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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

Supporting Information:

Supporting Information may be found in the online version of this article.

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Agent-Based Modeling 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 analyze 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 modeling framework. We find that distinct model components are required to account for divergent behavioral, 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 reflecting social cohesion, equality, health and education can generate impacts larger than those of technological and economic change, and comparable to those of modeled climate change. We develop an open-access, transferrable model framework and provide UK-SSP projections to 2080 at 1 km^2 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 modeling. This modeling supports the identification of pathways toward 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 modeling 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 behavior 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 their full interactions with RCP climate scenarios 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 in combination with UK-specific RCPs. We use a flexible agent-based modeling framework driven by national and global scenario storylines. In adapting this framework to each UK-RCP-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 modeling framework capable of representing paired SSP-RCP scenarios at national to continental scales, and evaluate its application through the comprehensive TRACE protocol (in Supporting Information S2). We also provide new projections to 2080 of the UK-RCP-SSPs at 1 km^2 resolution, accounting for key scenario elements related to human behavior, ecosystem service valuation and land management intensity within a changing climate. We use our findings to understand potential changes in the British land system in particular, and potential advances in the simulation of RCP-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, modeling of the British land system under alternate scenarios has been limited. Much of the modeling 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 modeling 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 useable for participatory processes and scenario analyses.

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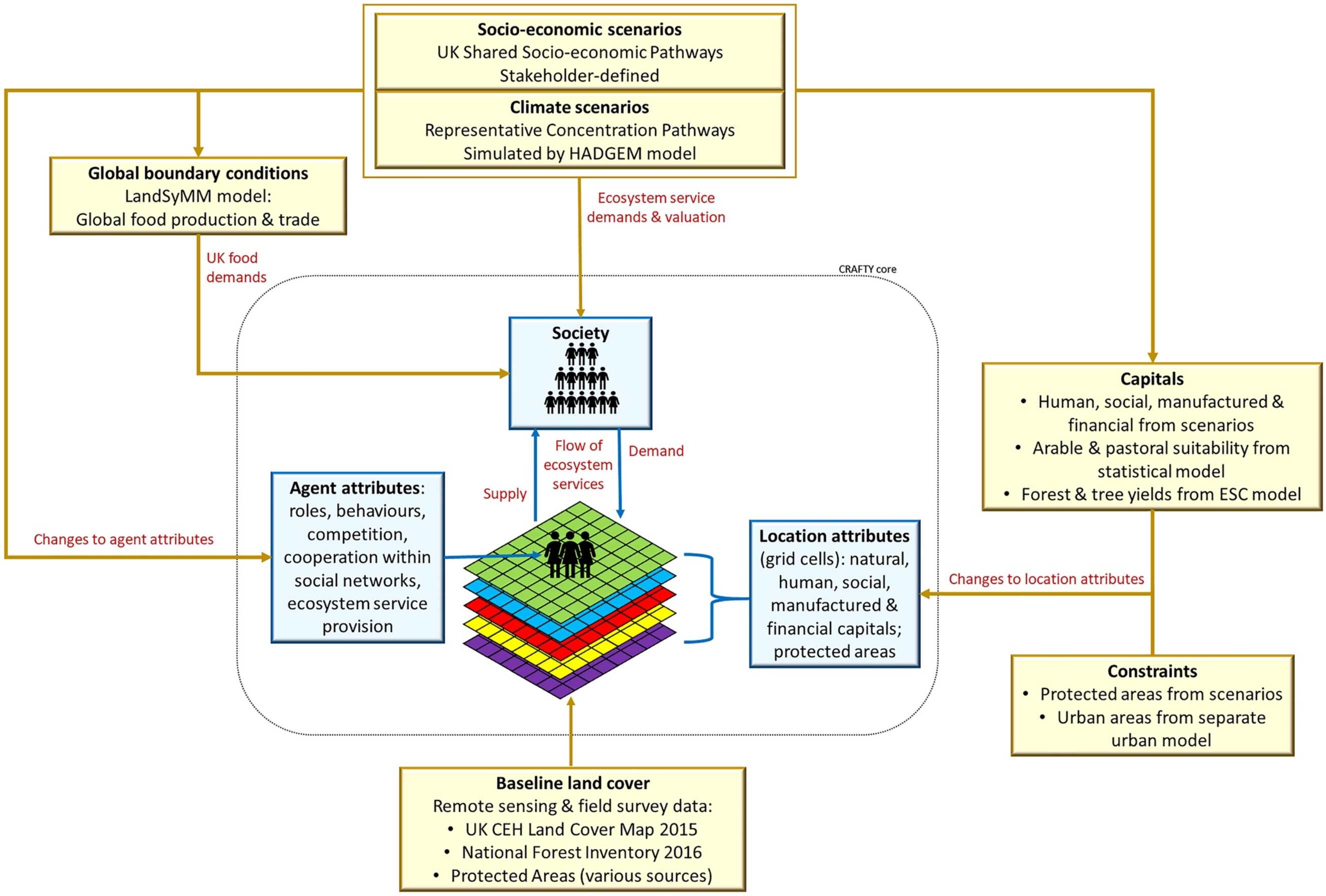

