AGU PUBLICATIONS

Earth's Future

Supporting Information for

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

C Brown[1], B Seo[1], P Alexander[2], V Burton[3,4], EA Chacón-Montalván[5], R Dunford[6], M Merkle[2,7], PA Harrison[8], R Prestele[1], EL Robinson[6], M Rounsevell[1,2,9]

[1]Institute of Meteorology and Climate Research, Atmospheric Environmental Research (IMK-IFU), Karlsruhe Institute of Technology, Kreuzeckbahnstraße 19, 82467 Garmisch-Partenkirchen, Germany

[2]School of Geosciences, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP, UK

[3]Forest Research, Northern Research Station, Roslin, Midlothian, EH25 9SY, UK

[4]Woodland Trust, Kempton Way, Grantham, Lincolnshire, NG31 6LL

[5]Mathematics and Statistics Department, Fylde College, Lancaster University, LA1 4YF, UK

[6]UK Centre for Ecology & Hydrology, Maclean Building, Benson Lane, Crowmarsh Gifford, Wallingford, Oxfordshire, OX10 8BB, UK

[7]School of Economics and Business, Norwegian University of Life Sciences, Chr. Magnus Falsens vei 18, 1430 Ås, Norway

[8]UK Centre for Ecology & Hydrology, Library Avenue, Bailrigg, Lancaster, LA1 4AP, UK

[9]Institute of Geography and Geo-ecology, Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany

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Additional Supporting Information (Files uploaded separately)

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

Introduction

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

Methods

Model components

CAPITALS

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

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

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

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

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

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

PROTECTED AREAS

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

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

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

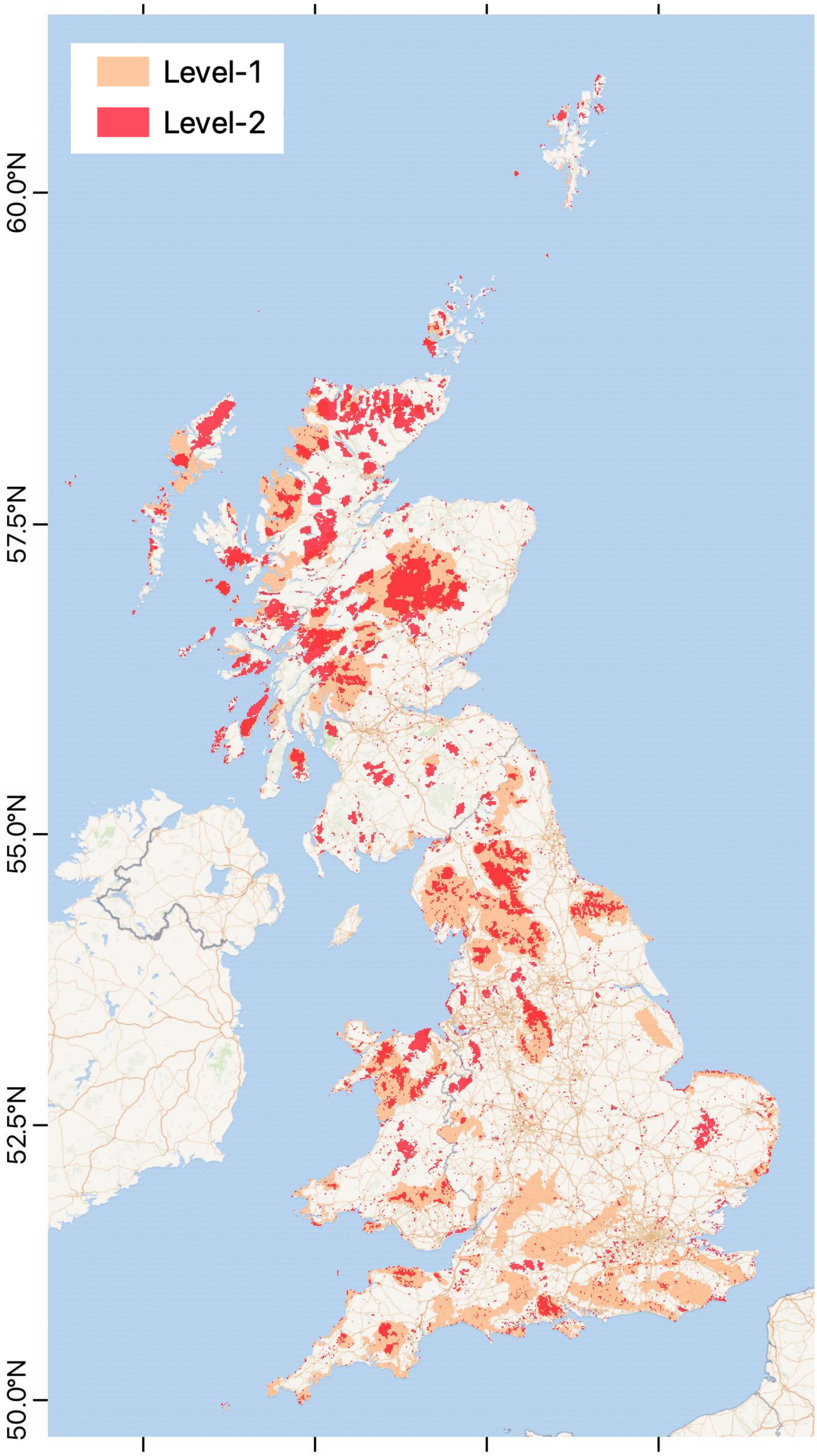


Fig. S1: Protected areas applied in CRAFTY-GB. The map is projected using OSGB1936 / British National Grid coordinate reference system (EPSG: 27700). The background map is provided by Wikimedia (https://maps.wikimedia.org/)

