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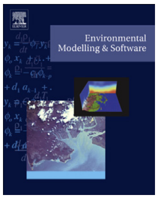

Combining agent functional types, capitals and services to model land use dynamics

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ABSTRACT

Models of land use change are becoming increasingly complex as they attempt to explore the effects of climatic, political, economic and demographic change on land systems and the services these systems produce. ‘Bottom-up’ agent based models are a useful method for exploring the effects of local processes and human behaviour, but are generally limited to small spatial scales due to the complex parameterisations involved. Conversely, ‘top-down’ land allocation models can be applied at large spatial scales, but are less adept at accounting for human behaviour and non-economic factors such as the supply of ecosystem services. Models that combine the strengths of these two approaches are required for the advancement of land use science. Here, we present an agent based land use modelling framework designed to be run over large spatial extents and to be capable of accounting for relevant forms of human behaviour, variations in land use intensities, multifunctional ecosystem service production and the actions of institutions that affect land use change. We give a full description of this framework, called CRAFTY (Competition for Resources between Agent Functional TYpes), and provide details of how it can be applied and extended, including some simple examples of its ability to model important processes of land use change. These include changes in demand for and supply of ecosystem services, variation in land use intensity and multi-functionality, and heterogeneous behaviour amongst land managers.

Software availability

Name of software:: CRAFTY
Developer:: Dave Murray-Rust
First Available Year:: 2013
Software requirements:: Java, Eclipse. Programming language: Java
Program availability and cost:: Free, GPL, https://www.wiki.ed.ac.uk/display/CRAFTY/Home
Contact Person:: Calum Brown
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1. Introduction

Land system science has developed rapidly in recent years, as interdisciplinary research questions concerning the effects of climate change, policy intervention and human behaviour on socio-ecological systems have gained importance (Turner et al., 2007). Pressures on land are high across the world as human population increases and patterns of consumption change (Smith et al., 2010). Biological diversity is decreasing as habitats and species are lost through land use and land cover change (LULCC) (Butchart et al., 2010), and climatic changes (partly driven by LULCC) are affecting land use productivity and natural processes (Pielke, 2005; De Chazal and Rounsevell, 2009). There is now widespread awareness of the need to investigate and respond to these issues in an integrated way (Heistermann et al., 2006; Heller and Zavaleta, 2009). Land use models provide a platform to combine

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Abbreviations: AFT, agent functional type; CRAFTY, competition for resources between agent functional types (name of model); ES, ecosystem services; LULCC, land use and land cover change; ABM, agent based model.

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knowledge and data from disparate disciplines to assess the interactions within and between socio-ecological systems. The land system science approach, which harnesses the synthesizing capabilities of land use models, has proven useful for exploring the effects of alternative futures (i.e., scenarios) that incorporate changes in demographics (Alcamo et al., 2011), economics (Abildtrup et al., 2006), and policy interventions (van Delden et al., 2010).

A key challenge in designing a land use model that produces applied results of genuine scientific value is the identification of a coherent system and a clear rationale for dividing endogenous and exogenous factors (Lambin et al., 2000). This challenge is amplified when land use models, which are typically created for case study applications, are applied over large spatial extents. Many anthropogenic and ecological processes are scale variant, and so contemporary land system research has fostered linkages between models that describe distinct processes at specific scales (e.g. Agarwal et al., 2000). These model combinations are typically ‘top-down’ in nature, using global economic models to simulate tradeflows that generate large-scale land demands, which are then downscaled to spatial units, often pixels, using geographic land allocation models. Local conditions therefore influence allocation, but not the extent of land use change (e.g. van Delden et al., 2010).

A characteristic of top-down approaches is the use of aggregate decision-making (occurring at the level of regions or other large spatial units), homogeneous decision-making rules, and algorithms that optimise land uses according to economic or other criteria (Heistermann et al., 2006; Jantz et al., 2010). In reality, however, the characteristics and behaviour of individual land managers differ and encompass a variety of different drivers of decision making, of which economic rationality is only one (Meyfroidt, 2012). The degree of heterogeneity between land managers means that their aggregate behaviour diverges from that assumed under traditional mathematical land allocation and macro-economic models. Bottom-up modelling approaches such as agent-based modelling (ABM) are able to represent individual decision-making and explicitly address heterogeneity in actors (Parker et al., 2003; Matthews et al., 2007), but have not yet been applied to socio-ecological systems at continental or global scales (Rounsevell and Arneth 2011; Filatova et al., 2013).

Top-down land use models also typically require a demand for land use that determines a quantity of land use that is subsequently spatially allocated. In reality, however, demands are made for spatially implicit services and goods derived from or provided by the land. A proper incorporation of demand and supply of services requires the representation of land use intensities, as these influence the quantities of goods and services that are produced per unit area. Moreover, land use intensity also influences the consequences of this production for environmental factors such as biodiversity (Kleijn et al., 2009) or soil degradation (García-Ruiz, 2010). A simple representation of land cover classes without an indication of actual underlying land uses, including management intensities, is therefore insufficient for many purposes (Letourneau et al., 2012).

A related limitation of many land use models is the assumption that land uses are monofunctional, being dedicated to the production of a single good or service (e.g., meat, cereals, timber or recreation). This assumption is reflected in one-to-one links between economic models and land allocation models in existing top-down land use models (e.g. Sands and Leimbach, 2003; Wang et al., 2004;). For example, population may be directly related to the acreage of residential areas, and demand for agriculture directly related to the acreage of agricultural land (Verburg et al., 2009). However, the majority of real-world land uses generate multiple goods and services. Such multifunctionality is increasingly encouraged by national and international policies (Lambin et al., 2000; Cubbage et al., 2007), and land use models therefore need to represent it in order to meaningfully assess the effects of such policies. However, while multifunctional land uses and density gradients have been touched upon for urban land uses (van Vliet et al., 2012), land use models that comprehensively include multifunctional land uses or gradients of land use intensity are rare (but see e.g. Willemen et al., 2012).

The ability to assess changes, synergies and trade-offs among multiple services and land management decisions is particularly important for the treatment of ecosystem services (ES). These represent the benefits that people derive from the stock of natural capital, and include provisioning services (e.g. food and fibre production), regulatory services (e.g. water cycling and climate regulation), supporting services (e.g. soil processes and nutrient cycling) and cultural services (e.g. aesthetics and recreation) (De Groot et al., 2002). While there is widespread recognition of the importance of ES, current land use models usually treat them as an impact, rather than a driving force, of simulated land changes (Schröter et al., 2005; Metzger et al., 2006). Bottom-up models allow more realistic representations of the demand and supply of ES that interact with land-use change.

Finally, individual land managers are not the only decision-making entities that affect the functions and intensities of land use. A wide range of institutions play critical roles and have substantial influence over land manager decisions through policy instruments and direct interventions. For example, institutions may promote multifunctional land uses (Piorr et al., 2009), try to maintain stability in land systems (e.g. Dibden and Cocklin, 2009), or, as in the case of the European Union's Common Agricultural Policy, support some level of self-sufficiency of production (Stoate et al., 2009). A model intended to synthesize contemporary knowledge can act as a medium for discussion and subsequently increase the decision-making capacity of policy makers, which ideally includes representation of the various ways in which institutions interactively shape land use patterns.

This paper presents a land use modelling framework designed to produce agent-based models that take account of the challenges discussed above by operating across large geographical extents and at a high spatial resolution. The framework is intended to be applied by modellers and researchers representing different study regions, and to provide an alternative to currently available top-down models working at regional to global scales that frequently play a role in supporting political decision-making (see e.g. Rounsevell et al., 2012b for a discussion). In the next section, we describe the framework in detail and explain the design features that make it appropriate for this purpose. We then describe a number of synthetic experiments used to test the behaviour of the framework, followed by the results of these experiments. Finally, we discuss these results and draw some conclusions about the framework's usefulness for large scale land change modelling. Technical details and an ODD protocol are given in Appendix A, while further experimental details are given in Appendix B.

2. Materials and methods

2.1. *The CRAFTY framework*

2.1.1. *Design criteria*

The modelling framework presented in this paper, named CRAFTY (Competition for Resources between Agent Functional TYpes) was designed in response to the issues outlined in the introduction. Specifically, the design was based on the following criteria.

- Models using the framework must be able to run at large spatial extents. This requirement holds for runtime costs, complexity, and the availability of data to parameterise and calibrate models.
- The framework must be able to represent a diversity of human behaviour and land management.

- The framework must be able to represent differences in land use intensity and productivity, as a consequence of biophysical factors as well as agent's decisions.
- The framework should be able to represent multifunctional land uses, and be responsive to the trade-offs between the provision of different bundles of goods and services.
- The framework should be able to represent a wide range of ecosystem goods and services, including those that are not explicitly defined in monetary terms such as biodiversity.
- The framework should be able to represent institutional agents and the various mechanisms by which they influence land use change.