Figure 1. Schematic diagram of CRAFTY-GB structure and information flows. The blue features belong to the generic core of CRAFTY, and the yellow features are specific to the British model implementation, providing information to the core processes. This external information is derived from observational, modeled and stakeholder-developed data explained in detail in Supporting Information S1. Red labels describe particular information exchanges.

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 modeling framework to account for global change and the UK's international trade under each scenario. Here we give a brief overview of model design, calibration and evaluation, with a full stand-alone description and evaluation document provided in the Supporting Information (documents 1 and 2, respectively).

2.1. Model 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 1 km^2 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 modeling 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, Brown, et al., 2017), and Brazil (Millington et al., 2021)) while the inputs were tailored to the British context (Figure 1). Table 1 gives a summary overview of main model components, and these are described in full in Supporting Information S1.

Table 1
Overview of Main Model Components, Their Calibration, and Location of Full Descriptions

Component	Explanation	Details & sub-components	Input data & calibration	Further details
Capitals	Location attributes describing resources or attributes of each individual cell	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.	Social, human, financial and manufactured capitals derived from UK-SSP projections of eight socio-economic indicators (Merkle et al., 2022). Natural capitals: forest suitabilities modeled using the Ecological Site Classification (ESC) yield class model (Forest Research, 2021; Pyatt, 1995); arable, and improved and semi-natural pastoral suitabilities modeled statistically.	Supporting Information S1 section 'Capitals'; Tables S1 & S2 in Supporting Information S1
Protected areas	Protected areas constrain options for land use change	Protected areas belonging to 11 different types of national and international designation and to five different private land-owning organisations (NGOs) included in the model and varied according to SSP storylines	A wide range of data sources giving spatial extent of different protected areas, listed in Table S3 in Supporting Information S1.	Supporting Information S1 section "Protected Areas"; Table S3, Figure S1 in Supporting Information S1
Agent types	Typology representing the main forms of land use in Great Britain, including gradations of intensity and multifunctionality. Each type produces a different set of ecosystem services and has different behavioral parameters.	Agent types 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)	Typlogy based on the 2015 Land Cover Map (LCM2015) (Rowland et al., 2017), the National Forest Inventory (NFI) 2010–2015 (Forestry Commission, 2021) and design by the authors to ensure completeness across scenarios. Further datasets were used to define the extent, location of specific land uses and ecosystem service provision levels.	Supporting Information S1 sections "Land uses (agent types)" and "Behaviors"; Tables S4 & S5 in Supporting Information S1
Urban areas	A separate component based on an independent model of urban development to give scenario-specific projections.	Use of 1 km gridded urban surface projections derived from a newly developed urban allocation algorithm, based on neighborhood density, SSP-specific sprawl parameters, and SSP-specific land exclusions of protected areas and flood risk areas.	Input data and calibraton described in Merkle et al. (2022)	Supporting Information S1 sections "Land uses (agent types)" and Merkle et al. (2022)