LAND USES (AGENT TYPES)

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

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

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

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

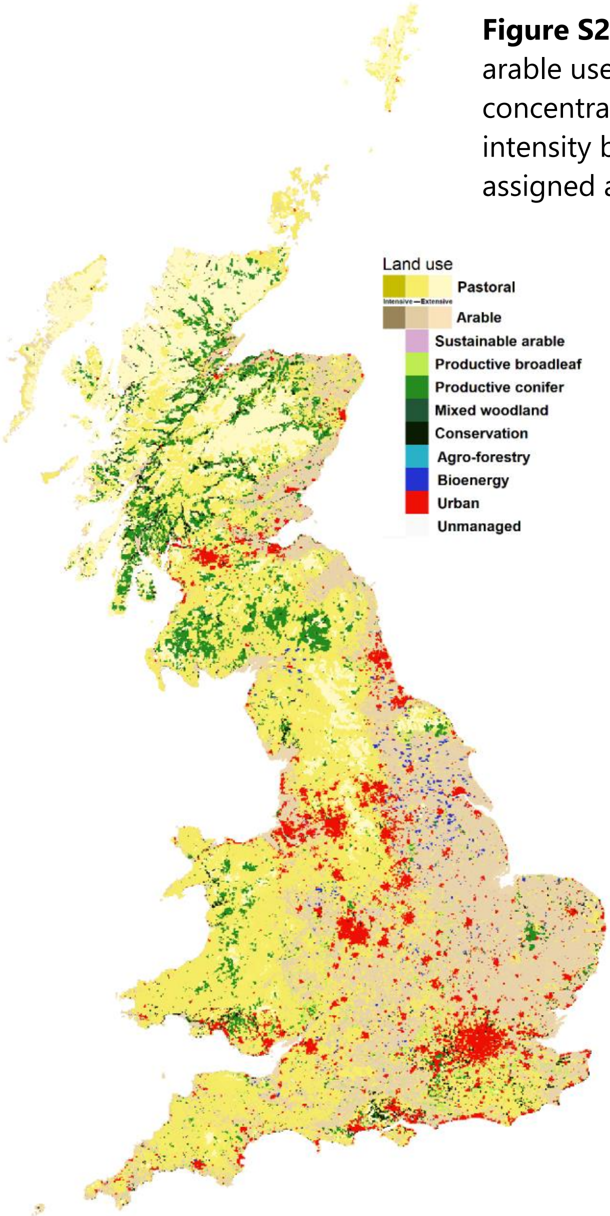


Figure S2: Simplified baseline allocation of land uses. Pastoral and arable uses are presented on coloured intensity gradients, and are concentrated towards the extensive end of the gradient because intensity becomes greater in some scenarios (intensity values are assigned as described in the text).

