations.

Summary:

Conceptual model evaluation has taken the following main forms:

- **The fundamental conceptualization of the system, represented by the CRAFTY framework, has been described in detail and justified on the basis of empirical knowledge and basic principles, in a number of publications. It is evaluated for the case of CRAFTY-GB in this document.**
- **The widespread application of the CRAFTY framework has provided a number of tests of conceptual model utility.**
- **The relevance of the conceptual model to the problem that CRAFTY-GB addresses is also evaluated here.**
- **The conceptual division of British land uses into agent functional types has been evaluated with respect to underlying habitat classes.**

A conceptual model evaluation is presented in Table 3 above, detailing the assumptions embedded in CRAFTY-GB as well as justifications for them on the basis of qualitative and quantitative information. This is a general justification, and not specific to the particular purpose of CRAFTY-GB. As such, it complements existing conceptual model evaluations of the CRAFTY framework given in (Brown, Brown, and Rounsevell 2016; Rounsevell, Robinson, and Murray-Rust 2012; Arneth, Brown, and Rounsevell 2014; Murray-Rust et al. 2014).

The relevance and value of this conceptual design has been assessed in various ways in publications applying the CRAFTY framework. CRAFTY has been applied in a number of theoretical or abstracted case studies (Murray-Rust et al. 2014; Arneth, Brown, and Rounsevell 2014; Brown et al. 2014; Brown, Holzhauer, and Metzger 2018; Synes et al. 2019; Urban et al. 2021; Holzhauer, Brown, and Rounsevell 2019), and to real-world studies in Yunnan Province, China (Synes et al. 2016), Sweden (Blanco, Holzhauer, et al. 2017; Blanco, Brown, et al. 2017), Scotland (Burton et al., in prep), Europe (Brown, Seo, and Rounsevell 2019; Brown, Holman, and Rounsevell 2021), Brazil (Millington et al. 2021) as well as Great Britain (Brown et al., in review). Not all of these applications contain formal conceptual model evaluations, but each speaks to the relevance of the model to particular research questions, and the fit of model assumptions to knowledge about real-world systems.

In the specific case of CRAFTY-GB, conceptual model evaluation has focused on the model purpose (Section 1), the main objective being **to allow exploration of British land system change under a wide range of climatic and socio-economic scenarios**. The ability of the conceptual model to capture scenario characteristics is therefore of paramount importance, and is described in detail in Brown et al. (in review). Table 11 below characterizes the fit between conceptual model design and scenario conditions. While the model is not able to represent every aspect of every scenario, it is felt to provide good coverage across a greater range of scenario conditions than existing models founded on more restrictive conceptual designs (see Brown et al. (in review) for further discussion of this).

Table 11: Descriptions of scenarios represented by CRAFTY-GB and the conceptual elements of relevance to each scenario.

Scenario	**Description**	**Conceptual model fit**			
		Behaviour	Capitals	Ecosystem service demands and valuations	Production
SSP1 - Sustainability	UK-SSP1 shows the UK transitioning to a fully functional circular economy as society quickly becomes more egalitarian leading to healthier lifestyles, improved well-being, sustainable use of natural resources, and more stable and fair international relations. It represents a sustainable and co-operative society with a low carbon economy and high capacity to adapt to climate change.	The presence of spatially-defined social networks allows the model to be tailored to social conditions and distinct impacts in each scenario. Land-use-specific decision-making, along with individual-level randomness in production and agent behaviour, allows the nature and rate of land use change to reflect individual, social and political scenario components. Individual-level randomness in production and agent behaviour allows	The presence of socio-economic as well as natural capitals allows the model to respond to the full range of scenario conditions, which directly affect ecosystem service provision. This is a key advantage over models that consider only certain influences on production (e.g. climatic or economic). The ability to mask protected, urban or other areas also allows for direct interventions in simulated land use change independently of capital dynamics	CRAFTY-GB is designed to incorporate a representative range of ecosystem services. The flexible nature of ecosystem service demand levels and valuation functions mean that model responses can reflect scenario-specific preferences for different services and means of providing benefits in return for service provision.	The dependence of production or provision levels on a full range of scenario characteristics (expressed through behaviours, capitals, and demands) as well as any directly-modelled policy interventions (e.g. support for particular land uses) means that production, in principle, varies in line with scenario storylines, rather than being a semi-independent outcome of biophysical conditions. Production of multiple services allows trade-offs at individual and higher levels to be assessed, and ensures that full impacts of land use changes can be accounted for, if ecosystem services are representative.
SSP2 – Middle of the Road	UK-SSP2 is a world in which strong public-private partnerships enable moderate economic growth but inequalities persist. It represents a highly regulated society that continues to rely on fossil fuels, but with gradual increases in renewable energy resulting in intermediate adaptation and mitigation challenges.				
SSP3 – Regional rivalry	The dystopian scenario, UK-SSP3, shows how increasing social and economic barriers may trigger international tensions, nationalisation in key economic sectors, job losses and, eventually a highly fragmented society with the UK breaking apart. It represents a society where rivalry between regions and barriers to trade entrench reliance on fossil fuels and limit capacity to adapt to climate change.				
SSP4 - Inequality	UK-SSP4 shows how a society dominated by business and political elites may lead to increasing inequalities by curtailing welfare policies and excluding the majority of a disengaged population. The business and political elite facilitate low carbon economies but large differences in income across segments of UK society limits the adaptive capacity of the masses.				
SSP5 – Fossil-fuelled development	UK-SSP5 shows the UK transitioning to a highly individualistic society where the majority become wealthier through the exploitation of natural resources combined with high economic growth. It represents a technologically advanced world with a strong economy that is heavily dependent on fossil fuels, but with a high capacity to adapt to the impacts of climate change.				