In addition, CRAFTY is designed to be easy to apply, refine and extend — in terms of scale and complexity — from simple, stylistic microsimulation examples to empirically- and agent-based case studies, and up to full high-fidelity continental-scale simulations of land use change. This requirement implies flexibility in the sets of services, land uses and agents included, as well as provision for adding complexity and variation to individual agents. In these ways, models implementing the CRAFTY framework will therefore be able to customise it accordingly.

2.1.2. *Model details*

CRAFTY is an open source model framework written in Java. Interaction between model components is specified using interfaces, so that users can compose existing components or create their own implementations without changing the core functionality. Because many land system scientists are not trained programmers, CRAFTY can be configured and setup to run through XML and CSV files (Fig. 3). This is a form of declarative specification, where a simulation is built by composing sub-models, which are then executed by the framework.

CRAFTY uses a Euclidean representation of space operationalized as a grid of cells, each of which can represent land management units of any size. Cells are grouped into regions, which can function independently. Cells are characterized by capitals, which describe the available levels of human, social, economic, environmental and manufactured resources for service production at that location. Their use is well-established in LUCC modelling (Scoones 1998; Boumans et al., 2002). Capitals can change over time, for example because of existing land use or climatic change. Each cell object maintains a record of capital levels.

Each cell is managed by a land-manager agent that may manage more than one cell. The population of agents is drawn from a typology that defines their general characteristics. We use agent functional types (AFT) to generalize characteristics (traits) of individual actors in the system. The use of AFTs is intended to provide gains in 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. AFTs are fundamentally synonymous with HFTs (Rounsevell et al., 2012b), but describe the characteristics of modelled agents rather than those of human land managers. Individual agents within a type share basic forms of interaction with their environment (such as the production of a given set of ES), but need not be identical in any respect, with values of parameters that affect individual agents being variable and, by default, drawn from probability density functions (which may be empirically parameterised; see, e.g. Valbuena et al., 2008). As a result, applications of CRAFTY can span the range from empirically based dynamic spatial microsimulation models to process-based agent-based models, depending on the complexity of behaviours included and the parameterisation methods used (Li and O'Donoghue, 2013).

Land-manager agents can leverage the capitals available in a cell to produce a range of ES. These can represent anything that is produced from the land, with or without the intervention of land managers, such as food, timber or recreation. Formally, each land manager agent has a production function F_{A} to map capital levels C in a cell i onto provision P_{S} of a suite of services S:

$$P_{\mathrm{S}} = F_{\mathrm{A}}(C_i)$$

There is no set form for the function F_{A}, but a Cobb–Douglas-style function (Douglas, 1976) is used by default to combine optimal production levels (o_{s}); which vary at individual level) with dependence on each capital to give service productivity:

$$p_s = o_s \prod\nolimits_C c_i^{\lambda_c};$$

where λ_c is a weighting factor specific to capital c, and p_{s} is the productivity for service s (in abstract production units). Functions of this form are well established as representations of land use productivity (e.g. Fulginiti and Perrin, 1998, Martin and Mitra 2001).

The 'value' of a given level of ES provision depends upon the level of demand for these services and overall supply levels. Demand is defined exogenously on behalf of an assumed non-spatial population within each region, and satisfied by the endogenous supply of ES by agents within the region. The quantification of demand for ecosystem services remains an on-going conceptual and operational challenge (Costanza et al., 2007, Carpenter et al., 2009). In particular, difficulty exists in quantifying cultural attitudes towards ES and how these vary across space. Acknowledging these challenges, CRAFTY has been constructed to enable different implementations of demand to be incorporated and applied to different spatial extents and imposed exogenously rather than explicitly incorporated as a process in the framework. Having specified demand for an ES, the difference between supply and demand is the residual (or unmet) demand, R. Residual demand (R) drives marginal utility of service production (i.e. the utility attributed to the production of one additional unit of a service), using the following function

$$m_s = u_s(r_s)$$

where m_s is the marginal utility for service s, u_s is a function that describes the utility of production of service s and r_s is the residual demand for service s.

The functional form of u_s has purposefully been left open, so that model users may include different services with contextualised societal implications. For instance, $u(r) = c$ (i.e. constant marginal utility) is consistent with a scenario of completely free trade with another, larger region, so that (in economic terms) the level of local production does not affect the market price of the service. Alternatively if $u(r)$ takes negative values (e.g. in a simple linear response), overproduction is actively penalised.

For a given bundle of ES provision (typically that provided by an agent leveraging a cell), the competitiveness (or utility) is given by:

$$U_S = \sum_S p_S m_S$$

In addition to land manager agents, CRAFTY explicitly represents institutions that can influence land uses as institutional agents. As a foundation for representing the complexity of institutional behaviours, we stylised three different actions that can be extended or complemented by additional actions created by CRAFTY users. First, institutions can manipulate capital levels. This can represent the effects of policies such as improving education provision to increase the expertise of the workforce or making credit more readily accessible (e.g. Swinnen and Gow, 1999). Second, by providing incentives (e.g. subsidies) for certain ES (production-based) or for managing the land in certain ways (activity-based), institutions can adjust agent competitiveness to improve service production (e.g. Huang et al., 2011). Third, institutions can enforce land use constraints that forbid land manager agents from taking over cells, effectively protecting an existing land use or restricting land use types in a specific area (e.g. Skinner et al., 2001).

Several institutions may be active in one region, and may have cumulative effects on capitals, competitiveness and restrictions. Taking I_{comp} to be the overall institutional effect on competitiveness, and I_{cap} to be the overall institutional effect on capital levels, a land manager agent (a) with individual production function $f_{a,s}$ has effective competitiveness at i ($U_{a,i}$):

$$U_{a,i} = \sum_s I_{\mathrm{comp},i}\left(f_{a,s}\left(I_{\mathrm{cap},i}(C_i)\right)u(r_s)\right)$$

2.1.3. *Land-use change*

Land use change may occur within CRAFTY through abandonment of land, adoption of unmanaged land by new agents, and the exchange of land from one agent to another (see Fig. 1). Land abandonment occurs when an agent's utility drops below an abandonment threshold, and designates the cell(s) occupied by that agent as being available to others. Adoption of abandoned or unmanaged land involves competition between agent types (based on an average agent within that type) within the framework. Each agent type calculates a competitiveness score for the available cell ($C_{a,i}$) and the probability of acquisition ($P(a)$) is proportional to this competitiveness.

$$P(\alpha) \propto c_{a,i}^{\gamma},$$

The winning agent type spawns a new agent of that type and draws agent attribute values (e.g., thresholds, productivity) from the distributions defined for that type. Finally, an allocation procedure runs between existing and potential agents to determine ownership changes based on competitiveness. This includes direct competition, where potential agents attempt to take over cells from existing agents. If a potential agent's competitiveness on a cell is greater than the existing agent's by a value larger than the existing agent's 'giving-in' threshold ($c_{\mathrm{new}} \geq c_{\mathrm{curr}} + \mathrm{giving\_in}_{\mathrm{curr}}$) then a new agent drawn from the potential type acquires the cell. Once an agent is located we assume it does not change location, due to the large computational costs involved in such an operation on large grids.

Giving-in and giving-up thresholds provide a stylised interpretation of factors that make human behaviour deviate from narrowly defined optimality. Their values can be used to represent personal connection to land, a way of life, or resistance to change, among other relevant characteristics (e.g. Siebert et al., 2006, Gorton et al., 2008; see Table A1), and are directly interpretable as minimum returns (in terms of economic and/or non-economic utility) that land managers are willing to accept from their land or land use. Agents may also age over the duration of a model run; this can affect demographic-sensitive attributes (e.g. giving-up or giving-in thresholds, productivity), and can be extended to include other demographic attributes. These characteristics are properties of an agent and they are accounted accordingly.

2.1.4. Model operation

The flow of operations within CRAFTY (Fig. 2, Appendix A) commences by updating (or, at first, initialising) the decision-making context for land use agents – the levels of demand, capitals and any active policies at the beginning of each time step (which, we suggest, should normally be taken to represent a single year).This has two stages.Firstly, updates are made to the levels of demand across each region, and levels of capitals within each cell. Values for demand and capital levels are typically loaded from external files, either as direct values or as functions to be sampled from (Fig. 3). Mechanisms are also available to modify capitals dynamically during run-time, for example in order to model land degradation through intensive agriculture, or productivity responses to climate change, allowing for a coupled human-environment feedback loop. Secondly, institutional agents may update their policies if the desired land-use effects have not occurred, according to user-defined criteria.

The land manager agents then respond to the new land system context. First, each agent updates its level of supplied services, based on current capital levels. The total supply of each service per region is then calculated. Next, current demand levels are used to calculate each agent's competitiveness, including the effect of any institutional policies. Any agents who give up are then removed from the model. Finally, new agents take over unmanaged land and competition for land takes place, again mediated by the effects of any active institutional policies. Once all of the land manager agents have been updated, final accounting is carried out. This involves calculating total supply and demand, creating output files, displaying model state and creating videos of changes in land management. The supply of ES does not necessarily meet demand at this (or any) point because all land use transitions are subject to the behavioural settings of agents and institutions, which may override the differences in utility that reflect unmet demand levels.

