TRACE document

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

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

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

The rationale of this document follows:

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

and uses the updated standard terminology and document structure in:

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

and

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

Contents

1 Problem formulation

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

Summary:

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

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

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

The questions that the model is intended to answer are:

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

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

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

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

2 Model description

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

Summary:

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

Introduction: technical overview

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

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

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

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

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

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

1. Purpose

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

2. Entities, state variables, and scales

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

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

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

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

Table 1: Variables of agents

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

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

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

3. Process overview and scheduling

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

Table 2. Basic simulation schedule for CRAFTY-GB.

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

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

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

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

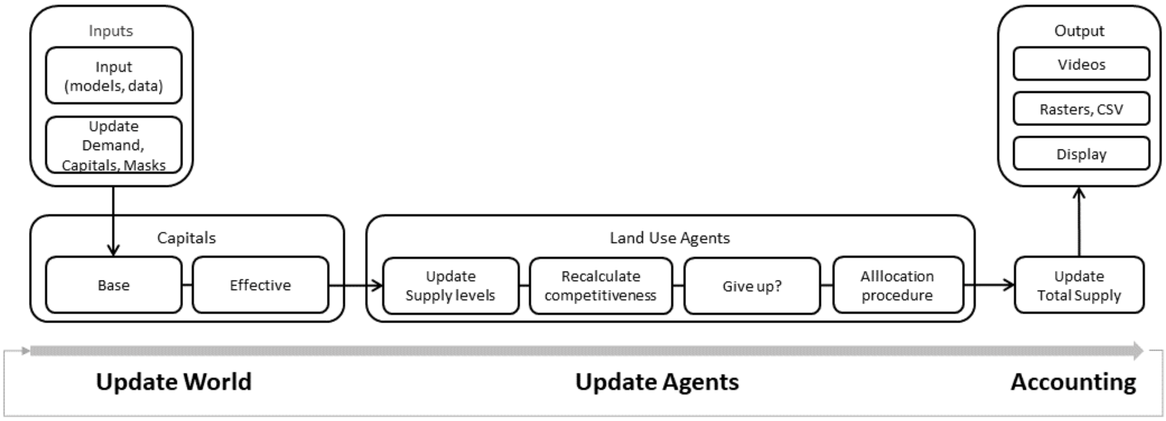

Figure 1. CRAFTY-GB flow diagram. This represents a single timestep for a single region.

4. Design concepts

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

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

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

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

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

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

Table 3: Design assumptions made in CRAFTY-GB

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

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

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

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

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

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

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

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

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

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

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

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

Table 4: CRAFTY output matrix

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

5. Initialization

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

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

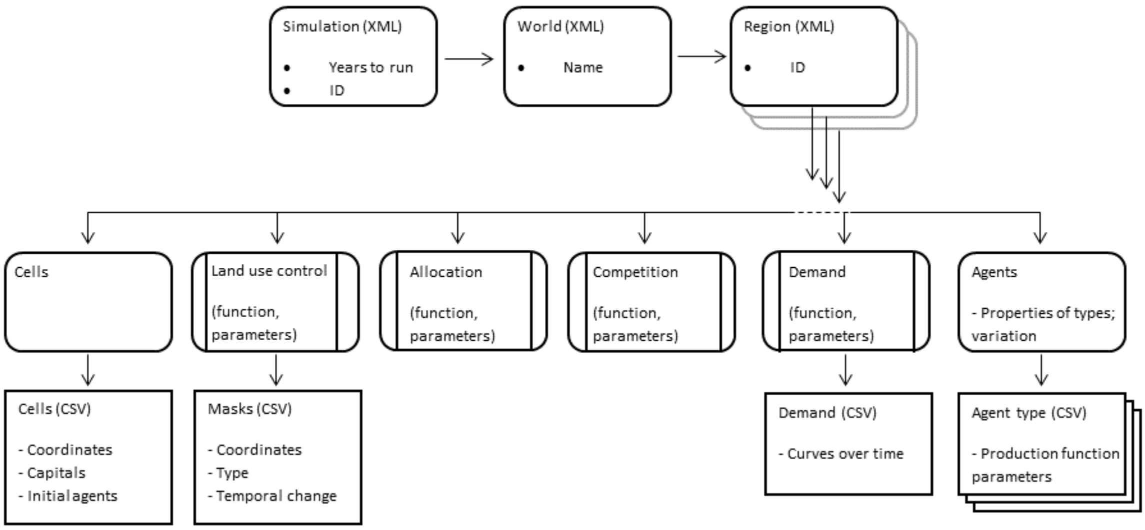

Figure 2: Overview of model configuration, showing relationships between files and what each file provides.

6. Input data

Capital levels.

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

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

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

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

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

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

Protected areas

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

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

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

Land uses (agent types).

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

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

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

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

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

Services and demand levels.

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

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

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

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

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

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

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

Services and demand levels

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

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

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

7. Submodels

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

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

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

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

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

where λ_c is a weighting factor specific to capital c.

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

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

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

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

3 Data evaluation

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

Summary:

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

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

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

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

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

4 Conceptual model evaluation

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

Summary:

Conceptual model evaluation has taken the following main forms:

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

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

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

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

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

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

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

5 Implementation verification

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

Summary:

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

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

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

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

6 Model output verification

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

Summary:

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

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

7 Model analysis

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

Summary:

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

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

8 Model output corroboration

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

Summary:

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

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

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

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