Table 1
Continued

Component	Explanation	Details & sub-components	Input data & calibration	Further details
Ecosystem services	Each modeled land use 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	Services included: Food crops, Fodder crops, Grass-fed meat, Grass-fed milk, Bioenergy fuel, Softwood, Hardwood, Biodiversity, Landscape diversity, Carbon sequestration, Recreation, Flood Regulation. Employment, Sustainable production.	Potential and required provisioning services varied according to the UK-RCP-SSP scenarios: demand levels for foods derived from the LandSyMM (Land System Modular Model; www.landsymm.earth) global modeling framework running global RCP-SSP scenario combinations (Rabin et al., 2020). Non-food demands taken from the UK-SSP scenarios (Merkle et al., 2022)	Supporting Information S1 section 'Services & demand levels'; Tables S6 & S7 in Supporting Information S1.
Climate scenarios (UK-RCPs)	Representative Concentration Pathways specified for the UK to give climate impacts on service provision	Covers several physical climate variables to 2080 at 1 km spatial resolution and time steps from daily to decadal averages, including temperature and precipitation, potential evapotranspiration and growing degree days. Used as inputs to the crop, grassland and forest modeling.	Based on CHESS-SCAPE future climate Dataset and UK Climate Projections 2018 (UKCP18) (Lowe et al., 2018; Met Office Hadley Center (MOHC), 2018).	Supporting Information S1 section "Scenarios" and Robinson et al. (2022)
Socio-economic scenarios (UK-SSPs)	Shared Socio-Economic Pathways specified for the UK to give socio-economic conditions	Substantial extensions of the global SSPs providing narratives and quantifications of social, economic and political developments across the UK until 2100.	Integration of stakeholder knowledge on locally-relevant drivers and indicators with information from European and global SSPs. Global consistency via LandSyMM global land system modeling.	Figure 2, Supporting Information S1 section "Scenarios" & Table S8 in Supporting Information S1, Pedde et al. (2021), Harmáčková et al. (2022) and Merkle et al. (2022)

Note. A complete stand-alone methods description can be found in the Supporting Information (SI1).

The basis for modeled land use change in CRAFTY-GB is a set of capitals that describe location resources or attributes for each 1 km^2 cell, 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 (Table 1 and Tables S1–S3 in Supporting Information S1). Each cell is also assigned an agent representing a specific form of land management either on the basis of observational land use data (for the baseline) or through a modeled process of competition with other agents (for future projections; see Table S4 in Supporting Information S1). These agents use the capitals to produce services that satisfy societal demands, which are exogenously defined during scenario development (Table S6 in Supporting Information S1). Each service also has a defined value per unit unmet demand, which represents both economic and non-economic valuation. Competition between agents is driven by the difference in value of the bundle of services produced by different agents on any given cell, with the agent generating the highest value best-placed (but not certain) to assume management of that cell. Competition is also affected by the behavioral characteristics of the agents, as well as cooperation between them through modeled social networks.

This basic model circuit is driven by exogenous scenarios that describe climatic (RCP) and socio-economic (SSP) changes over time (Table 1). These changes can affect capital values, agent characteristics, service demand levels and valuations, competition processes and policy objectives. The nature and spatio-temporal properties of modeled 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 modeled processes are active, which is a novel aspect of the approach. RCP-SSP combinations were chosen to: (a) cover a broad range of uncertainty in both emissions (and hence climate) and socio-economic developments; and (b) 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, and 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. As the main developments in this study relate to the UK-SSPs, these are summarized in Figure 2 and Table 2 as well as in Supporting Information S1.

2.2. Model Evaluation

Model evaluation is presented in detail in a TRACE ("TRAnsparent and Comprehensive model Evaludation") model evaluation document in Supporting Information S2 (Augusiak et al., 2014; Ayllón et al., 2021; Grimm et al., 2014; Schmolke et al., 2010), with main components summarized 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 modeled 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 (a) LCM 2015 (Rowland et al., 2017), to provide a summary of the translation of LCM classes into CRAFTY-GB classes (Table S4 in Supporting Information S1), (b) The standardised European EUNIS habitat classification scheme at 100 m resolution (European Environment Agency, 2019; Weiss & Banko, 2018), (c) 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.