Altogether, a number of modelling assumptions are made in the design of CRAFTY, and we have tried to summarise and justify these above and in the Appendix (Table A1). The outcome of these assumptions may differ under different applications of the framework to different study areas. Since this is the case, we are unable to provide an overarching validation of the framework within the scope of this publication, as has been argued as necessary by some land-use scientists (e.g., Bennett et al., 2013). Subsequent instantiations of CRAFTY are likely to require some form of validation to gain traction and credibility of results. Nevertheless, CRAFTY's ability to reproduce realistic processes of land use change is investigated below, and we used unit tests to ensure that all the code used in CRAFTY operated correctly.

2.1.5. Data requirements

Data requirements vary considerably between applications of the CRAFTY framework. In theoretical applications of the kind presented here, no empirical data is necessarily needed for model setup, while real-world applications may have considerable requirements that are likely to vary in form and extent from case to case. Nevertheless, certain requirements – and challenges – are shared by all real-world CRAFTY applications (along with other land use models). These relate to the establishment of spatially explicit capital values, agent typologies and characteristics (at both typological and individual level, including the description of intra-type variation), patterns of demand and supply, ES sets and utility values. Some of these are likely to be relatively easy to satisfy, while others may require approximations or experimental variations to be made. Further details of the data requirements of real-world CRAFTY applications are given in Appendix C, along with examples of relevant data sets.

2.2. Experimental design

To illustrate the application of CRAFTY, we present a series of computational experiments that systematically increase in complexity, based on factors driving land use change. The experiments are designed with simplicity rather than verisimilitude in mind, to demonstrate the effects of different mechanisms within the framework. Hence, in each experiment there are a limited number of agents, capitals and services. Similarly, the complexity of supply, demand, and competition dynamics are kept to a minimum (Supporting Information demonstrates the use of CRAFTY at large spatial extents (Appendix B)).

Each experiment is run on a 100 × 100 cell grid that consists of hills and valleys, without any explicit representation of human settlements or water bodies. Four services are considered: production of meat and cereals for food (representing societal dietary preferences); production of timber; and the provision of recreation. Six capitals underpin the provision of these services (see Table 1 and Fig. 4): productive potential for cereals, livestock and timber, nature value, and economic and social capitals (the background wealth and social support abilities of the region). The spatial distribution of the productive and natural capitals is described in Table 1 and illustrated in Fig. 4. The marginal utility function for providing services in these experiments is a linear function of their residual demand.

Each simulation includes up to five agent types. Their modelled interpretations are given in Table 2, and they may be described as follows:

- Commercial crop farmers represent intensive monocultural farmers that produce large quantities of cereals only. Consequently they have a strong sensitivity to productive potential, and a need for reasonably high economic capital to support their requirements for machinery, labour and other inputs.
- Non-commercial crop farmers represent multifunctional part-time farmers. They are dependent on crop productivity, but are quite adaptable and can still produce cereals and recreation in less productive regions. They are not strongly affected by economics, but benefit from social capital, where present, which allows peer support networks to develop and increase productivity.
- Livestock farmers (commercial and non-commercial) are analogous to the equivalent crop farmers.
- Foresters are multifunctional land managers, primarily dedicated to the production of timber, but also allowing recreation on their land.

Details of the experimental scenarios are given in Table 3. The first pair of scenarios, 0a and 0b, are designed to illustrate the differences between conventional top-down land allocation models and bottom-up models where the total acreage per land use type depends on the agent's decisions. In the former case, an exogenous demand for each type of land use drives land allocation that occurs according to locational characteristics such as (some form of) suitability. Agents are implicitly assumed to achieve uniform and optimal production levels, irrespective of their location. In scenario 0a, agents are assigned land on this basis, with cells ranked by their capital levels for each service and then assigned in order until demand is satisfied (where levels of different capitals are equal so that no single service has an advantage, cells are randomly assigned). Demand is kept low, so that not all of the land is required to fulfil demand. In scenario 0b, productivities depend upon capital levels as described above, and agents compete for land on the basis of their productivities.

The remaining scenarios are intended to demonstrate the response of the model to increasingly complex conditions, and its ability to simulate realistic drivers and processes of land use change. In these, demand is increased so that the entire simulated world is required for production, generating competition for land between agents. Scenarios 1a and 1b explore the behaviour of the model over a limited number of time steps with constant demand levels, and with mono-functional land uses (scenario 1a) and with multifunctional land uses (scenario 1b, which also represents the reference scenario for subsequent scenarios). In scenarios 2a and 2b we extend the simulation period and investigate the effects of increasing demand

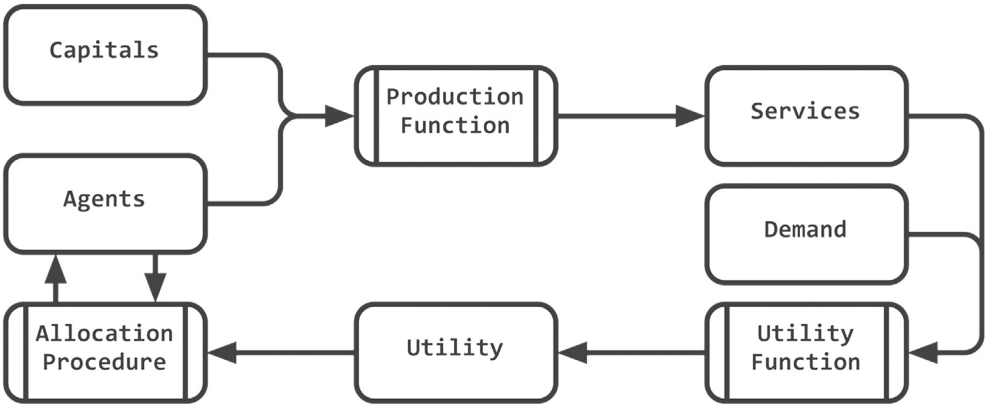

Fig. 1. An overview of CRAFTY showing the relationship between key components of the framework and agents. The actions of institutional agents are shown in Fig. 2.

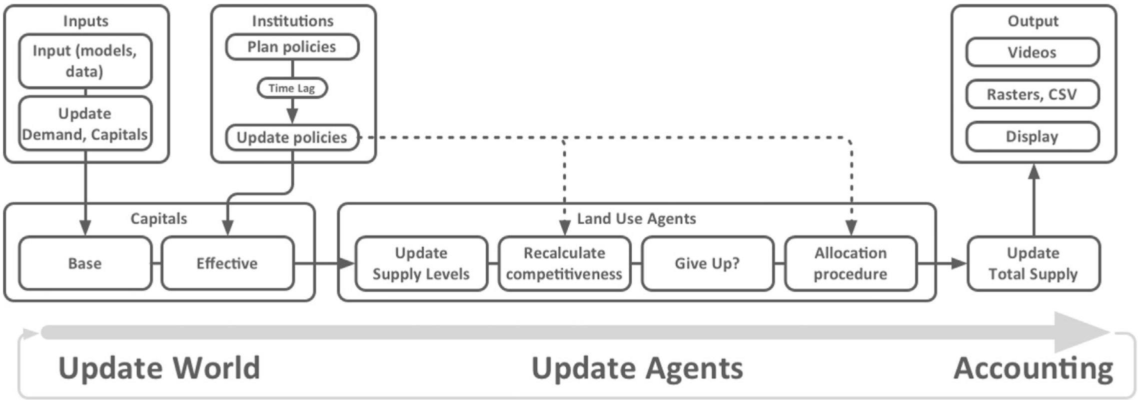

Fig. 2. CRAFTY flow diagram. Solid lines are hard sequencing constraints; dotted lines are direct influences without temporal requirements. This represents a single timestep for a single region. The lower light grey line represents feedbacks between time steps. At the first timestep, CRAFTY reads in all files and parameters from CSV and XML files (see Fig. 3) and so begins initialisation with the 'Inputs' tab above.

