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

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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).

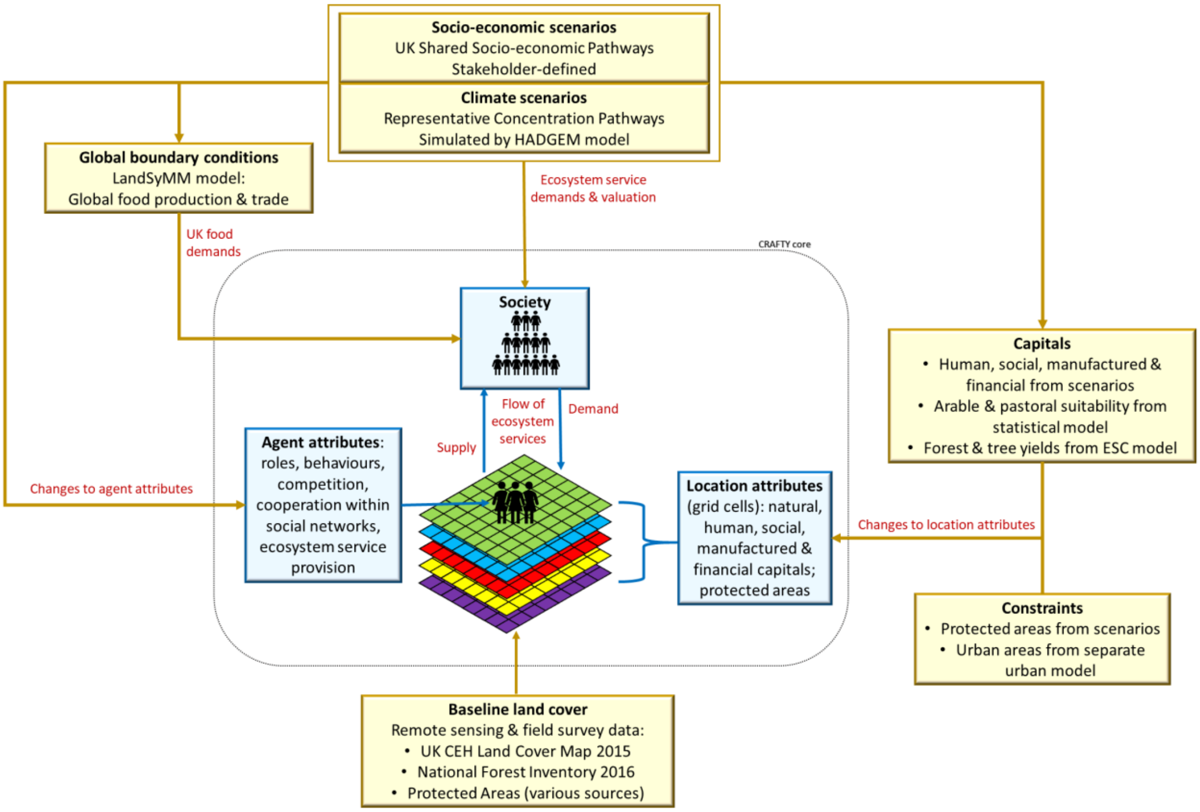

Figure 1.: Schematic diagram of CRAFTY-GB structure and information flows. The blue features belong to the generic core of CRAFTY, and the yellow features are specific to the British model implementation, providing information to the core processes. This external information is derived from observational, 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.