2.3. 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 modeled production levels. For the purposes of illustration these are combined multiplicatively here and used to select color 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

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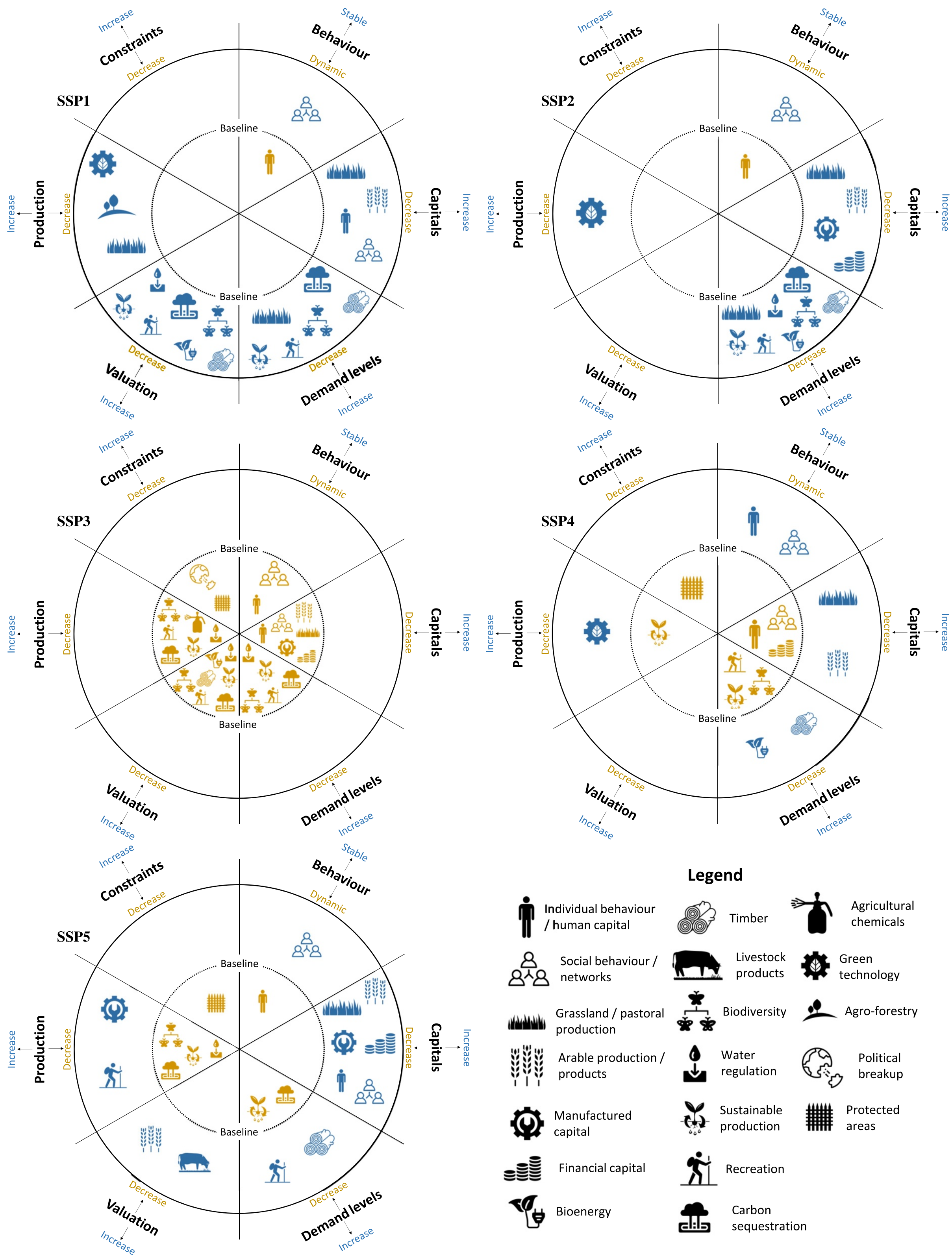

Figure 2.

does however make scenario 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 (Supporting Information S1 section "Agent typology evaluation", Figures S4–S9 in Supporting Information S1). The baseline mapping reproduced the LCM classes that were the primary data used to locate agents geographically (Figure S2 and Table S4 in Supporting Information S1), with the largest inconsistencies in forest types. EUNIS habitat classes were widely distributed between agent types, but with clear associations that were generally as expected (e.g., woodland habitats with forest types) (Figures S6–S8 in Supporting Information S1). 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. As expected, chemical inputs were most strongly associated with intensive arable areas, with evidence of productive broadleaf woodlands also being associated with agricultural areas and hence chemical inputs (Figure S9 in Supporting Information S1).