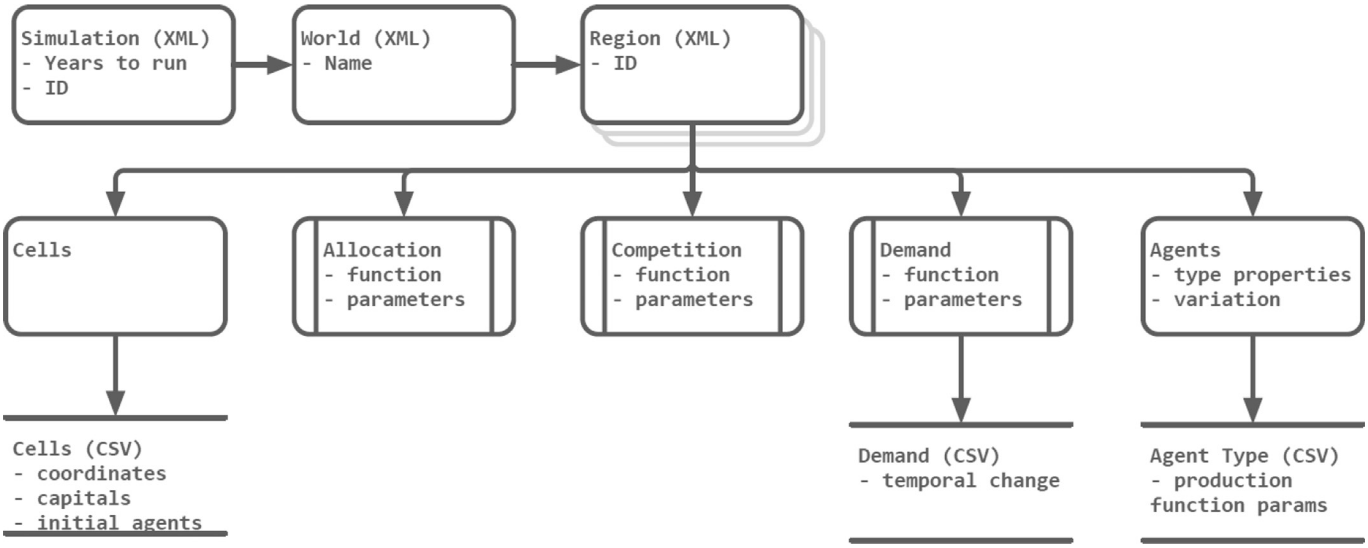

Fig. 3. Overview of the configuration of CRAFTY, showing relationships between files and what each file provides. CSV files provide basic data about cells, demand levels and agent production functions, and any temporal change in these, while XML files are used to identify these CSV files, to parameterise allocation, competition and demand functions, and to parameterise agent behaviour. An application of CRAFTY can therefore be set up using only the CSV and XML files shown here.

for meat and cereals (scenario 2a) and increasing economic capital (scenario 2b). Finally, in scenarios 3a, 3b, 3c and 3d we add behaviour that is typological (scenario 3a), individual (scenario 3b), spatially variant, driven by social capital (scenario 3c), and institutional (scenario 3d).

The design and parameterization of the model in each scenario is outlined in Table 3. In addition, this table presents our predictions about the results of these scenarios. We run 30 realisations of each scenario in order to explore variation between realisations and show results from these in terms of the generated land use pattern, the productivity, the productive efficiency and the number of agents by type. We also give specific parameter values that vary between the scenarios in Tables B1 and B2, and make the experimental application used here freely available online[3].

3. Results

Examples of final land-use maps generated by Scenarios 0a, 0b and 1a are shown in Fig. 5, while Figs. 6–9 show example land-use maps and other complete results, including temporal changes in the supply of services, the productivity of land use agents, and the total number of agents on the grid, for each simulation in scenarios 1, 2, and 3.

Scenario 0 illustrates the difference between demands expressed as areas of land and as quantities of services. Our results show that, with low demand levels, considerably more land is used by the CRAFTY implementation (ABM) than by the land allocation solution, which assumes uniform productivity equal to that of the highest found in the region (Scenarios 0a and b, Fig. 5). The ABM allows production per unit area to depend on the productive capacity of each location, and so requires a larger number of cells to fulfil demand and thus produces a far more mixed land use pattern (Fig. 5b). Because demand levels are low, there is little reason for agents to seek out more productive areas.

Scenario 1 demonstrates the effect of demand for services being increased to a level at which it cannot be satisfied in the modelled world by mono-functional (scenario 1a) or multifunctional land uses (scenario 1b). In both cases, competition between agents is strong and the land use configuration resembles that

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[3] See https://bitbucket.org/cbrown23/EMS_CRAFTY_world

Table 1
Capitals used in example simulations and descriptions of their forms in the modelled world (these forms are not necessarily intended to capture real-world characteristics of these capitals).

Capital	Form
Productivity: Cereals	High in the plains, decreases sharply with height
Productivity: Livestock	High in the plains, decreases gradually with height
Productivity: timber	Equally productive everywhere below a tree line, beyond which it declines rapidly to zero
Nature value	Increases with height (because of assumed long-term anthropogenic disturbance at lower elevations)
Economic	Constant for the region but can change in response to socioeconomic scenarios
Social	Uniform in most scenarios; higher in one area (upper valley) in Scenario 2c.

under land allocation (scenario 0a) (Fig. 6a). The inclusion of less-intensive, multifunctional land uses principally affects marginal land, where agents now produce a combination of services (Fig. 6b), slightly decreasing food production (Fig. 7b). The differing intensities of land uses separate out along the capital gradients, with commercial cereal production dominating the lowest (most fertile) areas and commercial livestock farming forced onto higher ground. Beyond this there is a rough transition to non-commercial cereals and then non-commercial livestock, before marked bands of forestry and non-commercial livestock increasingly occupy the high ground (Fig. 6b). This result (scenario 1b), is the baseline simulation against which subsequent scenarios are compared.

When demand levels for meat and cereals are increased over time (scenario 2a), the final land use map is far more clearly divided between land uses, because commercial farming outcompetes non-commercial farming in most areas (Fig. 6c). This limits the production of non-food services and slightly increases their productive efficiency (Figs. 7c and 8c). Increases in meat production are found to occur partly at the expense of cereal production, which is driven by the replacement of non-commercial cereal farmers with commercial livestock farmers (Fig. 9c). Increases in economic capital (Scenario 2b) clearly favour commercial producers, who take over land from non-commercial producers and contribute to an intensification of agriculture, as predicted (Figs. 6d, 9d). Consequently, food production increases while the area and production of non-food services decreases. Average productivity increases for all services except timber production, which is constrained in less productive, elevated areas (Fig. 8d). Oscillations in production levels occur in all scenarios so far, as commercial and non-commercial producers compete for land on which they are nearly equally productive, repeatedly altering demand levels and their relative competitiveness.

The results of scenarios 3a onwards show the effects of some non-economic motivations of land manager agents. The introduction of typological behavioural thresholds in Scenario 3a blurs the spatial boundary between commercial and non-commercial agent types (Fig. 6e), as non-commercial agents persist under competition from commercial agents. This prevents changes in the numbers of agents of each type prior to 2015 (Fig. 9e), while each type responds smoothly to demand and capital level changes after