BEHAVIOURS

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

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

Table S5: Behavioural effects included in CRAFTY-GB

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

SERVICES & DEMAND LEVELS

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

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

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

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

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

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

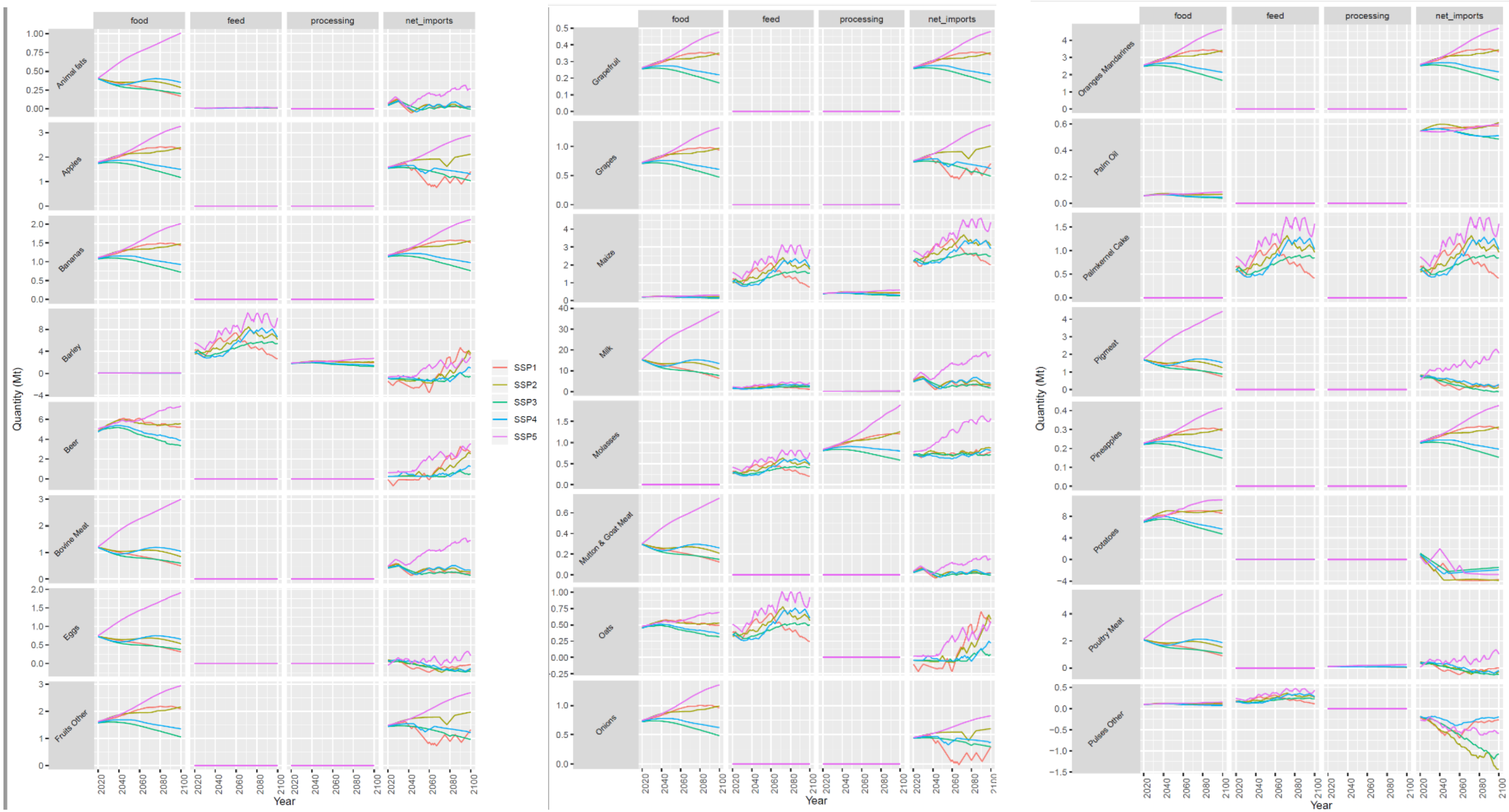
Approximate relative value

0 **1**

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

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

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



food
feed
processing
net_imports
Quantity (Mt)
Year
SSP1
SSP2
SSP3
SSP4
SSP5
Animal fats
Apples
Bananas
Barley
Beer
Bovine Meat
Eggs
Fruits Other
Grapefruit
Grapes
Maize
Milk
Molasses
Mutton & Goat Meat
Oats
Onions
Oranges Mandarines
Palm Oil
Palmkernel Cake
Pigmeat
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Potatoes
Poultry Meat
Pulses Other

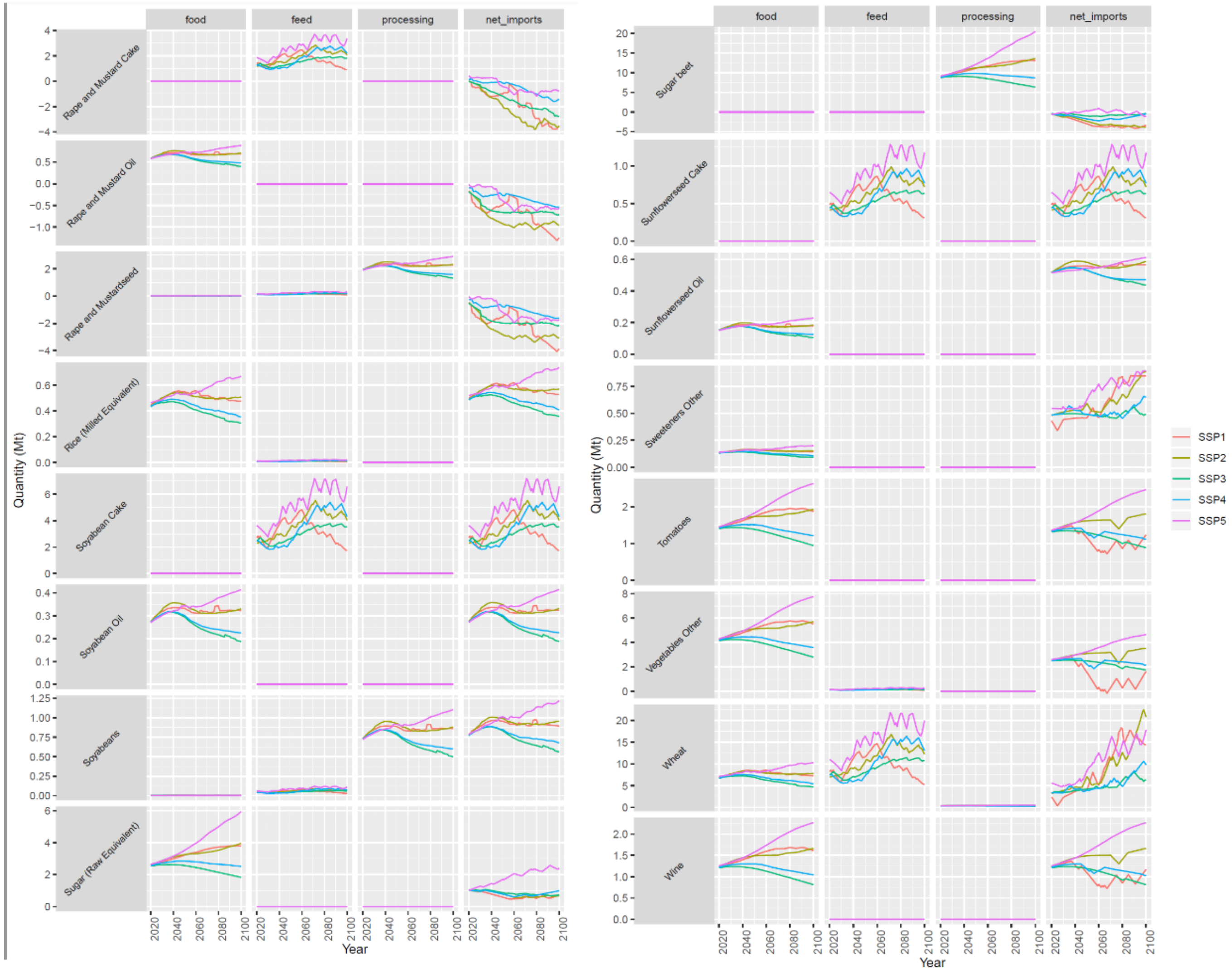


Figure S3: Food commodity demand levels supplied by the PLUM model as part of LandSyMM, prior to conversion for use in CRAFTY-GB