A final evaluation exercise with relevance to conceptual model design focused on the division of British land uses into agent functional types. This division was evaluated with respect to underlying habitat classes, and so is not only conceptual but also partly practical in nature. This evaluation is described in detail in Brown et al. (in review), and summarized here. First, the extent of agreement between baseline land uses and the underlying input data (Land Cover Map 2015) was assessed. This showed good general agreement between AFTs and LCM land-cover classes, although with large variations across individual grid cells. Second, the extent of EUNIS ecosystem types (European Environment Agency, 2019) within each land use type was examined. Because they are derived from different sources, these two maps were not expected to align closely but to reveal the basic ability of the land use typology to capture ecosystem characteristics. Nevertheless, results showed good agreement between classes in each dataset, but again with large variation within types (as expected, given the range of characteristics allowable in each CRAFTY-GB class). Third, land use types were compared to the 'CEH Land Cover® *Plus*: Pesticides v2.0' and 'CEH Land Cover® *Plus*: Fertilisers 2010-2015 (England)' datasets. These datasets report annual application intensity per km² grid cell of 162 ingredients for pesticides and nitrogen (N), phosphorus (P), and potassium (K) for fertilisers. Once more there was large and expected variation of application levels within individual cells assigned to each land use class, and good agreement of average application levels with land use types. Intensive agricultural AFTs showed the highest application intensities of both pesticides and fertilisers, while the application is substantially lower in extensive AFTs (both arable and pastoral). While this evaluation was not used to calibrate model parameters, it provided some indication that the conceptual design of agent functional types was suitable for capturing land use and ecosystem variations in Britain.

5 Implementation verification

This TRACE element provides supporting information on: (1) whether the computer code implementing the model has been thoroughly tested for programming errors, (2) whether the implemented model performs as indicated by the model description, and (3) how the software has been designed and documented to provide necessary usability tools (interfaces, automation of experiments, etc.) and to facilitate future installation, modification, and maintenance.

Summary:

> **The core code of the CRAFTY framework, used in CRAFTY-GB, has been thoroughly tested, using a combination of unit tests, debugging and sense checks on outputs. Model outputs were also iteratively evaluated during model development to ensure that performance was as expected, and the model description compared to model functioning. The software has been designed with a range of usability tools, including a graphical user interface that updates 'live' as the model runs, an online interface to explore model outputs, and an open-access, documented code base.**

Unit tests were used in the development of the CRAFTY framework, with thorough checks also made on model implementation and performance (Murray-Rust et al., 2014). This ensured that the shared code base is sound for all applications of the framework. In the case of CRAFTY-GB, model performance was also assessed by comparing expected and realized outcomes across a range of parameterisations, though the primary aim here was to check on input data and calibration (as described in Sections 3 and 4 above). This also ensured performance in-line with the model description.

Substantial effort has been put into model usability. By default, CRAFTY provides facilities to graphically control and monitor model parameters, processes and outputs, as well as a range of file types and contents to capture model results. CRAFTY-GB adopts these facilities and therefore can provide a range of observations and displays to help understand model behaviour. Each of the submodels has a display, which is either numeric or graphical, showing curves for variables of note. A range of spatially explicit outputs is also available; these include maps of agent types, capital levels, competitiveness scores and supply of services. Any of these displays can be used to create videos of the model's behaviour over time (see Table 4, above).

The CRAFTY framework code is open-access and documented through ODD protocols as well as informal written descriptions. Installation and usage instructions are also provided. CRAFTY-GB is available through an online interface, where a model description is available to help users interact with pre-generated outputs visualized in a range of figures. All of these usability tools are available via https://landchange.earth/CRAFTY.