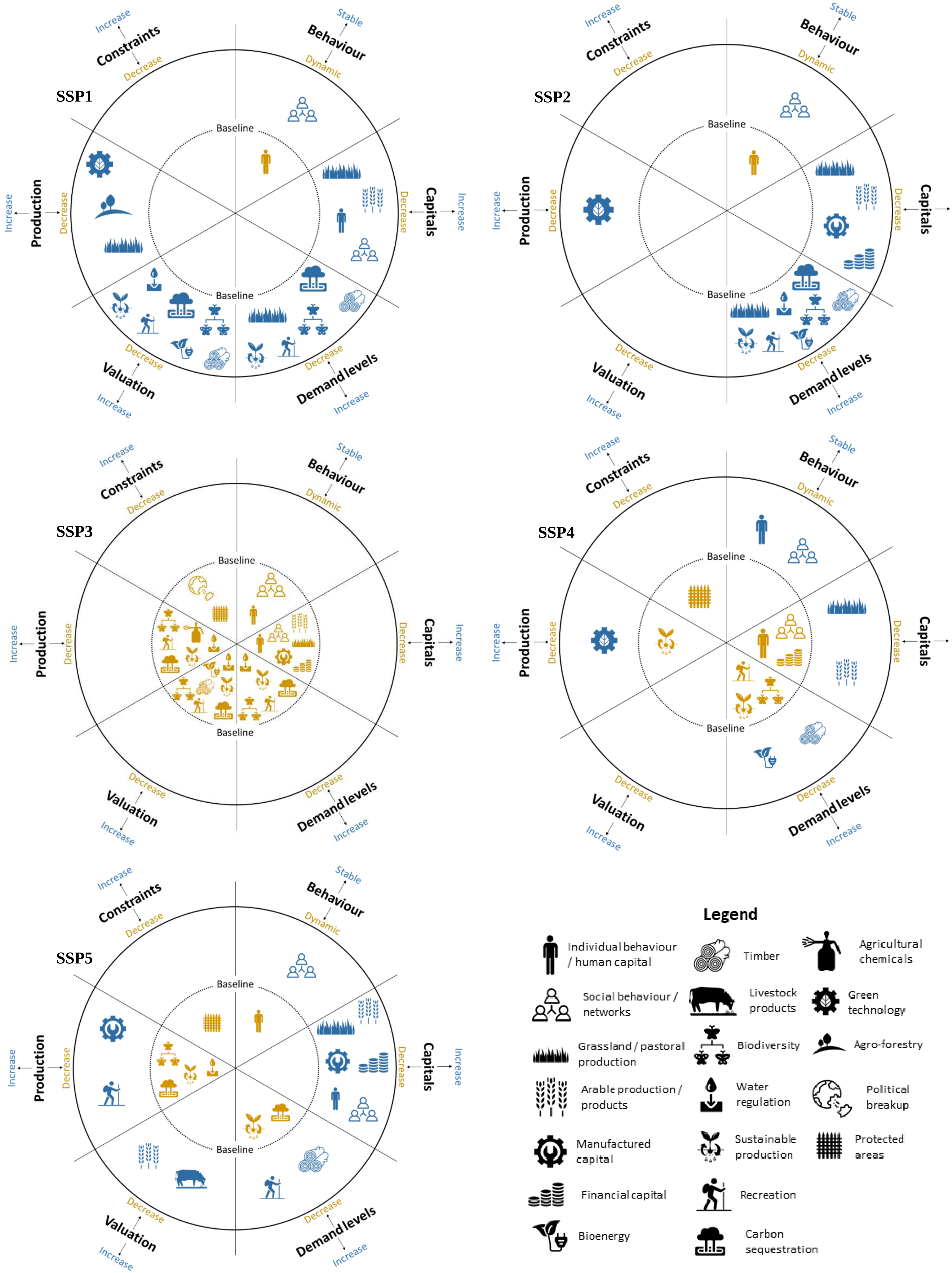
SSP1
SSP2
SSP3
SSP4
SSP5
Constraints
Increase
Decrease
Behaviour
Stable
Dynamic
Capitals
Increase
Decrease
Demand levels
Decrease
Increase
Valuation
Decrease
Increase
Production
Increase
Decrease
Baseline
Legend
Individual behaviour / human capital
Timber
Agricultural chemicals
Social behaviour / networks
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.