Scenarios

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

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

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

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

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

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

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

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

INTENSITY REPRESENTATION

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

Results

<u>Agent typology evaluation</u>

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

LCM 2015

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

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

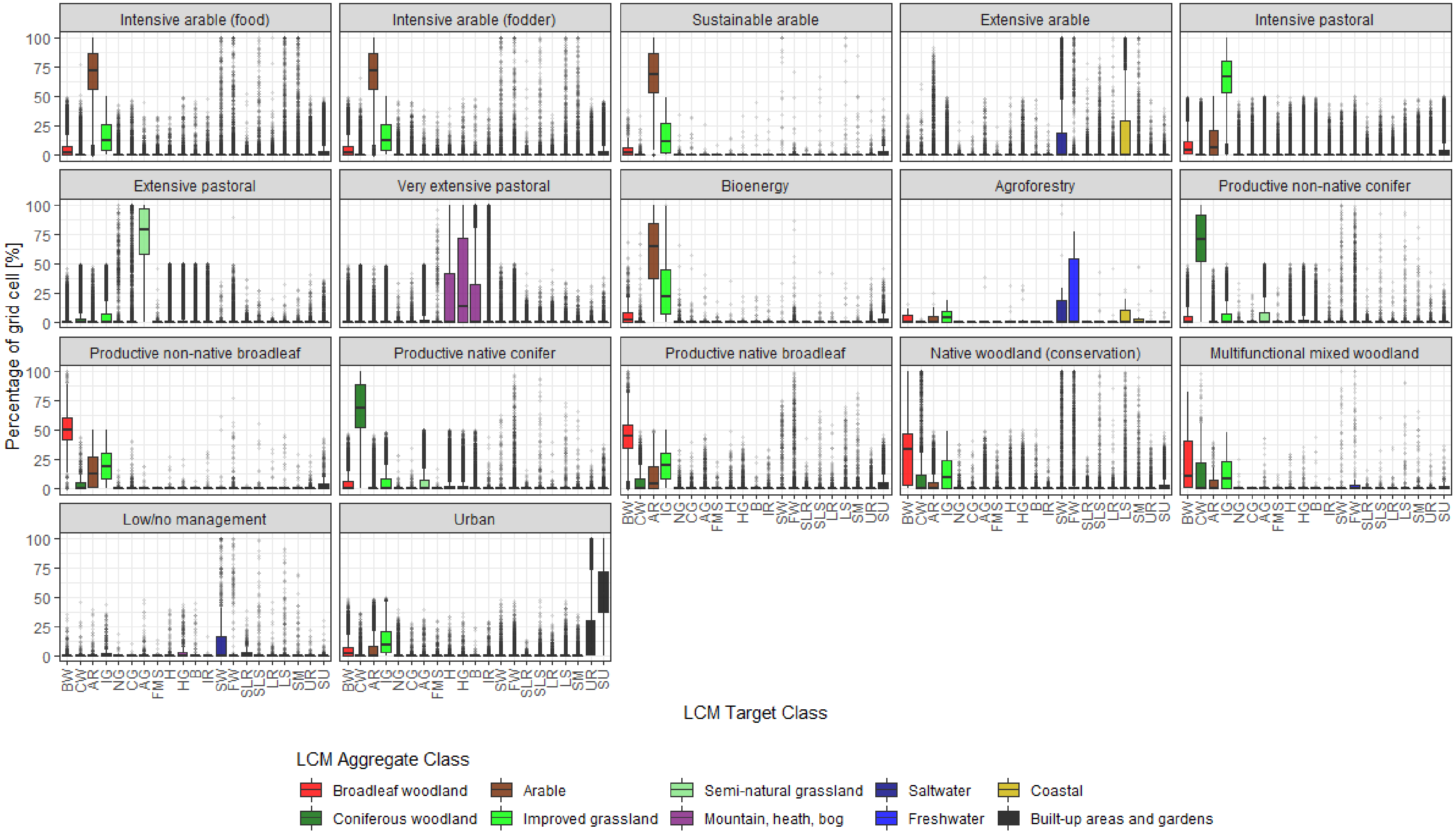


Figure S4: Sub-grid scale distribution of LCM classes within CRAFTY-GB agents. LCM classes as follows: **BW** Broadleafed woodland. **CW** Coniferous woodland. **AR** Arable and horticulture. **IG** Improved grassland. **NG** Neutral grassland. **CG** Calcareous grassland. **AG** Acid grassland. **FMS**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

