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Description of an agent-based model of European land use change, literature meta-analysis and model inputs

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Preface

This Deliverable is divided into three sections describing an agent-based model (ABM) of land use change, developed for application at the European scale (Section 1), a literature meta-analysis conducted to support this development (Section 2), and the inputs required to establish a final European model along with possible data sources for these inputs (Section 3). Example theoretical applications of the model are also presented.

The ABM presented here can be used in relatively small, focused applications such as the VOLANTE case studies, but can also be applied at very large spatial scales, where considerable variation exists between land uses and between land managers. Within the VOLANTE project, the model is now intended for application at EU scale, where it will provide a basis for comparison with ‘top-down’ models of land use change being developed in Work Package 7, which do not account for land manager (agent) behaviour. The ABM will therefore also allow consideration of the effects of human behaviour as part of the roadmapping process (Work Package 13). Deliverable 6.3 will build on the work presented here and describe the expansion of the model to European scale and detail its final uses in the VOLANTE project.

Model development was primarily carried out by Dave Murray-Rust, with assistance from all other authors. Calum Brown was responsible for the example model applications, and Jasper van Vliet for the meta-analysis of agricultural land use change. Calum Brown and Dave Murray Rust were lead authors of Section 1, Jasper van Vliet of Section 2, Calum Brown and Jasper van Vliet of Section 3, and Calum Brown of Appendix A1. All authors contributed to the planning and text of the Deliverable.
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SECTION 1: Combining Human Functional Types, Capitals and Services to model European land use dynamics

Abstract
In this Section we present the agent-based model (ABM) of land use change in Europe being developed for the VOLANTE project. We discuss the background to and requirements for this model, detail the model's structure, give some examples of its operation in theoretical contexts, and outline its future development and wider significance.
1.1 Introduction
In recent years, land system science has developed rapidly, as interdisciplinary questions concerning the effects of climate change, policy intervention and human behaviour on Socio-Ecological Systems (SES) have gained importance (Turner et al., 2007). Pressures on land are high across the world as human populations increase and patterns of consumption change (Smith et al. 2010), biological diversity is decreasing as habitats and species are lost (Butchart et al. 2010), and climatic changes are already having effects on land uses and natural systems, with greater changes expected (Pielke 2005). There is now widespread awareness of the need to investigate and respond to these issues in an integrated way (Heistermann et al. 2006; Heller & Zavaleta 2009). Land use models provide a platform to study these issues and explore future changes as a consequence of alternative conditions, including demographic changes (Alcamo et al., 2012) economic scenarios (Abildtrup et al. 2006), and policy interventions (Van Delden et al., 2010).

Ecosystem services
Of particular importance to land use models in this context is the consideration of interactions between land uses and ecosystem services. These services reflect the flow of 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 these services, they are rarely treated robustly in models of land use change (Schröter et al. 2005; Metzger et al. 2006). This is partly because societal recognition and valuation of ecosystem services, while having considerable impact on their provision, are not constant geographically or temporally (e.g. Martín-López et al. 2007; Potschin & Haines-Young 2011). The treatment of ecosystem services as externalities or as secondary to economic model components can therefore conceal the true effects of land use changes and misrepresent their feedbacks to societal demands - particularly where economic systems drive large-scale land use transitions without accounting for environmental consequences (Robertson & Swinton 2005; Godfray et al. 2010; Lambin & Meyfroidt 2011).

Scale of application
Land change analysis and modelling has also mainly focussed on local to regional scales, while land uses and ecosystem services are influenced by many national and international policies. This suggests that large-scale models that capture such influences may be particularly informative. The European Union (EU) is an appropriate subject for such a model due to its (partial) political coherence: many policies concerning land uses and cover apply at this scale (e.g. the Common Agricultural Policy, the Habitats and Birds Directives); a common and partially protected market is fundamental to the Union; and many of its geographical boundaries occur on real physical features such as oceans. Furthermore, there is a need for large-scale land use change models to inform the design and coordination of Europe-wide policies that influence land uses (van der Sluis et al. 2012).