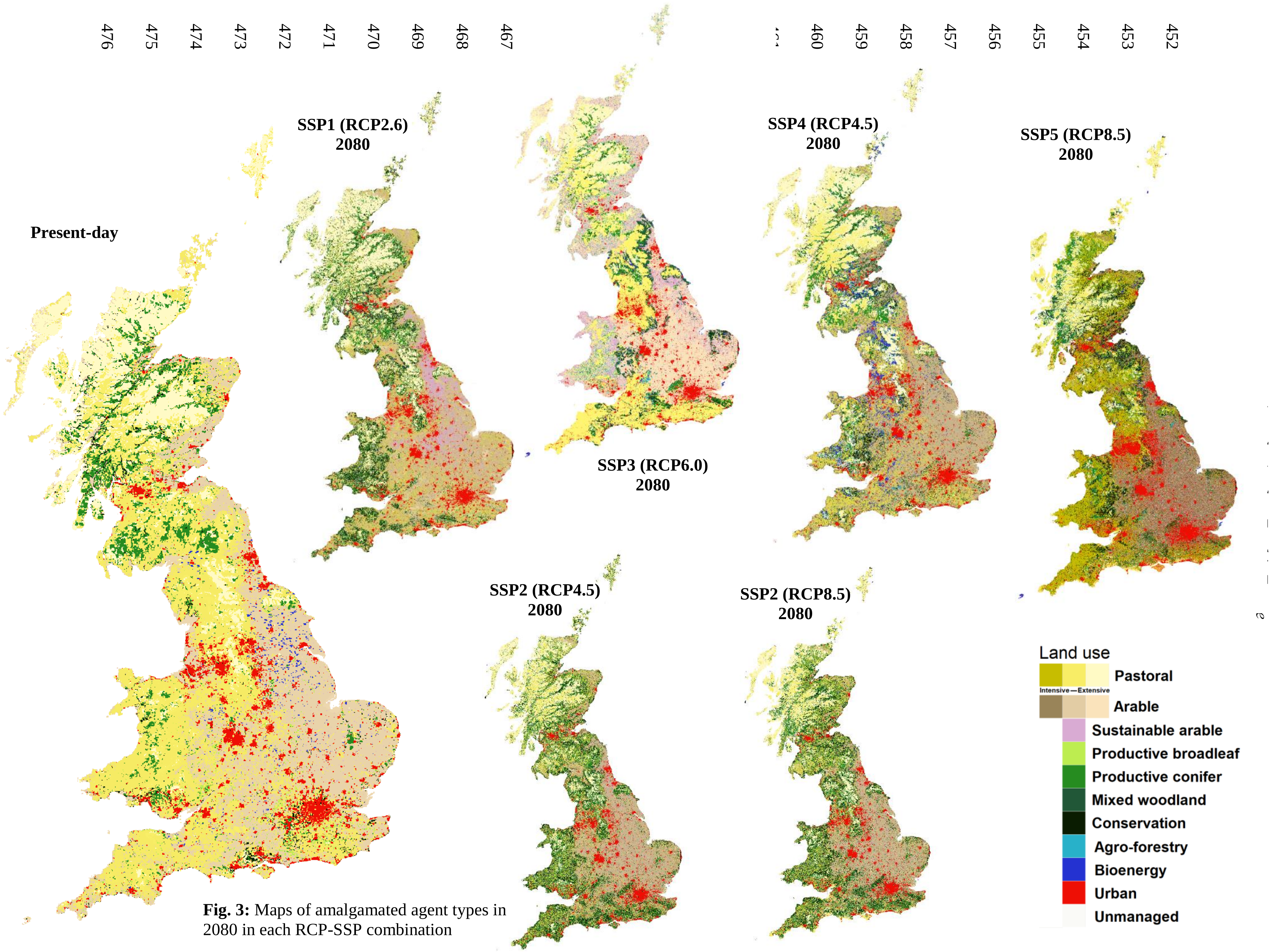

Fig. 3: Maps of amalgamated agent types in 2080 in each RCP-SSP combination

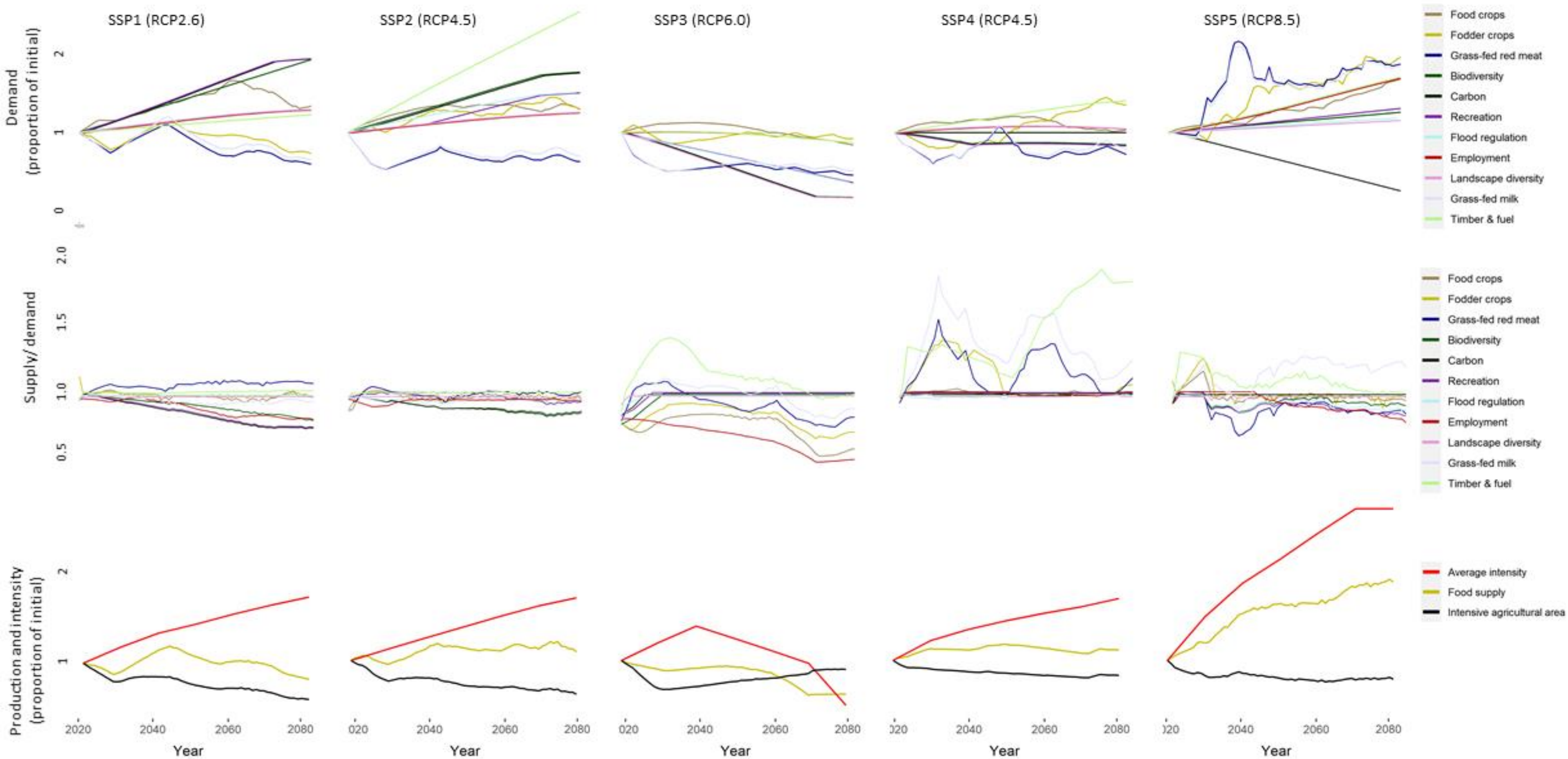

Fig. 4: Demand levels, supply as proportion of demand, and land use intensity, food supply and intensive area throughout each SSP scenario (RCP8.5-SSP2 results were very similar to those shown for RCP4.5-SSP2, and can be found in Fig. S11).