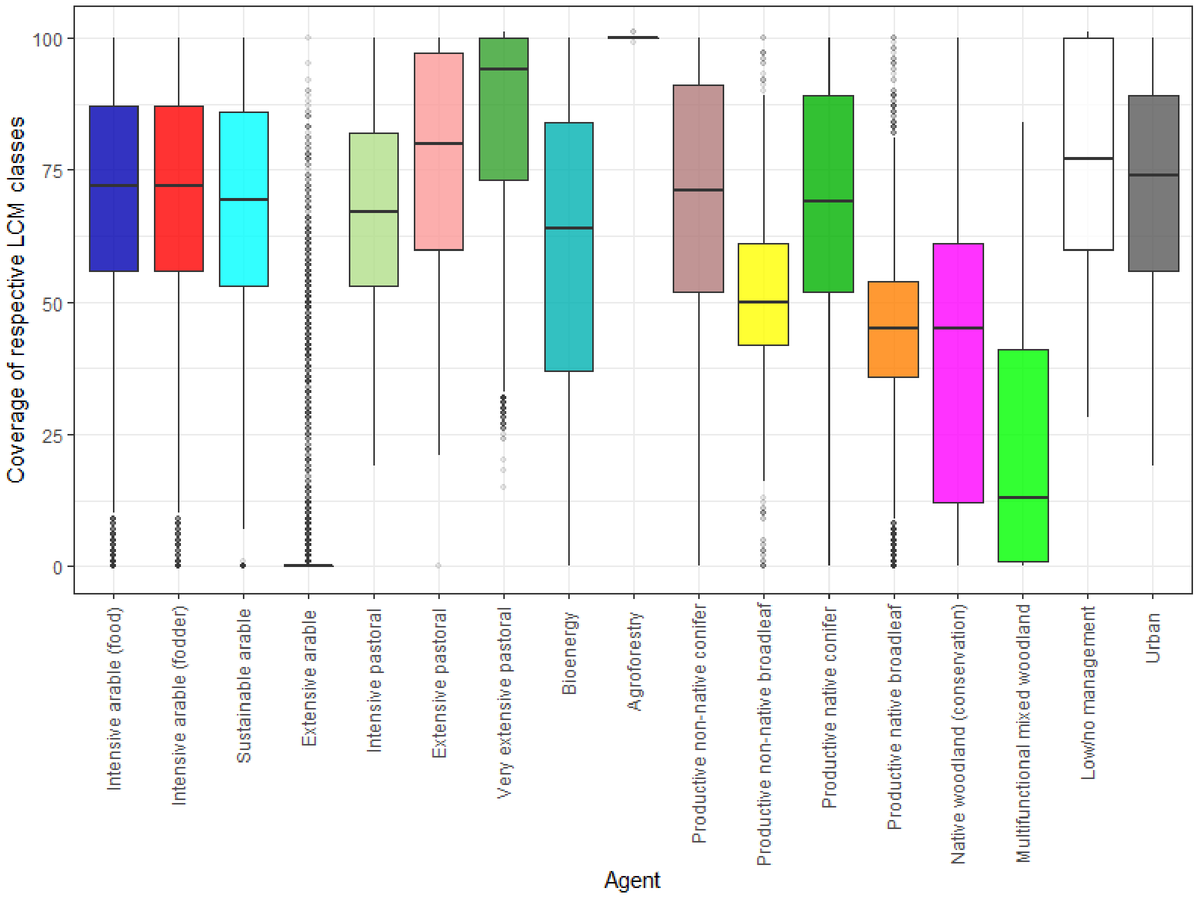


Figure S5: Sub-grid scale distribution of the LCM classes that correspond to CRAFTY-GB agents according to Table S4 (not accounting for additional data that has been used for allocation). For example, for agent 'Intensive arable (food)' fractions of LCM 'Arable' have been considered. As 'Agroforestry'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

EUNIS habitats

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

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

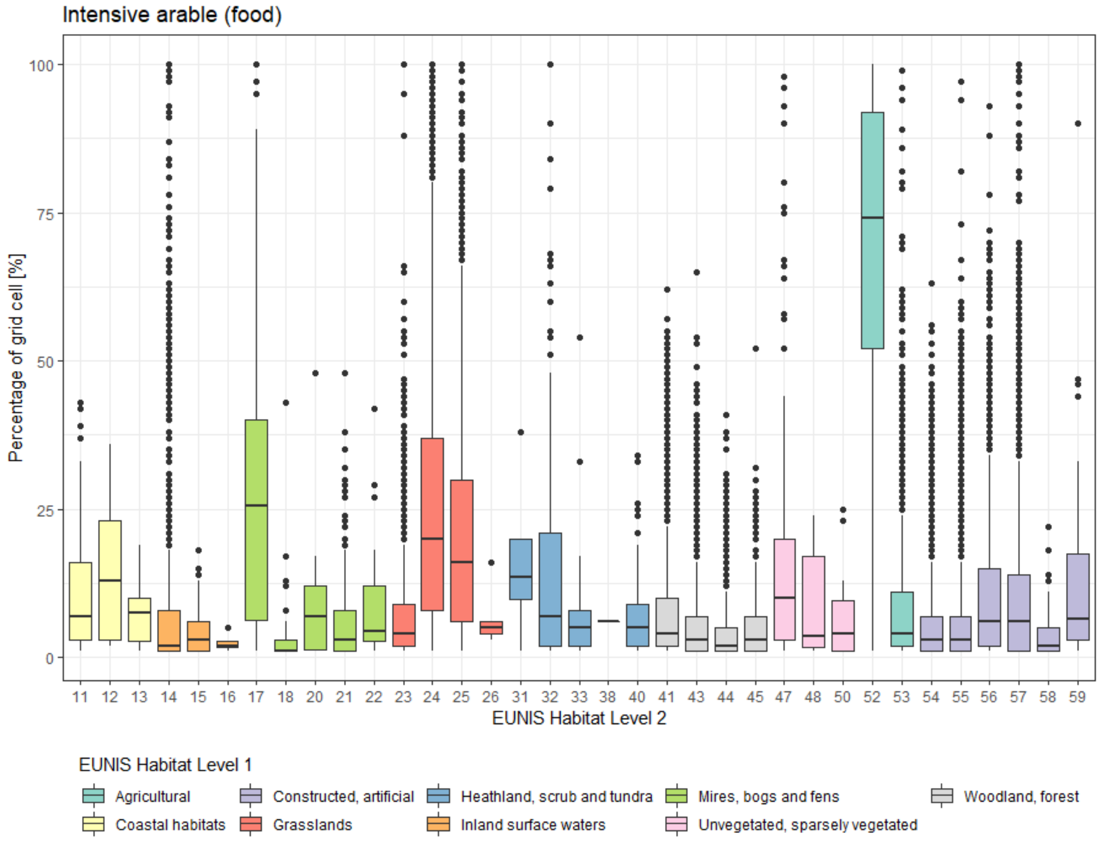


Figure S6: The distribution of EUNIS habitat types within the CRAFTY-GB 'intensive arable (food)' class. Habitat identities are explained in Table S9.