The need to select geographical scales that allow coherent systems to be modelled, or at least that provide a clear rationale for dividing endogenous and exogenous factors (Lambin et al. 2000; Verburg et al. 2004), has prompted the linkages or combinations of models that describe distinct processes at different scales (e.g. Verburg & Overmars 2009; van Delden et al. 2011; Lotze-Campen et al. 2012). In many cases, such linkages are implemented in a ‘top-down’ manner: global economic models simulate trade-flows that influence the demand and supply of commodities at a large regional resolution. The results of these models are then downscaled to spatial units, often pixels, using
geographic land use allocation models. Local conditions therefore influence allocation, but not the final quantities of land use change. All operational land change models in the EU describe the system via this top-down approach (e.g. Rounsevell et al. 2006; Verburg et al. 2012; van Delden et al. 2010).

Human behaviour

Bottom-up models, and agent-based models (ABMs) in particular, have become very popular in land science in the past decade (Filatova et al. 2013). Such models give far greater emphasis to local or individual decision-making and explicitly address heterogeneity in actors and environmental factors. However, such models have not yet been developed at continental or global scales (Rounsevell et al. 2012; Filatova et al. 2013). Instead, models of this scale treat land managers as a single homogeneous entity that optimises land uses according to economic or other criteria (Heistermann et al. 2006; Verburg et al. 2012b).

In reality, the behaviour of individual land managers differs, and certainly does not comply with any single concept of ‘rationality’ (An 2012; Meyfroidt 2012). As a result, their aggregate behaviour diverges from that assumed under land allocation models. This can have dramatic impacts on land use change and on the assessment of the effects of policies and other interventions. Agent-based models, being well-suited to accurate description of a wide range of individual behaviours and decision-making strategies, are therefore crucial to accurate investigation of land system change (Matthews et al. 2007; Robinson et al. 2007). Furthermore, the development of methods for applying ABMs at large spatial scales is an important challenge for land system science (Rounsevell & Arneth 2011).

Multifunctionality and intensity

The scope and complexity of LUCC research means that other simplifications have so far been essential, so that several important elements remain under-developed or absent from LUCC models. Not only are land users divided into groups (Valbuena et al. 2010) with assumed economic rationality (Parker and Filativa, 2008), and interacting ecological systems treated as steady-state or via simple trends (Verburg et al. 2004), but another particularly common assumption is that land uses are uni-functional, being dedicated to the production of a single good or service (such as meat, cereals, timber or recreation). This assumption is reflected in the links between economic models and land allocation models, which are typically one-to-one - for example population is directly and proportionally related to the acreage of residential areas, and demand for agriculture is directly and proportionally related to the acreage of agricultural land (Verburg et al. 2009).

In real-world systems, however, the great majority of 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 its widespread adoption is a key land use issue. However, while multifunctional land uses and density gradients have been explored for urban land uses (Van Vliet et al., 2012), we are not aware of any application that comprehensively includes multifunctional land uses or gradients of land use intensity.

Additionally, the production of goods and services differs from location to location as a function of the productive capacity of the land, current land management and the local or global demand for these goods and services. In particular, the intensity of land management not only influences the direct production of goods and services but also the consequences of this production for environmental factors such as biodiversity (Kleijn et al 2009) or soil degradation (Garcia-Ruiz 2010). A simple representation of land cover classes without an indication of actual underlying land uses, including
management intensities, therefore does not suffice for many impact assessment purposes (Verburg et al 2012a).

**Institutions**
Land use models are also incomplete without some treatment of the role of institutions in prompting or preventing land use change. Indeed, institutions are of fundamental importance to the landscape of Europe, having substantial influence over land managers through policy instruments and direct interventions. For example, several international bodies promote free trade and economic liberalisation, and the European Common Market (Sleuwaegen 1988) and bodies such as the WTO (Subramanian & Wei 2007) actively support these in Europe. More commonly, governments and other institutions enact policies designed to protect particular land users in particular areas and to maintain stability in their land systems (e.g. Potter & Burney 2002; Baldwin 2006; Dibden & Cocklin 2009). Such policies may attempt to balance the interests of productive and economically important industries, protection of biodiversity, and democratic planning control (Lambin & Meyfroidt 2011), or they may simply be examples of protectionism (Potter & Burney 2002; Dibden & Cocklin 2009). Increasingly, as above, they are used to promote ‘multifunctional’ land uses (Wiggering et al. 2006; Piorr et al. 2008). The European Union’s Common Agricultural Policy (CAP) has several such objectives (Sampson & Yeats 1977; Potter & Tilzey 2005). Originally intended to maintain a level of self-sufficiency in food production in Europe, it was criticised for its tendency to stimulate overproduction and environmentally damaging intensification of agriculture (e.g. Rabbinge & van Latesteijn 1992; Stoate et al. 2001), which later modifications have sought to resolve (Piorr et al. 2008).