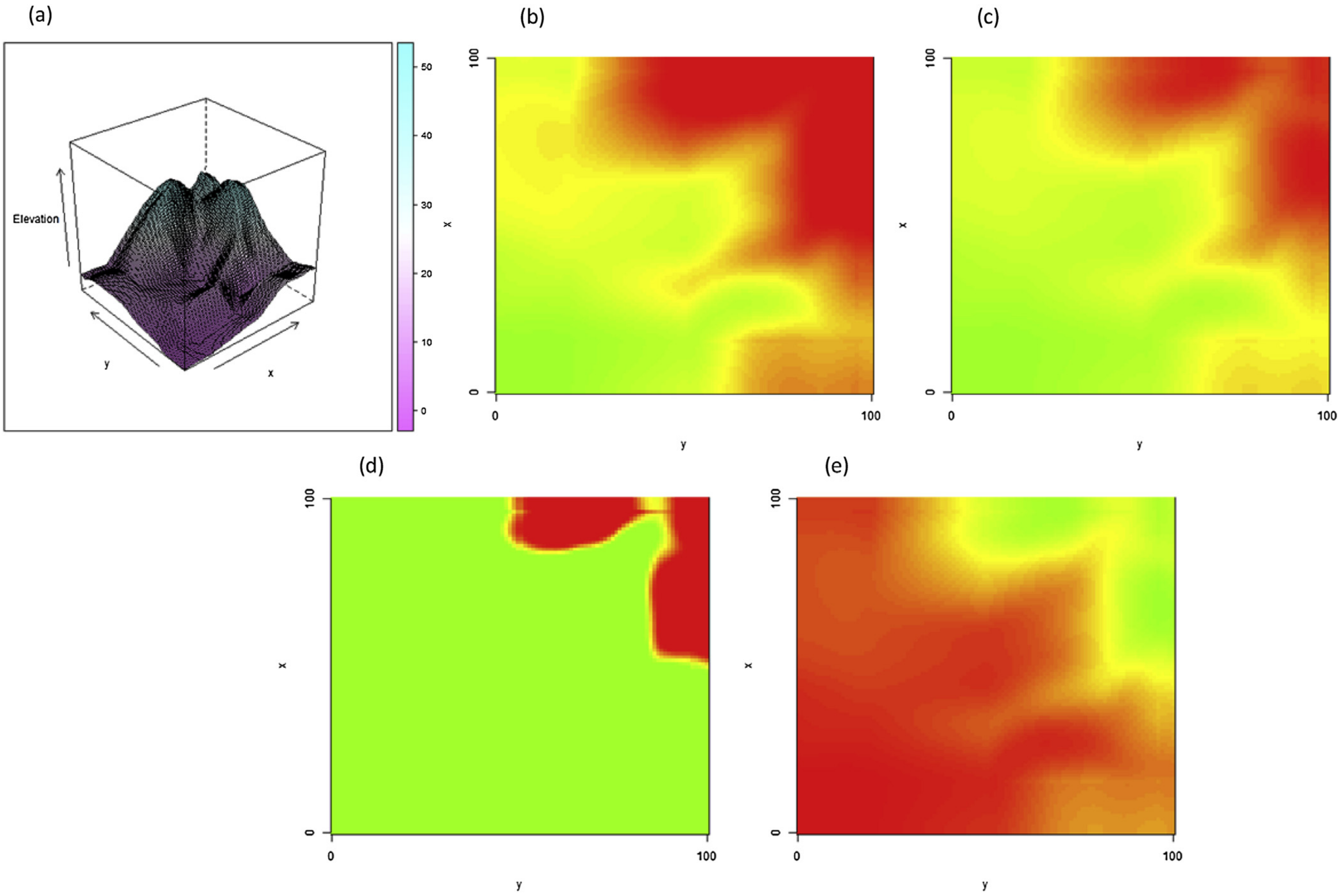

Fig. 4. Elevation map and derived capital maps for the simulated world. (a) elevation, (b) cereal productivity, (c) livestock productivity, (d) timber productivity, and (e) natural capital. All capitals vary between 0 and 1, with red representing values close to 0 and green representing values close to 1. Economic capital (not shown) initially takes a uniform value of 0.5, before varying as described in the text. Social capital is not initially included and then varies as described in the text.

Table 2
Agent characteristics: services produced and capital sensitivities.

Agent type	Produces	Sensitive to
Commercial cereal farmer	Cereals, no recreation	Very sensitive to cereal productivity, economic capital; mildly sensitive to social capital
Non-commercial cereal farmer	Cereals, small amount of recreation	Mildly sensitive to cereal productivity, nature; very sensitive to social capital
Commercial livestock farmer	Meat, no recreation	Very sensitive to livestock productivity, economic capital; mildly sensitive to social capital
Non-commercial livestock farmer	Meat, small amount of recreation	Mildly sensitive to livestock productivity, nature; very sensitive to social capital
Forester	Timber, recreation (but no recreation in Scenarios 0a and 0b)	Very sensitive to timber productivity, nature value, social capital

2015, reaching similar final configurations as in scenario 2b. This is particularly clear in plots of overall production levels, which are nearly constant prior to 2015 in scenario 3a, as agent behaviour dampens the variations and oscillations visible in previous results (Fig. 7e).

Scenario 3b illustrates the effects of heterogeneity in agent characteristics, the result of which is clearly visible in the final land-use map (Fig. 6f). This map shows far more heterogeneous land uses across the region, as some agents tolerate lower productivity and relative competitiveness than others. As a consequence, the productivities of different land uses is lower than in previous scenarios (Fig 8f) for all except forester agents (who, in occurring more widely across the region, are more likely to encounter favourable capital levels than unfavourable). The decline in the number of non-food and non-commercial producers after 2015 is reduced, as is the increase in commercial farmer numbers (particularly cereal farmers, who were already located in the most productive areas in previous simulations) (Fig. 9f).

Scenario 3c shows the effect of spatial variation in social capital. Higher capital levels in the bottom-right of the map provide more support for foresters and non-commercial farmers, improving the productivity of these agents and enabling them to out-compete commercial farmers (Fig. 6g). This has a clear knock-on effect in areas where social capital is unchanged, with commercial agents dominating because altered production levels have given them a competitive advantage (e.g. top-left of map). Overall production levels and productive efficiencies therefore remain similar to, though slightly higher than,those in the previous scenario (Figs. 7g and 8g), with non-commercial livestock farmers being the greatest beneficiaries across the region (Fig. 9g).

Scenario 3d, finally, includes a single institution that intervenes in the competition process to support producers of recreation when their competitiveness falls below a threshold value. This intervention tends to favour an uncompetitive recreation producer over a more competitive (productive) one, and so has little effect on total levels of recreation (Fig. 7h). By allowing foresters to expand into areas previously managed by commercial farmers, however, it increases timber production and the average productivity of livestock farmers (Fig. 8h). It also reduces the effect of raised social capital levels in the bottom-left of the region, allowing commercial livestock farmers to take over land there (Fig. 7h). The unanticipated knock-on effects of institutional intervention are therefore demonstrated, and would lead to a policy adjustment by the institutional agent in a full treatment.

4. Discussion

4.1. CRAFTY performance

Our experiments were designed to illustrate how CRAFTY fulfils the requirements for land use models identified in the introduction, and how the representation of land use decision making in CRAFTY mimics real processes of land use change using a relatively simple structure. The presented experiments demonstrate that the CRAFTY framework allows users to represent explicitly the demand and supply of ES, variation in intensity and types (e.g. multifunctional) of land uses, and represent heterogeneity in the behaviour of land-manager agents, which facilitate modelling socio-ecological systems across large spatial extents. Although the experiments presented here may be described as microsimulation rather than agent based modelling, they demonstrate the capacity for describing decision-making processes within CRAFTY, and these may be more detailed or complex in specific applications. Interactions between agents and the bases on which individual decisions are made are expected to be of particular interest to users of the framework.

We first explored the practical differences between land allocation models that assume invariant production levels and models that take account of varying levels of land productivity. Results indicate that there can be a considerable difference in the total land area needed to fulfil the demand for ES. This difference depends, of course, on the specified invariant production level in the top-down model. However, since the acreage required to fulfil this demand in the CRAFTY implementation depends on the land allocation there is no way to *a priori* determine the appropriate average productivity. Another consequence was that, while more land was used, less large-scale specialisation occurred until demand levels were increased to the point where competition for land was relatively intense. These results highlight a weakness in the separation of the area and allocation of land uses that vary in productivity, as occurs in many continental scale land use models (Verburg and Overmars 2009; van Delden et al., 2010).

Next, we showed that the representation of multifunctional land uses allows the simulation of trade-offs in the land system as a result of changes in demand for different ES. In scenarios with increasing demands for food, multifunctional land managers with low food productivities relinquished land to commercial farmers with high productivities. This conversion came at the cost of the supply of other ES (specifically recreation, in our experiments) that are not commonly treated in land use models. Representing trade-offs between ES is a clear requirement for land use models, not only because multifunctionality and trade-offs are both essential components of the land use system (de Groot, 2006; Verburg et al., 2009; Rounsevell et al., 2012b), but also because multifunctional land uses are increasingly being adopted and encouraged in policy (Cubbage et al., 2007; Jongeneel et al., 2008; Zasada, 2011).

Another important consideration is the role of institutions in driving land use change (or preventing it), and the ability to model this is one of the distinguishing characteristics of CRAFTY. Our results demonstrated the wide-ranging and often unintended consequences of a single institutional intervention, and CRAFTY allows institutional agents to respond adaptively to these consequences (see Appendix A for further information). In reality, a wide range of local, regional, national and international bodies intervene in land uses through many different mechanisms and to a number of different ends (e.g. van der Sluis et al., 2012). The differences in the

Table 3
Description of the storyline, purpose, parameterisation and our prediction for each of the scenarios presented in the text.