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 2). 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 competition between agents in 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, with climatic and socio-economic conditions favoring different land uses and intensities at different points. The changes highlighted below are emergent consequences of competition between agents, rather than exogenously imposed conditions, unless otherwise stated.

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, with available intensification options being less competitive. Reduced meat demand caused a substantial move away from pastoral management in many areas (Figure 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 (Figure 4), but overall sustainable and extensive management became more competitive and widespread. By 2080, sustainable arable management dominated eastern England, while the British uplands were largely given over to extensive pastoral management (Figure 3). Nevertheless, substantial areas were also covered by natural vegetation (whether unmanaged or managed for conservation) and, in forestry, native conifer and broadleaf species (Figure S10 in Supporting Information S1). 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

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 summarized in Figure 4. The "Behavior" segment in the plots varies between "stable" and "dynamic" rather than "increase" and "decrease" because behavioral variations are not directional but affect the heterogeneity and temporal dynamism of agent behavior (see Table S5 in Supporting Information S1). "Production" refers to the maximum potential production of the ecosystem services shown, and varies around the management-specific values shown in Table S7 in Supporting Information S1.

Table 2
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

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 toward 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, nationalization 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

Table 2
Continued

Scenario	Description	Distinguishing features in CRAFTY-GB	Main outcomes
SSP5—Fossil-fueled 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 Increasing intensification options Removal of Protected Areas and low demands for related ecosystem services	High pressure on land area and strong competition between land uses Very high levels of intensification in agriculture supporting large increases in production Expansion of productive land uses into natural areas, with consequent abandonment in upland and marginal areas not under protection.

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 Supporting Information S1). 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. Conservation management was 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 (Figure 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; Figure 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 (Figure 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 as lack of inputs made intensive management uncompetitive) (Figures 3–5). This extensive agricultural management occupied large, contiguous areas as growing food for survival became the primary demand (Figure 3). Many forest areas were converted to arable agriculture because of relatively high food values, with remaining forests dominated by conifers (Figure S10 in Supporting Information S1). As the scope for intensive management decreased during the century, supply levels fell below demands and utilization 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 (Figure 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