**Purpose of model**
Here, we describe the structure and give example applications of an ABM of land use change intended to operate at the European scale. The model takes account of individual human behaviour, the effects of climatic and environmental change, and may be adapted to a range of applications and scenarios. The model is founded on accurate but efficient and tractable description of individual behaviour and decision-making, making it a powerful tool for investigating SESs on large scales. The ABM applies exogenous demand levels which agents attempt to meet according to behavioural rules and service productivity. Where individual behaviour is absent, agents effectively optimise their land uses according to supply and demand levels, but as the variety and strength of behaviours increase, these become a dominant factor in determining land use change. Our framework allows the adoption of different land uses, variations in the intensity of land uses, diversification into multifunctional land uses, land abandonment and competition for available land.

The description of the model below depends on several concepts. Capitals describe the available levels of resources for service production in a particular location (they are not stocks or flows). Their use is well-established in LUC modelling (Scoones 1998; Boumans et al. 2002), and their identities may be varied to suit the application in this model. Human Functional Types are a concept used to group land use agents by their productive behaviour. Land-use modellers are familiar with the use of typologies, especially in constructing agent-based models as representations of real-world actors (Robinson et al. 2007; Valbuena et al. 2008). Typologies allow generalisations of the attributes (traits) of individual actors in a system that simplifies model development and application, and provides a more transparent representation of agent decisional processes and behaviour. Human Functional Types (HFTs) are proposed here as a means of generalising models of human-environment interactions. The HFT concept derives from a direct analogy with the use of Plant Functional Types (PFTs) in Dynamic Vegetation Models (e.g. Lavorel et al. 2007). Finally, Services, including Ecosystem
Services, are demanded by society and supplied by land users who compete for land resources. Services can represent anything that is produced from the land resource, with or without the intervention of land managers.

1.2 Materials and Methods

Design Criteria
The design criteria we used for specification of our model were based on the issues outlined in the introduction, as follows:

1) The model must be able to run at European scale. 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 the full range of societal demands, including those which are not explicitly defined in monetary terms such as preservation of nature.

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 and land management found across the EU.

5) The model should be easy to refine and extend – in terms of scale and complexity – from simple, stylistic examples to empirically-based case studies, and up to a full European simulation. This includes incorporating different sets of services, capitals, land uses and agents, as well as adding complexity and variation to individual agents.

Model Overview
EuroABM is based on a grid of cells, typically representing 1km². Each cell has defined levels of a range of Capitals, which describe the availability of particular social, environmental or economic resources. Cells are grouped into Regions, which function autonomously. Within a Region, a non-spatial population is assumed to exist and to generate demands for certain Services, such as food, timber and access to nature. Each Cell may be managed by a single land use Agent, which uses the Capitals available on the Cell to provide Services according to its own Production Function. The Competitiveness of a given level of service provision can be calculated on the basis of societal demands, overall supply levels and marginal utility functions. Agents can make decisions based on their current competitiveness, and participate in an Allocation procedure with potential new agents that results in land use change (see Fig. 1.1).

FIGURE 1.1: system overview: relationships between main actors and model components.
We give detailed definitions of the above terms in the following, throughout which $c$ represents the level of a particular capital and $C$ represents the levels of all capitals; $s$ represents the provision of a single service and $S$ the provision of all services; $d$ represents the demand for a single service and $D$ the demand for all services. Characteristics of an agent are subscripted with $A$ (e.g. $age_A$), and those of a Cell are subscripted $i$ (e.g. $C_i$).

**Cells and Capitals**
Each Cell in the model has a level for each Capital, representing the availability of various resources. These typically include human and social factors, infrastructure, economics and natural capitals. These Capital levels can be explicitly altered over time as drivers of land use change (e.g. greater wealth increasing access to Capitals, or improvement in education giving a more skilled population).