Scenario	Storyline	Purpose	Parameterisation	Prediction
0a	Land managers compete for best land but produce equal quantities of single services	To demonstrate top-down land allocation solution with uniform productivity and without multifunctionality	Analytical solution that does not employ model; allocates land under fixed, low demand levels assuming all agents produce to their maximum potential	Demand will be satisfied using minimum land area
0b	Productivity of land determines service supply levels	To demonstrate bottom-up model that allows productive intensity to vary with land characteristics	Begin with random agent distribution and run for 15 timesteps under constant, low service demand. Giving-up and giving-in thresholds are set to 0.	Service demand will be satisfied using a larger area than scenario 0a; rapid specialisation of agents to areas of favourable capital levels.
1a	Productivity of land determines service supply levels, under increased demand	To demonstrate effect of demands that cannot be met	As scenario 0b but with higher demand for services	Higher demand will lead to less or no unmanaged land, stronger competition and more optimal land use allocation than in 0b
1b	Land managers specialise by intensity: either high production of single service or lower production of multiple services	To demonstrate effect of competition between mono- and multi-functional agents	As scenario 1a, but with the addition of multifunctional agent types	Lower mean production per cell due to multifunctional agent types; monofunctional agents locate in more productive areas than multifunctional agents
2a	Population increase leads to greater food demand and increasing wealth alters dietary preferences, so demand for meat grows more rapidly than demand for cereals.	To demonstrate handling of dynamic demands and trade-offs between services that result	As scenario 1b, but after 15 timesteps cereal demand doubles and meat demand increases 2.5 times over another 10 steps, before remaining constant for 5 timesteps.	Increase in area used for food production at expense of forestry, hence reduction in recreation provision and productive efficiency of food, as more marginal land is used to satisfy demand.
2b	Population increase leads to greater food demand, but also generates an increase in economic capital, providing financial support for land managers	To demonstrate intensification rather than expansion under favourable capital conditions and rising demand	As in scenario 2a, with addition of doubling of economic capital levels as food demand increases.	Intensification of agriculture expected as rising economic capital favours commercial farming on less productive land. Smaller changes in the areas of each land use than in Simulation 2a are expected as a result.
3a	Land managers are not economically rational but vary in willingness to abandon land depending on type: foresters and non-commercial farmers accept lower returns and less willing to give in to competition.	To demonstrate the effect of typological agent behaviour on land use change process	As scenario 2b, with commercial farmers having giving-up thresholds of 0.3 and foresters and non-commercial farmers having giving-in thresholds of 0.3	Delayed transition to commercial agriculture as increases in demand and economic capital initially fail to overcome agents' unwillingness to change land use
3b	Land managers also vary individually, with some more committed to their land use than others	To demonstrate effect of individual agent behaviour	As scenario 3a, with addition of individual (Gaussian) variation around each agent type's giving-up or giving-in thresholds	Individual behaviour expected to smooth temporal fluctuations seen in previous scenarios, and to alter the final productive efficiencies of each service
3c	Individual variation is not purely random; inhabitants of the upper valley have strong sense of community and peer-support networks, increasing productivity and reducing the likelihood of giving-up or giving-in	To demonstrate handling and effect of systematic spatial variations in human behaviour such as (spatial) social networks.	Social capital takes value of 1.0 in upper valley (lower right corner); non-commercial producers and foresters are more sensitive to social capital than others (Tables 1 and 2).	Distinct transition in the upper valley expected
3d	Producers of recreation with low competitiveness are supported by institutional intervention designed to protect low-intensity land management	To demonstrate handling of institutions	An institution subsidises recreation production by multiplying its utility by 1.2 where the producing agent has a competitiveness less than 0.2	Agents with low production levels take over land from monofunctional agents; service production drops

ways that formal and informal institutions access and effect drivers of land-use change suggest that the creation of an institutional typology could be of great interest and use in land change science research and specifically modelling land use and land cover change (Rounsevell et al., 2012a).

The most important feature of any land use ABM is its treatment of agency. Scenarios 3a, 3b, and 3c showed the influence of non-economic behaviour in CRAFTY, including within-type and spatial behavioural heterogeneity. Results indicated that such behavioural factors yield sub-optimal allocation of land use agents, as indicated by productivity. This reflects a wide range of non-economic motivations such as culture or family tradition, which play important roles in the decision making of real-world farmers (Gorton et al., 2008; Siebert et al., 2006; Polhill et al., 2010). It is possible to include behaviours of varying complexity in applications of CRAFTY (see Section 2.1.2, above), and these behaviours may or may not be empirically or theoretically linked with the real-world characteristics of land managers.

The design requirement that instantiations of CRAFTY should be capable of running at large spatial extents implies not only the robust treatment of the above factors, but also an efficient design that makes large-scale applications feasible. This is typically

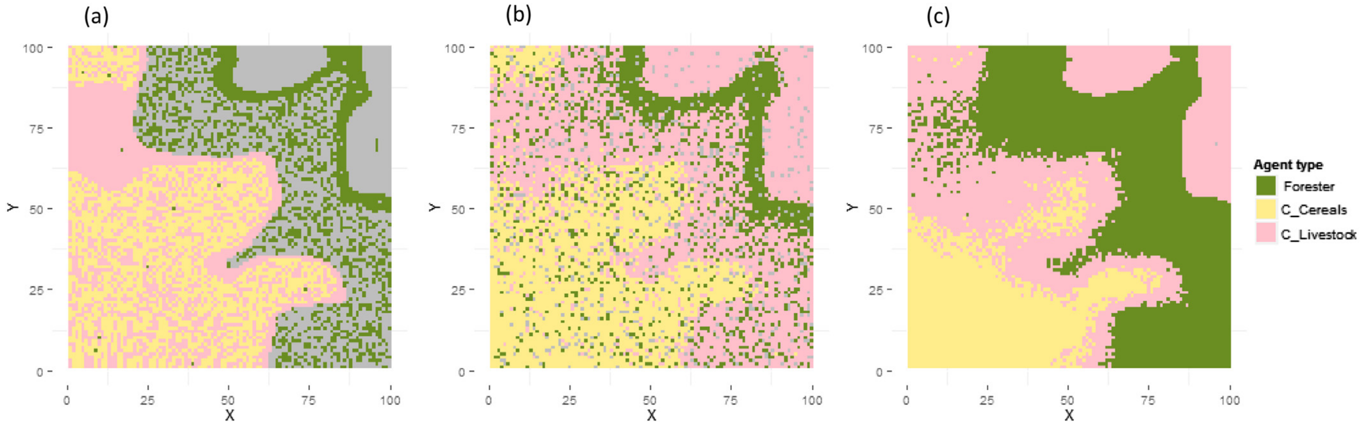

Fig. 5. Maps of final agent locations in one realisation of each Scenario: (a) Scenario 0a (land allocation); (b) Scenario 0b (CRAFTY land competition); (c) Scenario 1a (CRAFTY land competition). Demand levels are equal in (a) and (b) and substantially higher in (c). These maps establish baseline outcomes for the series of scenarios presented in Fig. 6 onwards.

achieved through the combination of economic, social and ecological models, each of which may be more or less complex than the others (e.g. De Aranzabal et al., 2008; Quétier et al., 2008; Gaube et al., 2009). The structure of CRAFTY, by contrast, endogenises a full range of ES and entities with influence over land use, from individual land managers to large-scale institutions. The model's ability to operate at large scales depends therefore upon its efficiency. CRAFTY has been developed with this in mind and its structure, as described above, is intended to be both flexible and efficient.

The maximum duration of the presented scenarios was 120 s (i.e., 10,000 cells). Initial tests using approximately 1 million cells show an average timestep of 1 h (Appendix B). At a resolution of 30 m, which is often used due to the availability of Landsat imagery, 1 million cells (900 km^2) would represent an area equivalent to the size of the city region of Berlin (~892 km^2). Alternatively, if our grid cells represented a medium resolution still useful for representing land use change and land management (e.g., 1 km^2), then a spatial extent equivalent to the UK, Ireland, and France would be represented. While CRAFTY has not yet been applied empirically at very large scales, its success and speed in small-scale tests indicate that this will be possible.

4.2. Future research

The application of CRAFTY to simulate real world, continental scale land use changes requires further work, not least in terms of characterising land managers and relevant institutions through typologies. The importance of land manager behaviour expressed via giving-up and giving-in thresholds, productivities and capital sensitivities, was confirmed by our experiments. Nevertheless, we did not investigate certain aspects of behaviour that CRAFTY is designed to incorporate. These include agent age, which is known to be a strong determinant of land use decisions, particularly among farmers (Potter and Lobley 1992; Siebert et al., 2006), and the effects of spatial and non-spatial peer groups on decision-making (Siebert et al., 2006; Polhill et al., 2010).The incorporation and treatment of such additional behaviours will largely be determined by whether applications of the framework are intended for microsimulation or agent-based modelling (Li and O'Donoghue, 2013).

Finally, there are some limitations to the approach with respect to the parameterisation of real world applications. One relates to the expression of diverse human behaviours and characteristics in a workably small number of numerical values such as giving-up and giving-in thresholds. While these are believed to offer a robust description of the most important individual variations between land managers, it is difficult to establish their absolute values for any given agent or type except where minimum acceptable returns can be discovered or estimated (Appendix C). It may be impossible to model all observed forms of behaviour using the parameters available in CRAFTY. Similar difficulties relate to quantifying the effects of institutions, and to assuming the validity of externally derived demand values. In attempting to ground such parameter values in empirical data, modelling efforts like ours are also susceptible to an acknowledged bias in the literature towards marginal regions where rapid land use change has occurred. While an increasing amount of relevant data is freely available, this is certain to remain a constraint. The calibration of ecosystem service utility functions is another challenge in model application, and a variety of existing methods, may be used depending on the context (e.g. Paetzold et al., 2010; Sherrouse et al., 2011). We also currently use an unrealistic simplification that land use change occurs only when a different modelled agent (potentially representing the same land manager) takes a cell over, although we plan to relax this assumption in later model development.