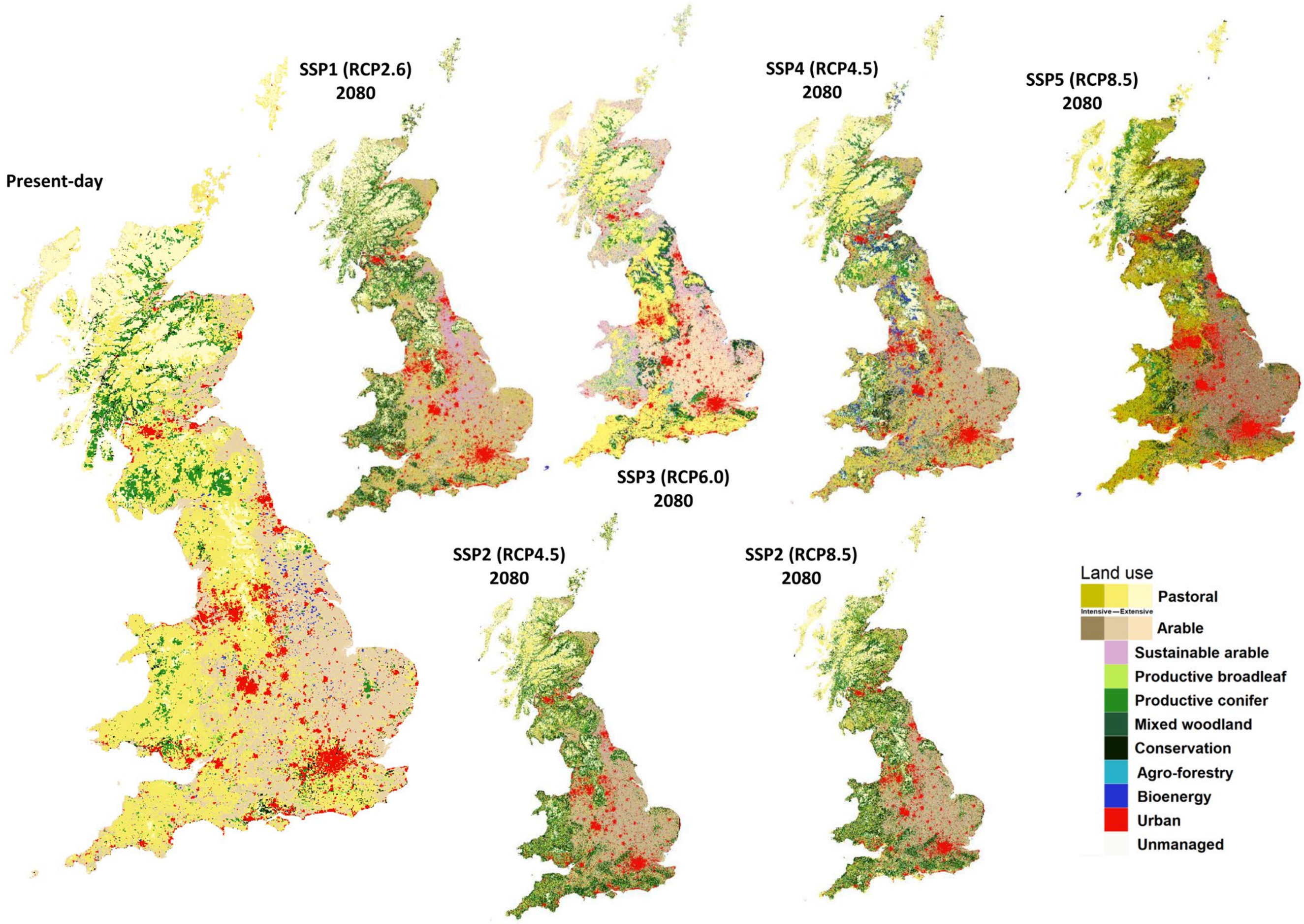

Figure 3. Maps of amalgamated agent types in 2080 in each RCP-SSP combination.

increasing arable extent and intensity (Figure 5), because investments allowed intensive agents to out-compete extensive ones. 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) (Figure 4). Conversely, intensive arable production increased as pastoral decreased, as did bioenergy, which was ultimately grown across the country in marginal agricultural areas (Figure 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. These strong pressures overshadowed the effects of climate change, allowing agents to profitably produce goods and services even where suitabilities and yields declined. Protected areas were removed as concern for the environment was low. Declining social capital made marginal production vulnerable to climate 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 sufficient combinations of low-priority ecosystem services in some cells to outcompete intensive, mono-functional alternatives. 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 (Figure S10 in Supporting Information S1).

Figure 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 Figure S11 in Supporting Information S1).

The pastoral land area was almost maintained in this scenario due to very high demands for livestock products (Figure 5). Despite some urban expansion into productive land and extensification of unproductive land, overall land use intensity increased dramatically (Figure 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.