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

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

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

Table S9: EUNIS habitat identities.

CEH Pesticides and Fertilisers

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

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

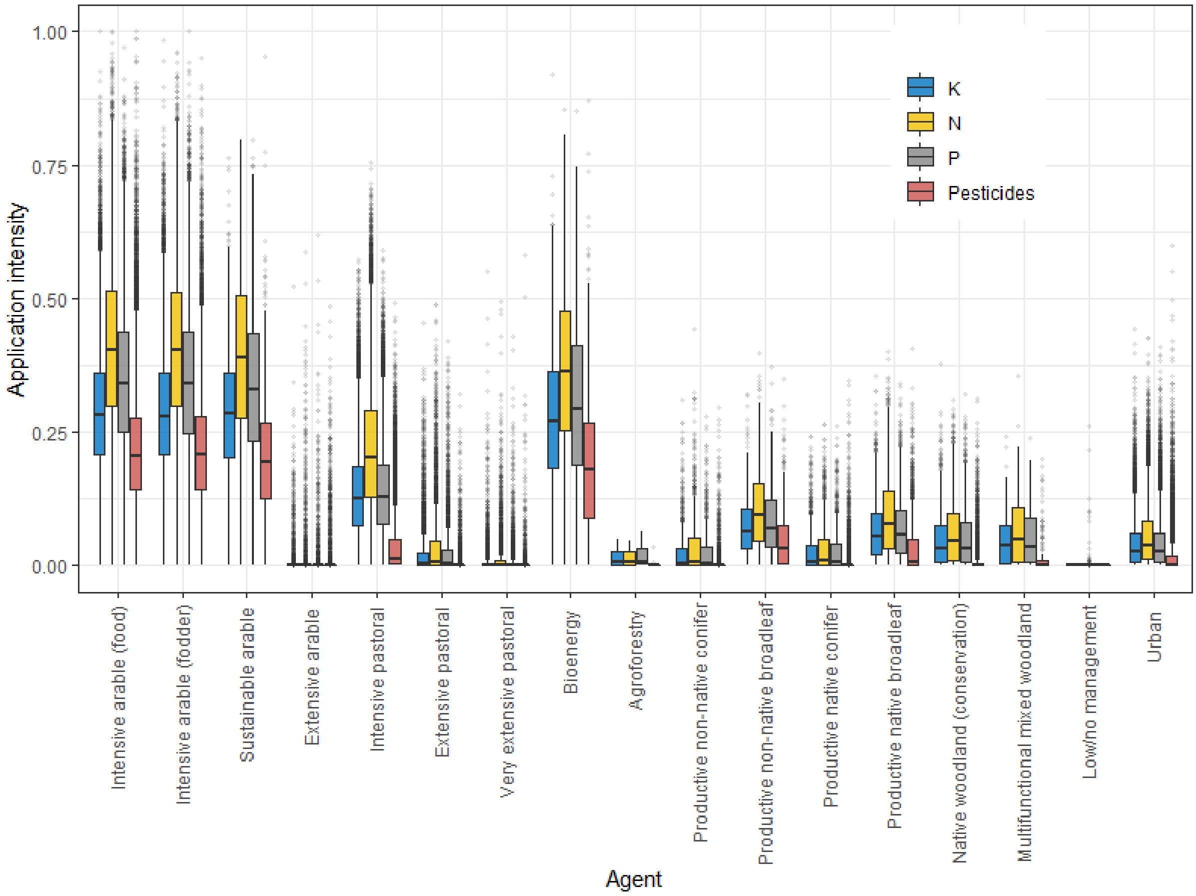


Figure S9: Associations between CRAFTY-GB agent types and application of fertilisers and pesticides as described in independent baseline data.