5. Conclusion

Experimental results have shown that the CRAFTY framework provides a powerful tool for microsimulation and agent-based modelling of land use change in theoretical settings, suggesting that it is suitable for real world applications. The model includes a robust treatment of ecosystem services, multifunctional land uses and land use intensities. A separation of code and data ensures that no case-specificity is built into the model, so that new data can easily be incorporated. This also allows different users to apply the model to a wide range of applications in any region. This bottom-up model offers an alternative for currently available top-down modelling approaches for continental-scale land use scenarios and policy testing. Specifically, it complements macro-economic approaches by allowing for agent heterogeneity and non-economic behaviour in land use decision making.

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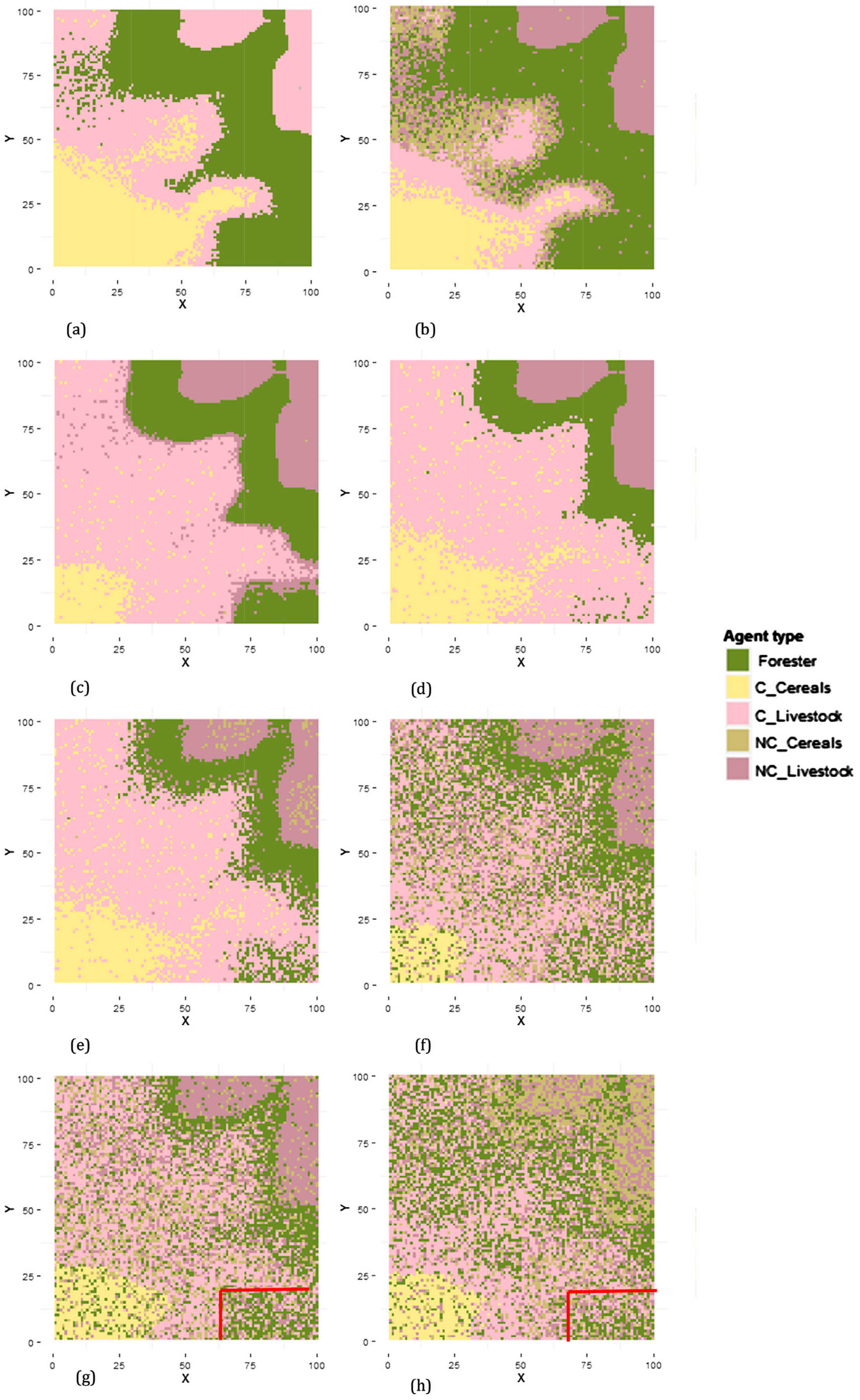

Fig. 6. Land use maps at the end of one simulation in each of the scenarios 1a–3d. Scenario 1a = (a), scenario 1b = (b), scenario 2a = (c), scenario 2b = (d), scenario 3a = (e), scenario 3b = (f), scenario 3c = (g), scenario 3d = (h). The area of higher social capital in scenarios 3c and 3d is outlined in red in (g) and (h). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

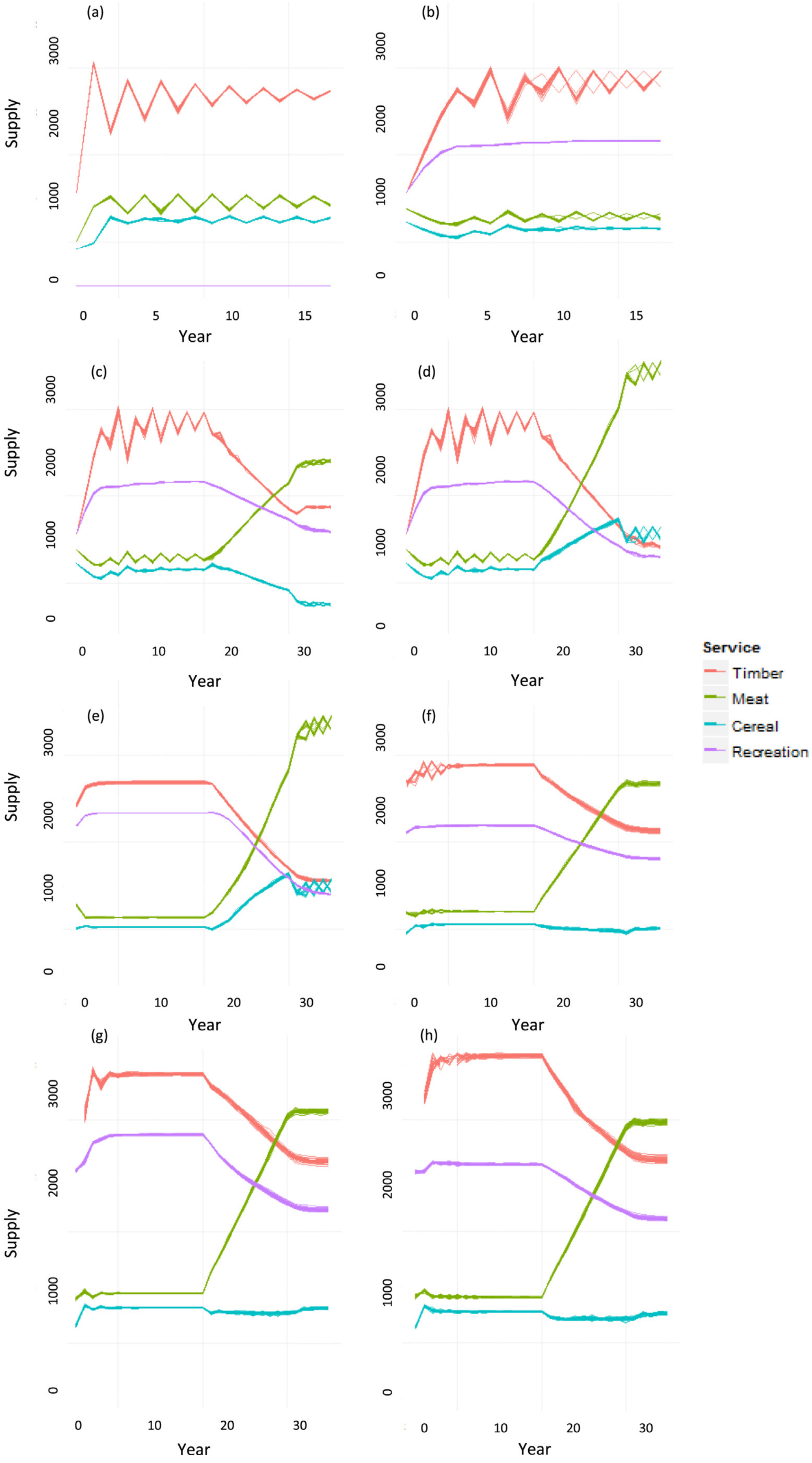

Fig. 7. Total productivities for each service in each of the scenarios 1a–3d. Scenario 1a = (a), scenario 1b = (b), scenario 2a = (c), scenario 2b = (d), scenario 3a = (e), scenario 3b = (f), scenario 3c = (g), scenario 3d = (h). For each scenario, 30 realisations were completed and the results from each are plotted as a single line. Scenarios 1a and 1b ((a) and (b)) have constant demands for services, while the remaining scenarios are extended and have demand levels that change as described in the text and Table 3.