**Population, Services, Demand and Utility**
We make the assumption that there is a population present in any given Region, which has a certain level of demand for services $D$. This represents the needs of the population for consumables such as food, timber and housing, and less tangible desires such as those for ecosystem services and recreation opportunities. 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:

$$m_s = u_s(r_s);$$

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 form of the function $u_s$ has purposefully been left open, so that the model can include many different services with different 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 $u(r)$ can take negative values (e.g. in a simple linear response), overproduction is actively penalised.

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

$$U_S = \sum_S p_s m_s;$$

where $p_s$ is productivity for service $s$ (in abstract production units).

**Land Use Agents and Potential Agents**
A land use Agent is able to leverage the Capitals available in a Cell to provide a range of Services. Each Agent has a production function, which maps Capital levels onto Service provision:

$$P_S = F_A(C_i)$$

Again, there is no set form for this function, but typically a Cobb-Douglas function is used to combine optimal production levels ($o_s$) with dependence on each capital to give service productivity:

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

where $\lambda_c$ is a weighting factor specific to capital $c$. 
In addition to their ability to produce services, agents have two attributes that influence land use dynamics. If an agent’s competitiveness falls below a “giving up” threshold that 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 a competing agent’s competitiveness is greater by a value larger than a “giving-in” threshold then the first agent relinquishes that 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. Between them, these parameters provide a stylised interpretation of factors that make human behaviour deviate from narrowly defined optimality, such as personal connection to a landscape or way of life, or resistance to change. Finally, agents may have an age that will be updated by the model, and can be extended to include further demographic attributes.

Agents are drawn from a typology that defines general characteristics of agents, and which is based on the Human Functional Types (HFT) approach. As well as defining extant agents, the typology allows for new agents to be created, and for the comparison of productivity, utility 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, including production functions, age and giving up/giving in thresholds can be drawn from distributions to provide within-type heterogeneity.

**Allocation**

Land ownership within the model 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 individual characteristics such as age or a competitiveness score that falls below the 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 \( \gamma = 0 \) gives a random selection and \( \gamma \to \infty \) tends towards optimal selection. Finally, 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: \( c_{\text{new}} \geq c_{\text{curr}} + \text{giving up}_{\text{curr}} \). Different allocation models are possible, however, to explore the relationships between human behaviour and local or global optimality (see experiment details).

**Institutional Agents**

As previously noted, modelling institutions is crucial to understanding European land use dynamics. While understanding – let alone simulating - the full complexity of policies which impact land use is a considerable challenge, we have constructed a mechanism which can be used to create stylised versions of many policies. In this, a Region includes a collection of Institutions, each of which can influence land use transitions in three different ways. Firstly, institutions can manipulate capital levels. This simulates the effects of policies such as improving education to increase the expertise of the workforce (modelled as an increase in human capital) or making credit more readily accessible (increasing economic capital). These manipulations are carried out spatially, so could be used, for instance, to give support to declining rural areas.
Secondly, institutions can adjust agent competitiveness to improve the production of certain services. This is equivalent to the provision of incentives (e.g. subsidies) for certain services (production-based) or for managing the land in certain ways (activity-based). Again, these adjustments are spatially explicit, so particular areas can be targeted for incentivisation. Finally, institutions can forbid agents from taking over cells. This can be intended to protect existing land uses or to restrict the land uses allowed in a particular area.

Several institutions may be active in a Region, and they have cumulative effects on capitals, competitiveness and restrictions. Taking $I_{\text{comp}}$ to be the overall effect on competitiveness, and $I_{\text{cap}}$ to be the overall effect on capital levels, an agent's effective competitiveness is:

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

**Model Operation**

Figure 1.2 shows the flow of operation within each tick (or timestep) in the model. We have tried to design as simple a structure as possible, while maintaining necessary flexibility. Each timestep starts by updating the decision-making context for land use agents – the levels of demand, capitals and any active policies. This has two stages:

- Updates are made to the levels of demand across each region, and levels of capitals within each cell. These are typically loaded from external files, either as direct values or as functions to be sampled from on a yearly basis. Mechanisms are also available to dynamically modify capitals, for example in order to model land degradation through intensive agriculture, allowing for feedback loops in this SES.
- All of the institutional agents then have a chance to update their policies if the desired land use effects have not occurred, in particular their modification of effective capital levels.