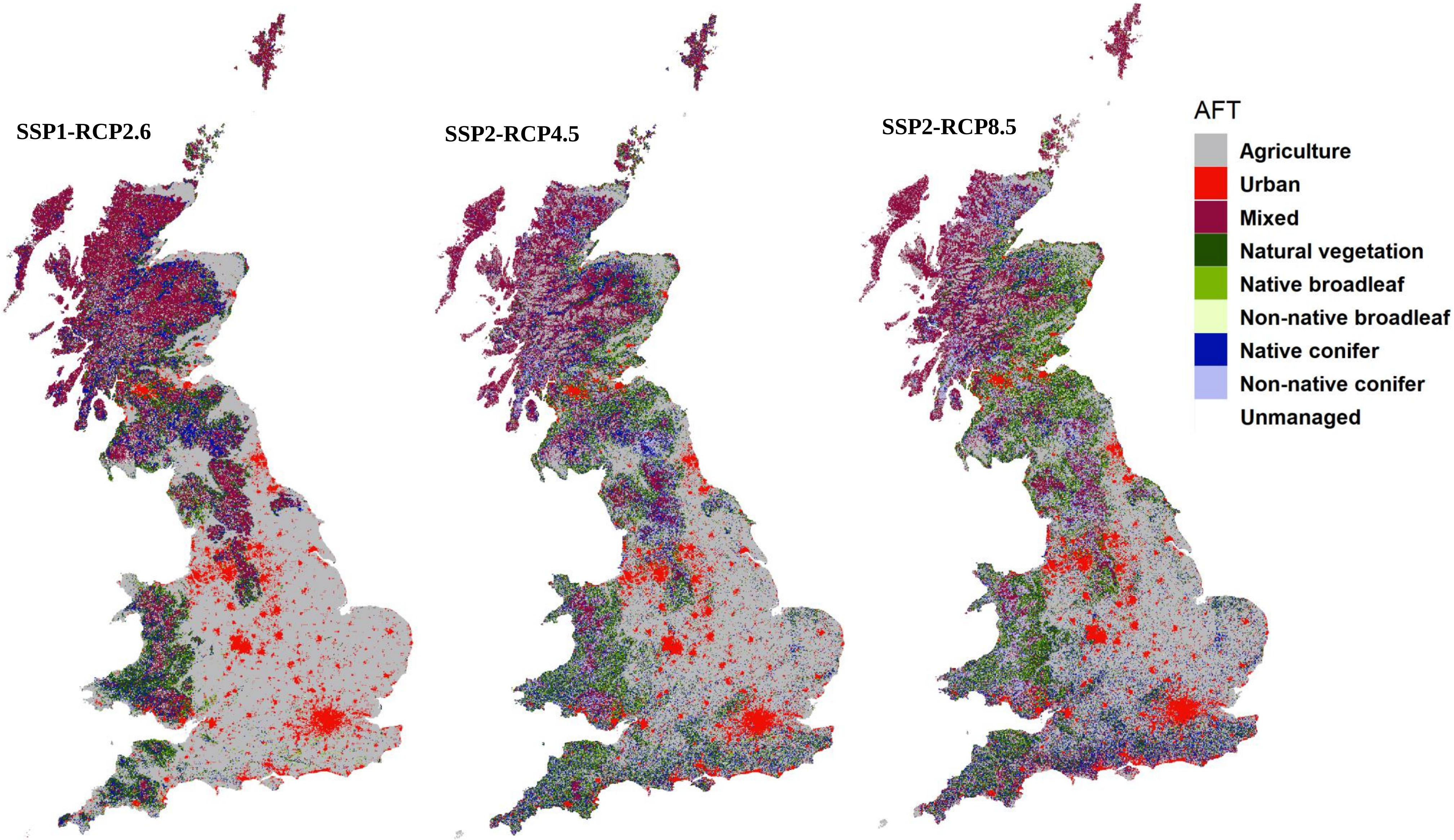
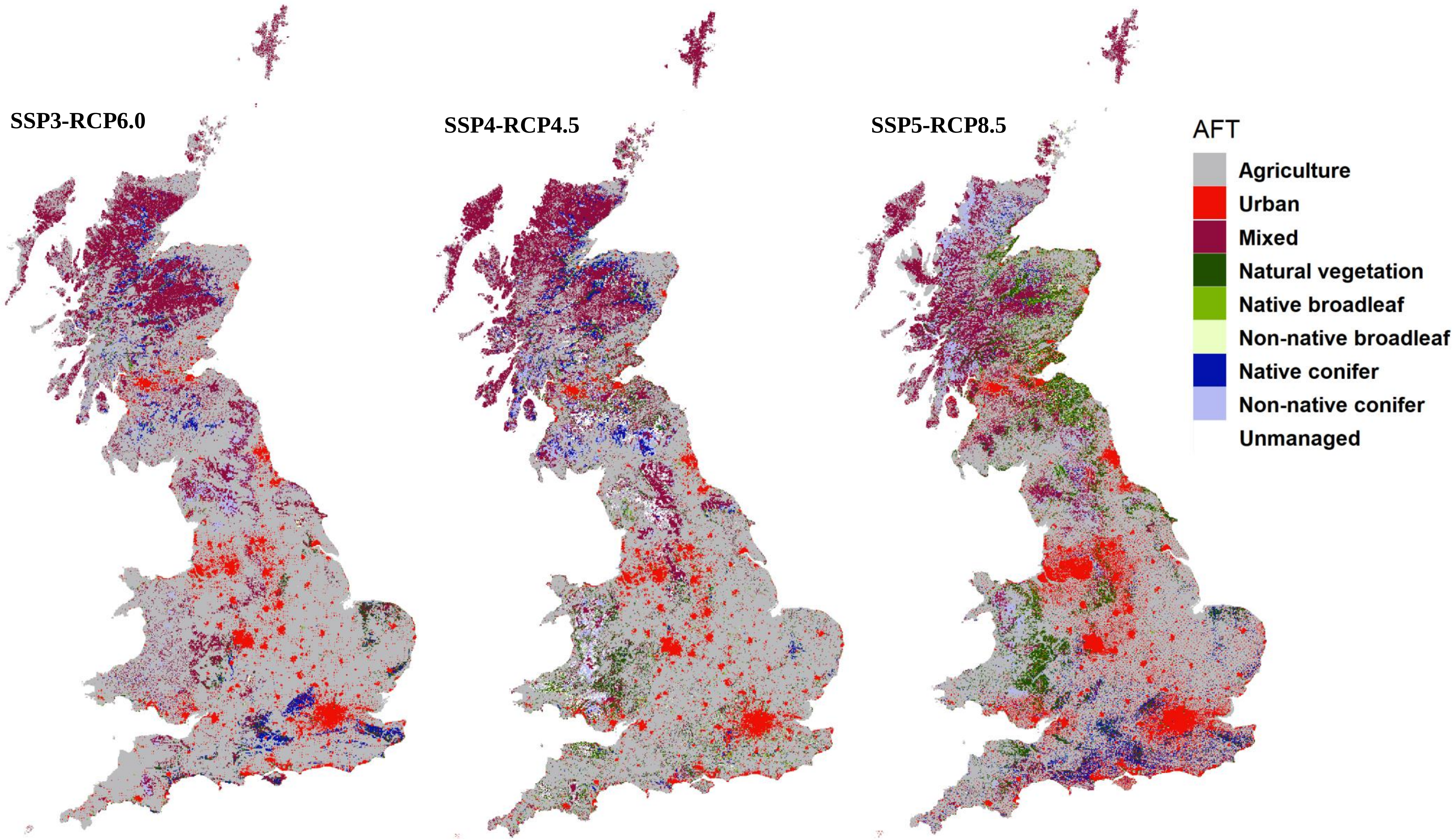
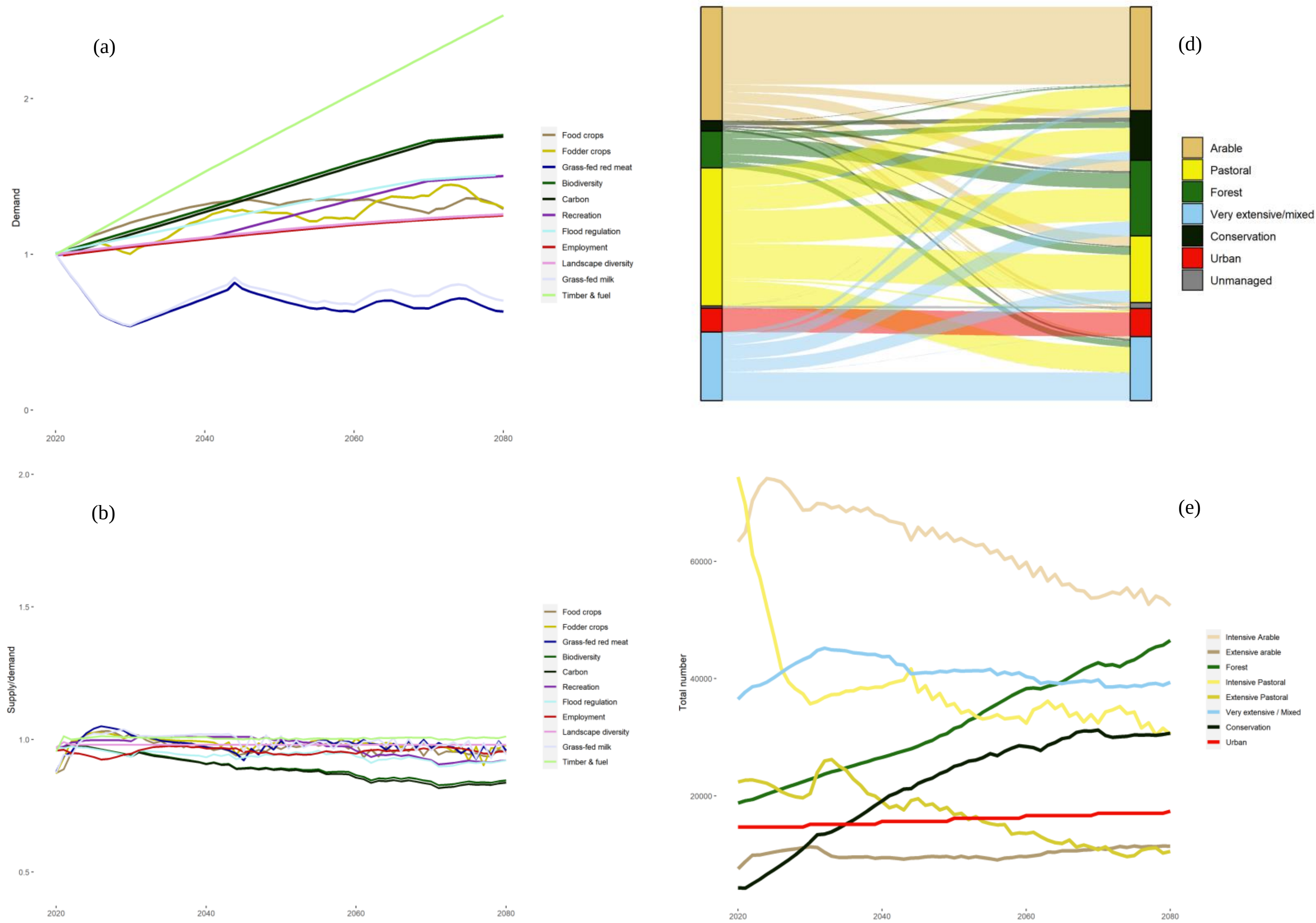