6 Model output verification

This TRACE element provides supporting information on: (1) how well model output matches observations and (2) how much calibration and effects of environmental drivers were involved in obtaining good fits of model output and data.

Summary:

Model output verification is of limited relevance for CRAFTY-GB because the model is designed to explore future conditions and relevant observations in historical or present-day settings are unavailable. A limited exercise to compare 'naïve' model runs against land cover data has been performed, but calibration was minimal. CRAFTY-GB reproduces data used in its development (e.g. in terms of stable baseline land uses and service supply levels), but has not been tested against independent data (Section 8).

As described in Section 3, some calibration to data was carried out by running the model without any baseline land use data (i.e. from an empty map) and comparing the resultant numbers and distributions of agents with those contained in the baseline land use data (as in Brown, Seo, and Rounsevell 2019). This comparison was used to check the parameterization of agent types, with some adjustments made to ensure that parameters were not unrealistic in their effects. No agreement target was used because real-world land use patterns are long-term products of numerous factors and processes not contained in the model, but movement towards observed land use distributions was interpreted as improvement. Four rounds of this calibration exercise were carried out, before the modelling team agreed that parameter values had no obvious inconsistencies with the data.

7 Model analysis

This TRACE element provides supporting information on: (1) how sensitive model output is to changes in model parameters (sensitivity analysis), and (2) how well the emergence of model output has been understood.

Summary:

Several analyses have been run on the CRAFTY framework that have relevance to CRAFTY-GB. However, CRAFTY-GB run-times are relatively long (e.g. approx. 9 hours on a consumer workstation), which limits the scope for rigorous sensitivity analyses. Model sensitivity and output emergence has been analysed qualitatively and to a limited extent, as described below, including in terms of model stochasticity.

Sensitivity analyses of the CRAFTY modelling framework underlying the CRAFTY-GB model show that model results are particularly sensitive to capital levels and demand values, with less sensitivity to parameters controlling agent behavior (e.g. Brown, Holzhauer, and Metzger 2018; Murray-Rust et al. 2014). An exception is the level of multifunctional production by agents (i.e. levels of production of more than one ecosystem service), which can have a large effect on the balance among land use classes. In the case of CRAFTY-GB, model sensitivity was not formally assessed, but we made explorative changes and used these for informal evaluation in modelling group. The scenario analysis presented in Brown et al. (in review) was itself a form of sensitivity analysis, and was used to understand main driving factors responsible for model outcomes.

8 Model output corroboration

This TRACE element provides supporting information on: How model predictions compare to independent data and patterns that were not used, and preferably not even known, while the model was developed, parameterized, and verified. By documenting model output corroboration, model users learn about evidence which, in addition to model output verification, indicates that the model is structurally realistic so that its predictions can be trusted to some degree.

Summary:

> **Formal model output corroboration has not been performed for CRAFTY-GB. The model does not produce predictions, and exploratory outputs are for a range of future scenario-based conditions. The relevance of the model to these future conditions is defined in the previous sections of this document. Qualitative comparisons to relevant observed outcomes are presented below.**

CRAFTY-GB's primary purpose is exploratory modelling of future scenario effects on the British land system. As such, it is impossible to verify that model outputs accurately reflect outcomes in those scenarios unless and until one actually occurs. Corroboration of alternative outcomes is possible in principle, for example in historical conditions or (qualitatively) in terms of responses to single drivers. However, these latter options are partially precluded by the absence of sufficiently detailed data. Historical data do not provide comparable, high-resolution time series of land uses, ecosystem service supply or demand levels, without which CRAFTY-GB results cannot be generated and/or assessed. Observations of effects related to single drivers are unavailable due to the concurrent actions of multiple drivers in reality. Nevertheless, checking model outputs qualitatively against independent information is possible and can be informative. Several such comparisons are presented below to enable readers to draw their own conclusions about model reliability.

- Changing demands; it is known that increasing demand for particular services does generate increased production in the land system, and that this tends to occur in more productive areas – as we find. However, there are also various ways that production can increase; for example intensification often follows from demand increases (and extensification from demand decreases) – both of which occur in our model results.
- Food production is generally prioritized in reality, and food supply approximately equals demand. Our valuation of ES is arbitrary but has the equivalent outcome.
- At a basic level, cross-sectoral trade-offs are a major feature of the land system, and can be explored here.
- Consolidation of productive areas and abandonment or change in marginal areas are strong patterns in British land use that are also replicated in the model.
- Low capitals produce inefficient, changeable land systems (SSP3)

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