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, including the effect of any institutional policies.
• Any agents who want to give up are removed from the model.
• The active allocation procedure now runs, assigning new agents to unmanaged land and allowing other land transitions to take place, again mediated by the effects of any active policies.

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.

**Technology and Initialisation**

EuroABM is an Open Source model, built on reusable software components and written in Java. Early versions of the software used the RepastS framework, but EuroABM is now an independent piece of software, although it can use RepastS for some visualisations and run management if desired.

Interaction between components is specified using interfaces, meaning that users can create their own implementations where desired. For example, the Agent interface specifies that agents have an ID number, manage a certain number of cells, have a current competitiveness, belong to a certain type and so on. If a user wants to implement their own type of agent, they are free to do so as long as it fulfils the contract of the Agent interface. At present, different types of agents are available with more or less individuality, depending on the trade-off between modelling behavioural mechanisms and runtime cost.

Configuration and setup for a run is done through the use of XML files, which are bound to Java classes using the SimpleXML library. 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 to be run. Each XML file defines one or more entities within the simulation, and will typically include other files for subcomponents. An overview of how configuration is carried out is given below, and summarised in Figure 1.3.

• A Scenario file encodes overall parameters of the simulation – the number of 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:
  o The coordinates and capital levels of the cells in the Region, typically using a CSV or ASCII raster file
  o The Allocation, Competition and Demand models used within the region, often using CSV files to specify time-varying quantities (e.g. changes in demand)
  o A set of agents and their properties, making use of CSV files as necessary.
In each of these cases, the files will specify the Java classes to be used along with their parameters, making it extremely easy for users to incorporate their own code in the model.

In contrast to the declarative approach taken to configuration, EuroABM uses a fixed scheduling approach. Fixing the order of scheduling is less flexible than a truly declarative approach (e.g. RepastS’s scheduling mechanisms), where each component can choose how it should be scheduled. This is conscious design decision made because our experience suggests that it is easier to communicate a model that has a single file encoding the flow of operations.

EuroABM provides a range of displays to help understand model behaviour. Each of the submodels has a display, which is either purely numeric or graphical, showing curves for variables of note. A range of spatially explicit outputs is also available; these include agent type, capital levels, competitiveness scores, supply of services, and so on (see results section). Any of these displays can be used to create videos of the model’s behaviour over time.

### 1.3 Scenario/Experiment Design

In order to illustrate the effectiveness of this conceptualisation of the dynamics of land use change, we present a series of simulations of gradually increasing complexity, based on representing factors which are often important in land use change. The simulations are designed with simplicity rather than verisimilitude in mind, so that the effects of different mechanisms are shown as clearly as possible. Hence, there are limited numbers of agents, capitals and services, and the complexity of supply, demand and competition dynamics are kept to a minimum.
All of the experiments are run on a 100x100 grid – this is an arbitrary choice made to balance fast runtimes with a map that is detailed enough to be interesting. The world consists of hills and valleys, without any explicit representation of either settlements or water bodies. Four services are considered: production of meat and cereals for food (so that societal preferences about diet can be represented); production of timber; and provision of recreation areas. Six capitals underpin the provision of these services (see Table 1.1 and Figure 1.4): 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 driven by height, while economic capital is spatially uniform and social capital, where used, is high in one area and uniform elsewhere (see below; Fig 1.5f). Five agent types are used; these are described below, with their modelled interpretations given in Table 1.2.

- Low intensity crop farmers are able to produce a medium amount of cereals. They are dependent on crop productivity but are quite adaptable and can still produce 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. In addition to producing food, they also allow a small amount of recreation over their land, dependent on nature value.
- High intensity crop farmers produce higher amounts of cereals, but due to their intensive, monocultural farming methods they do not support any recreation. Their higher cereal productivity also comes at the cost of an increased sensitivity to productive potential, and a need for reasonably high economic capital to support their requirements for machinery, labour and other inputs. They are relatively insensitive to social capital, however.
- Livestock farmers are parameterised using the same reasoning as crop farmers.
- Foresters are multifunctional agents, producing both timber and recreation. Their production of timber depends on the natural timber production capital, while production of recreation depends on both timber production and nature value.