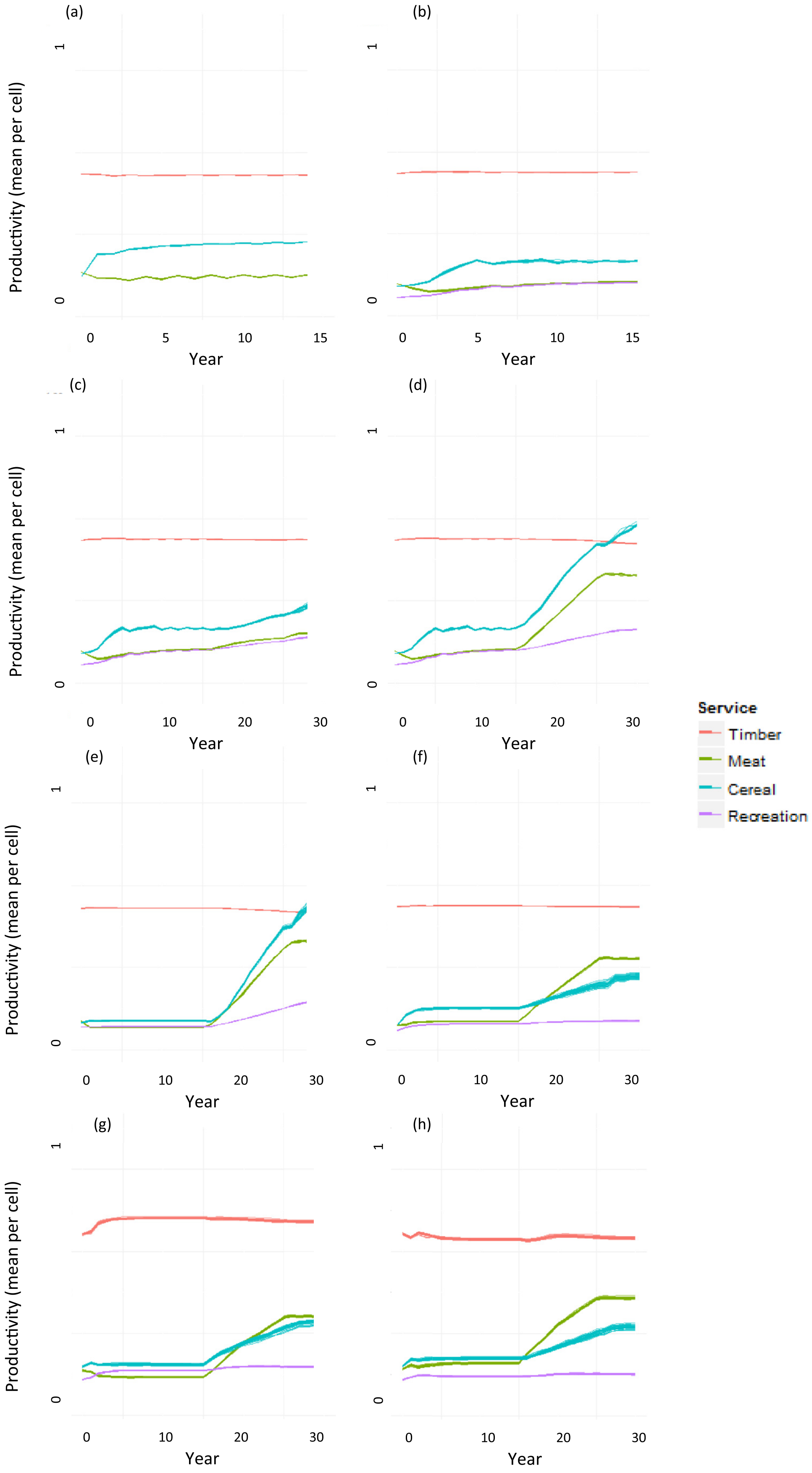

Fig. 8. Average per-cell productivities for each service in each of the scenarios 1a–3d. Scenario 1a = (a), scenario 1b = (b), scenario 2a = (c), scenario 2b = (d), scenario 3a = (e), scenario 3b = (f), scenario 3c = (g), scenario 3d = (h). For each scenario, 30 realisations were completed and the results from each are plotted as a single line. Scenarios 1a and 1b ((a) and (b)) have constant demands for services, while the remaining scenarios are extended and have demand levels that change as described in the text and Table 3. No recreation was produced in scenario 1a (a).

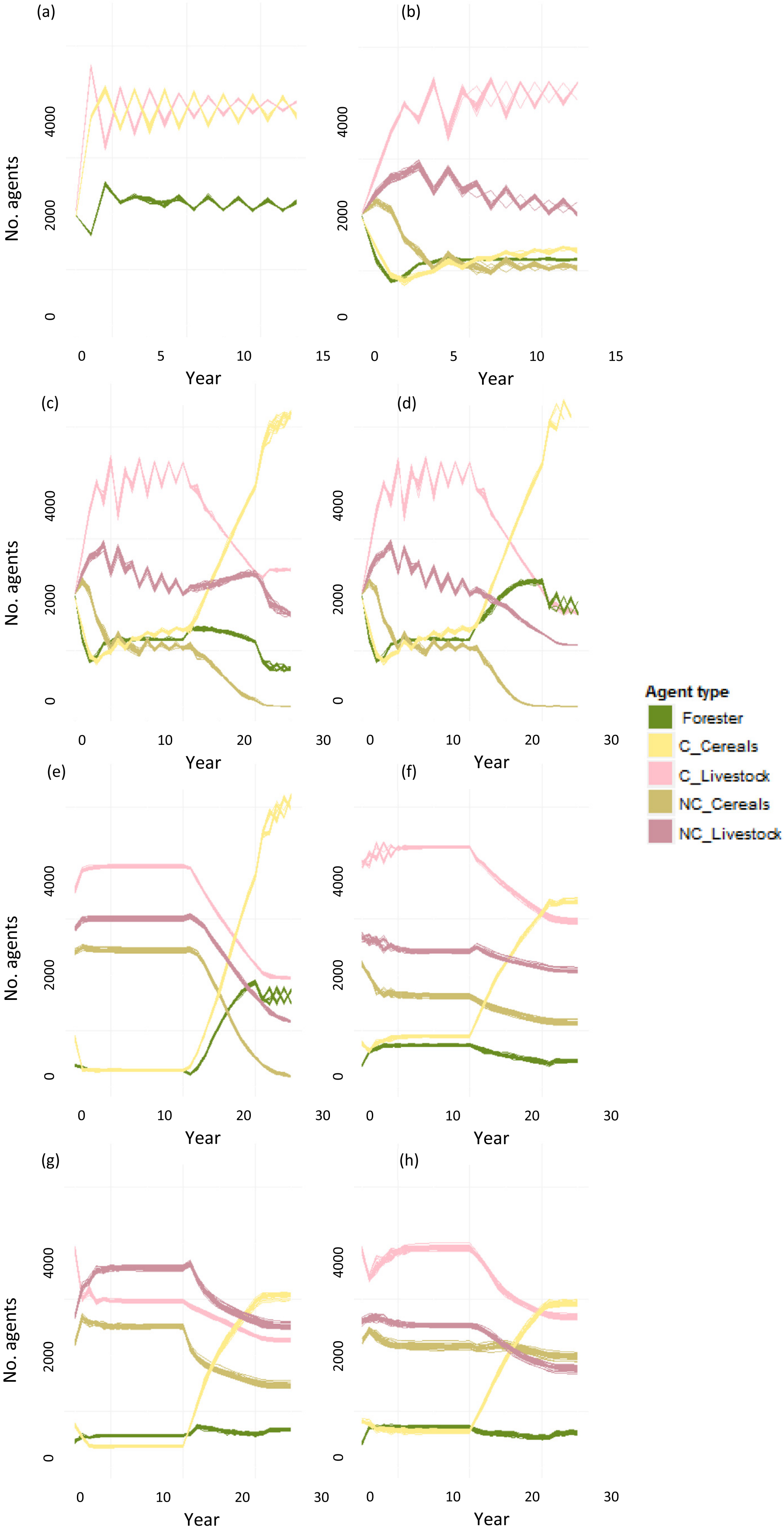

Fig. 9. Agent numbers by type in each of the scenarios 1a–3d. Scenario 1a = (a), scenario 1b = (b), scenario 2a = (c), scenario 2b = (d), scenario 3a = (e), scenario 3b = (f), scenario 3c = (g), scenario 3d = (h). For each scenario, 30 realisations were completed and the results from each are plotted as a single line. Scenarios 1a and 1b ((a) and (b)) have constant demands for services, while the remaining scenarios are extended and have demand levels that change as described in the text and Table 3. The abbreviations 'C' and 'NC' refer to commercial and non-commercial agents, respectively.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2014.05.019.

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