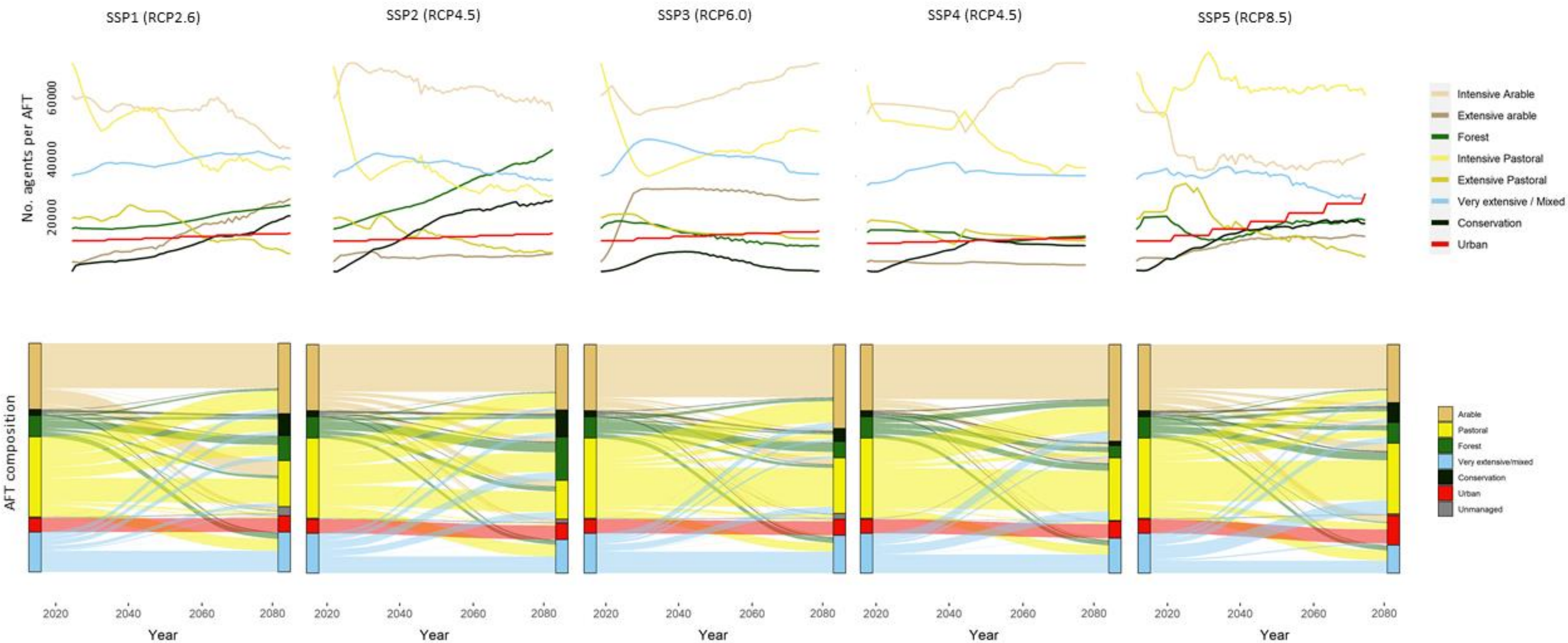

Fig. 5: Agent Functional Type (AFT) dynamics throughout each SSP scenario: numbers of agents within amalgamated AFTs (top) and transitions between broad land use types (bottom). RCP8.5-SSP2 results were very similar to those shown for RCP4.5-SSP2, and can be found in Fig. S11.

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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