We run 30 realisations of each scenario and show results from all of these where possible.
### TABLE 1.1: capitals used in example simulations

<table>
<thead>
<tr>
<th>Capital</th>
<th>Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Productivity: Cereals</td>
<td>High in the plains, decreases sharply with height</td>
</tr>
<tr>
<td>Productivity: Livestock</td>
<td>High in the plains, decreases gradually with height</td>
</tr>
<tr>
<td>Productivity: Timber</td>
<td>Equally productive everywhere below a tree line, beyond which it declines rapidly to zero</td>
</tr>
<tr>
<td>Nature value</td>
<td>Increases with height, as effects of long-term anthropogenic disturbance decreases</td>
</tr>
<tr>
<td>Economic</td>
<td>Constant for the region but can change in response to socioeconomic scenarios</td>
</tr>
<tr>
<td>Social</td>
<td>Not included in most scenarios; high in one area (upper valley) when included</td>
</tr>
</tbody>
</table>

### TABLE 1.2: agent characteristics: services produced and capital sensitivities.

<table>
<thead>
<tr>
<th>Agent</th>
<th>Produces</th>
<th>Sensitive to</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low intensity cereal farmer</td>
<td>Cereals, small amount of recreation</td>
<td>Mildly sensitive to Cereal Productivity, Nature; very sensitive to Social Capital</td>
</tr>
<tr>
<td>High intensity cereal farmer</td>
<td>Cereals, no recreation</td>
<td>Very sensitive to Cereal Productivity, Economic Capital; mildly sensitive to Social Capital</td>
</tr>
<tr>
<td>Low intensity livestock farmer</td>
<td>Meat, small amount of recreation</td>
<td>Mildly sensitive to Livestock Productivity, Nature; very sensitive to Social Capital</td>
</tr>
<tr>
<td>High intensity livestock farmer</td>
<td>Meat, no recreation</td>
<td>Very sensitive to Livestock Productivity, Economic Capital; mildly sensitive to Social Capital</td>
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</tbody>
</table>
FIGURE 1.4: elevation map and derived capital maps for the simulated world. a) elevation b) cereal productivity c) livestock productivity d) timber productivity 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 the n varies as described in the text (see Fig. 1.5f).

Basic Simulation (Scenario 0)
For the initial simulation, we start the model with a random distribution of agents. Demand for all services is held constant, and the model is run until there is little year-to-year change – i.e. a local optimum has been reached (found to have occurred by 2015 with a start year of 2000). The ‘give-up-give-in’ allocation model is used, with all behavioural thresholds set to zero, giving a (roughly) optimising model.

Population and Economic Growth (Scenario 1a)
The second scenario builds on the first, and adds variation described by the following storyline and parameterisation:

Storyline: Population increase in the modelled world leads to greater demand for food. Meanwhile, increasing wealth shifts the populations’ dietary preferences, so that demand for meat grows more rapidly than demand for cereals.

Parameterisation: We start with the initial scenario, and run it to completion. After 2015, the demand for food is gradually increased until 2025, with cereal demand doubling and meat demand increasing two and a half times.

The expected result of these changes will be to increase the area used for food production at the expense of forestry, hence reducing recreation provision and the productive efficiency of food, as more marginal land is used to satisfy the elevated demand levels.
Population and Economic Growth, with Economic Capital Change (Scenario 1b)

**Storyline:** The increases in population size and wealth described in Scenario 1a also generate an increase in economic capital, as financial support becomes increasingly available for land uses.

**Parameterisation:** The parameterisation of Scenario 1a is used with the addition of rising economic capital levels, which double from 0.5 to 1.0 between 2015 and 2025.

This simulation is expected to show intensification of agriculture, as increasing economic capital enables high intensity farming to become competitive on less productive land. Smaller changes in the areas of each land use than in Simulation 1a are expected as a result.

Behavioural Thresholds (Scenario 2a)

**Storyline:** Land managers are not simply rational economic agents, but have characteristics that vary with type. In particular, managers vary in their willingness to abandon or relinquish their land, with foresters and low-intensity farmers being willing to accept lower returns, and being less willing to accept competition, than high-intensity producers.

**Parameterisation:** The parameterisation of Scenario 1b is extended, with high-intensity farmers having increased giving-up thresholds (of 0.2) and foresters and low-intensity farmers having increased giving-in thresholds (of 0.1).