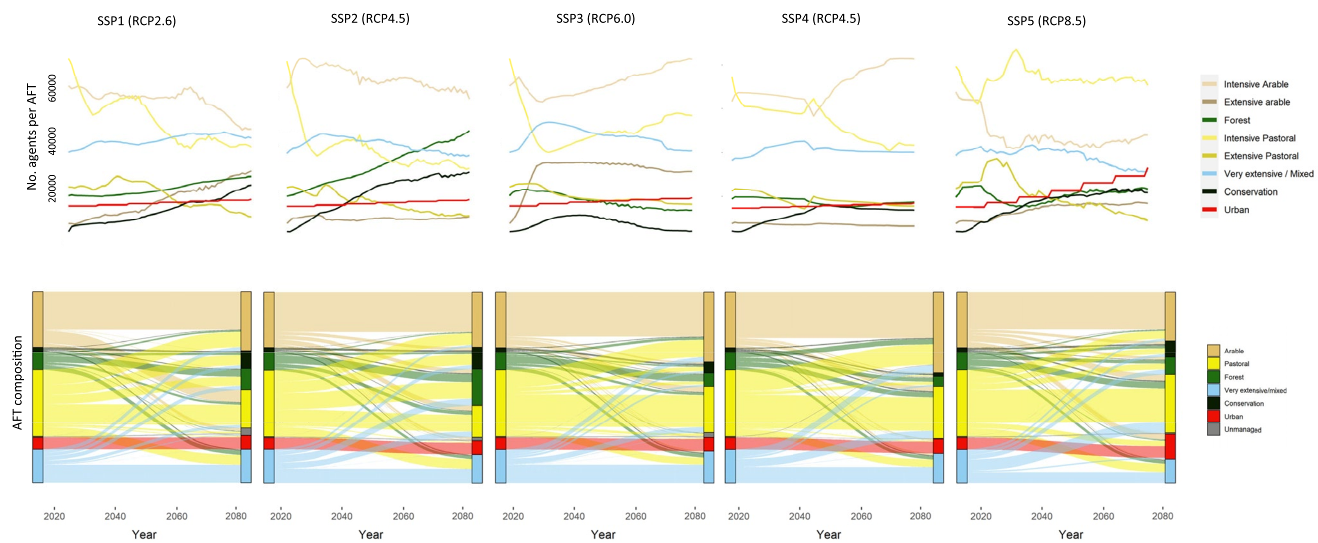

Figure 5. Agent Functional Type (AFT) dynamics throughout each SSP scenario: numbers of agents within amalgamated AFTs (top) and transitions between broad land use types (bottom). RCP8.5-SSP2 results were very similar to those shown for RCP4.5-SSP2, and can be found in Figure S11 in Supporting Information S1.

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4. Discussion

This study targets the gap between detailed stakeholder-developed SSP storylines and their representations in computational models used for exploring climatic and socio-economic impacts in the land system. We attempt to extend scenario modeling using flexible model structures and parameterisations that are not limited to the single pathway established by historical land use change (Figure 2, Table 2). 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). 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. This was mainly an effect of socio-economic conditions: 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 (and in spite of the strong climate change introduced by RCP8.5). 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 climate change, 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 more substantial effects than the climatic UK-RCPs with which they were paired (see also e.g., Brown et al., 2019; Kriegler et al., 2017; Molotoks et al., 2021; Wiebe et al., 2015). Nevertheless, the absence of some climate impacts including extreme events (absent because the spatial and temporal resolution of the climate modeling limits representation of such events) does imply that very large climatic impacts may be missing, from RCP8.5 especially (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). These omissions demonstrate the need for further advances in RCP, as well as SSP, scenario modeling, particularly to better represent feedbacks between the two.

Some of our findings are broadly consistent with the comparable study of (Bateman et al., 2013), who found that including ecosystem services in modeling 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 maneuver 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, not least in terms of climatic suitability. Two of these capitals, human and social, vary enormously across the scenarios, but are usually absent from scenario modeling. 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 emphasize the importance of social factors in achieving climate policy objectives (Liu et al., 2020), because those factors determine the policies' realized impacts.

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 and climate 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 modeling 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, Brown, 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 scenario conditions, and in turn has strong implications for the extent of climate change mitigation (Bukovsky et al., 2021). More accurate representation of policy interventions could also engage usefully with these improvements, for instance in testing management subsidies targeted at particular outcomes, the biodiversity impacts of protected area design, or the overall effects of land-based mitigation alternatives. At larger scales, technically-challenging feedbacks between national and global scale models are necessary to trace the impacts of varying supply levels on trade or land use change on climate.

Policy analysis could also benefit from more focused studies within the RCP-SSP framework. For instance, it is notable that the UK-SSPs reveal a belief that wholesale removal of protected areas is plausible. This may reflect the weakness of conservation designations in the UK and concern about further relaxation of protections within them (Starnes et al., 2021), but might also suggest a need for alternative scenarios for policy support. The long-term and general nature of the scenarios used here makes them particularly suitable for assessing coherent land-system trends under global change, and so for providing context and boundary conditions for targeted policy assessments over smaller spatial or temporal scales. These could include, for example, studies of species-specific adaptation potentials under habitat restoration (Whitehorn et al., 2022), or subsidy schemes to support the provision of particular ecosystem services in agricultural land (UK Government, 2021).

While we propose that these extensions of scenario modeling 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 paired RCP-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 modeling 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 toward societal objectives.

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Data Availability Statement

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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