Fig. S10: Mapped results for the year 2080 in each scenario focusing on forest vegetation types. The mapped categories represent the dominant type within each cell. 'Mixed' contains forest and non-forest vegetation and land uses.


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



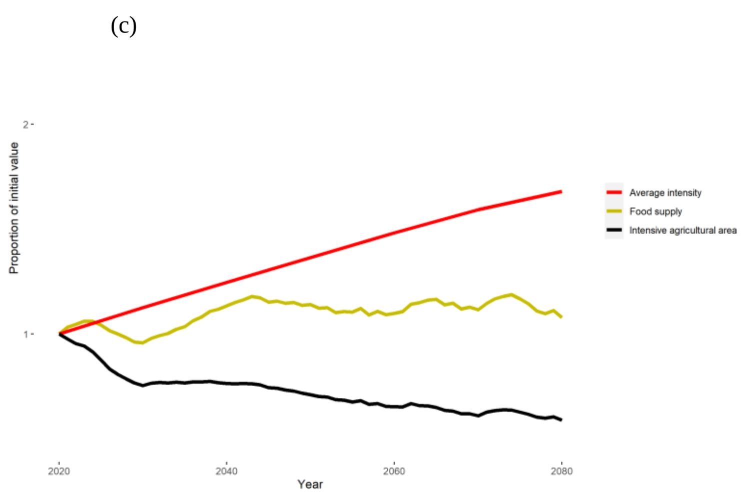


Fig. S11: Demand levels (a), supply as proportion of demand (b), land use intensity, food supply and intensive area (c), numbers of agents within amalgamated AFTs (d) and transitions between broad land use types (e) throughout SSP2-RCP 8.5 results.