We expect these changes to cause a delayed transition to high-intensity agriculture as changes in demand and economic capital initially fail to overcome agents’ unwillingness to change land use. We then expect something of a step-change as giving-in thresholds are suddenly reached.

Individual Variation (Scenario 2b)

**Storyline:** In addition to the broad behaviour in Scenario 2a, land managers vary individually, with some being more committed to their land use than others.

**Parameterisation:** The simulation is parameterised as Scenario 2a, with the addition of individual (Gaussian) variation around each agent type’s giving-up or giving-in thresholds.

We expect this individual behaviour to smooth the temporal changes seen in Scenario 2a, and to alter the final productive efficiencies of each service.

Systematic Spatial Variation (Scenario 2c)

**Storyline:** Individual variation occurs but is not purely random. In particular, the inhabitants of the upper valley have a strong sense of community and land managers are supported by a network of peers, increasing productivity and reducing the likelihood of giving-up or giving-in.

**Parameterisation:** We introduce social capital to Scenario 2b, which takes a uniform value of 0.5 across most of the region but a value of 1.0 in the upper valley. All agents are sensitive to this capital, regardless of where they are located, with low-intensity producers and foresters being more strongly sensitive than other agent types (Table 1.2).

We expect this simulation to show distinct transitions in the upper valley and elsewhere, with land use change occurring earlier in areas of low social capital.
FIGURE 5: maps of final agent locations in one realisation of each Scenario: (a) Scenario 0; (b) Scenario 1a; (c) Scenario 1b; (d) Scenario 2a; (e) Scenario 2b; (f) Scenario 2c.
1.4 Results

Examples of the final land use maps for each simulation are shown in Figure 1.5. In the baseline simulation (Scenario 0), high-intensity cereal production dominates the lowest (most fertile) areas of the region, with high-intensity livestock farming forced onto slightly higher ground. Beyond this there is a rough transition to low-intensity cereals and then low-intensity livestock, before a marked band of forestry and a marked band of low-intensity livestock occupy increasingly high ground (Fig. 1.5a).

When demand levels for meat and cereals increase (Scenario 1a), the final land use map is far more clearly divided between land uses, with high-intensity farming outcompeting low-intensity farming in most areas (Fig. 1.5b). As expected, this reduces the area available for non-food services, limiting their production and slightly increasing their productive efficiency (Figs. 1.6a, 1.6b, 1.7a, 1.7b). Increases in meat production are found to occur partly at the expense of cereal production, and plots of the number of agents of each type (equivalent to the area given to each land use) show that this is driven by the replacement of low-intensity cereal farmers with high-intensity livestock farmers (Figs. 1.8a & b).

Increases in economic capital (Scenario 1b) clearly favour high-intensity producers, who take land over from low-intensity producers and contribute to a general intensification of agriculture, as predicted (Figs. 1.5c, 1.8c). This allows the region’s producers to supply more food than in the previous simulations (Fig. 1.6c). The area given to and production of non-food services decreases as a result, while productive efficiencies increase for all services except timber production, which is constrained in less productive high areas (Fig. 1.7c).

The introduction of typological behavioural thresholds in Scenario 2a does not substantially alter the final land use map (Fig 1.5d), but it does affect the temporal dynamics of the simulation. Differences between individual realisations are smoothed out, and changes in the numbers of agents belonging to each type prior to 2015 are largely prevented (especially for low-intensity cereal farmers; Fig 1.8d). Instead, each type responds suddenly and smoothly to demand and capital level changes after 2015, following similar trajectories and reaching similar final configurations as in Scenario 1b. This is particularly clear in plots of overall production levels, which are nearly constant prior to 2015 in Scenario 2a, as agent behaviour dampens the variations and oscillations visible in previous results (Fig. 1.6d).

The principal effect of individual behaviour within agent types (Scenario 2b) is visible in the final land use map, which shows far more mingling of land uses across the region (Fig 1.5e), as some agents tolerate lower productivity and relative competitiveness than others. This limits differences in the productivities of different land uses, preventing food production levels from rising as high and non-food production levels from sinking as low as in previous simulations (Fig 1.6e), and also limits the average productivity of all but forester agents (who, in occurring more widely across the region, are more likely to encounter favourable capital levels than unfavourable) (Fig 1.7e). In terms of agent numbers, individual variation produces results intermediate between Scenarios 1b and 2a – variation between realisations is relatively large, and changes occur even under static demand levels (pre-2015) (Fig. 1.8e). The decline in the number of non-food and low-intensity producers after 2015 is lessened, as is the increase in high-intensity farmers (particularly cereal farmers, who were already located in the most productive areas in previous simulations).
FIGURE 6: Total supply of each service across all 30 realisations of each Scenario: (a) Scenario 0; (b) Scenario 1a; (c) Scenario 1b; (d) Scenario 2a; (e) Scenario 2b; (f) Scenario 2c.
FIGURE 7: Average supply of each service on each productive cell, across all 30 realisations of each Scenario: (a) Scenario 0; (b) Scenario 1a; (c) Scenario 1b; (d) Scenario 2a; (e) Scenario 2b; (f) Scenario 2c.
Our final Scenario (2c), in which one area of the region has higher social capital and therefore offers more support for foresters and low-intensity farmers, produces a substantial increase in the number of foresters throughout the modelled period (Fig. 1.8f). These agents enjoy greater productivity in the area with high social capital, and so are able to outcompete the low-intensity farmers. They have less of an advantage over high-intensity livestock farmers, however, and so this latter type also benefits. Productivities are not strictly comparable because of their added sensitivity to social capital in this scenario, but it is notable that the same relationships between the productivities of the agent types exist as in previous scenarios (Figs. 1.6f & 1.7f), implying that changes in one area have consequences for another, as agents attempt to satisfy regional demand.

1.5 Discussion

Our results are intended to illustrate the use of the EURO-ABM, and its ability to model realistic processes of land use change using a relatively simple structure. In each of the simulations presented above, we were able to translate practical storylines into model parameters and predict the temporal dynamics of land use change that resulted. In this way, we modelled processes of conversion of land to agriculture under increasing demand levels for food, intensification of agriculture under increasing economic capital levels, the dampening effect of differences between groups of land managers on land use transitions, the potential for individual behaviour to alter land use configurations and productivities, and the direct and indirect effects of additional localised support for particular land uses. All of these processes are important in the real world, and our model’s ability to replicate their effects in a theoretical setting suggests that its structure and parameters can capture many of the principal drivers of land use change, making it widely applicable.

Further development is necessary before the model is used in empirical settings and at the EU scale. The considerations involved in this development are similar to those involved in any use of the model, and we outline them below. Most require some underlying data, but the extent to which they can be supported by assumptions is likely to vary from case to case. We give full details of the model inputs in Section 3.

Firstly, it is necessary to generate spatially explicit maps of the relevant capitals, at the requisite scale. We initially define seven capitals: human, infrastructure, economic, grassland productivity, forest productivity, crop productivity and nature value. This list can be altered as required, given the necessary data. We have gathered data from a number of sources for these capitals and will continue to do so, ensuring that all data are consistent and expressed at 1km² scale across the EU. These data will be used to establish maps and spreadsheets of capital levels for use in the model. Similarly, EU-wide data on land cover is needed, and this will be used to establish the current locations of different agent types. At smaller scales, other forms of data may be used (e.g. lists of actual land managers, where available).

The model is intended to operate with exogenous scenario-dependent changes in demand levels for services, generated by other models that take account of predicted climatic, population, economic and environmental changes. It is also possible to set demands wholly arbitrarily, in order to investigate the possible effects of specific changes, or to use historical data. Interactions between land uses, demand levels and capitals may be included, and may also be calibrated empirically or theoretically.
FIGURE 8: Numbers of each agent type (equivalent to number of cells per land use) throughout all 30 realisations of each Scenario: (a) Scenario 0; (b) Scenario 1a; (c) Scenario 1b; (d) Scenario 2a; (e) Scenario 2b; (f) Scenario 2c.
The division of agents into productive types has an empirical basis (Rounsevell et al. 2012), although it is primarily motivated by modelling efficiency. While such divisions can reasonably be assumed between, for example, foresters and farmers, the extent of subdivisions within these broad types depends upon the context and objectives of the model. For our European model, the agent typology will remain broad and relevant to land cover, with variation within types accounted for as described in Sections 2 and 3.

The most important feature of a land use ABM is its treatment of agent behaviour. This is especially true here, as one aim of our model is to examine the boundaries between top-down land allocation models and the Euro-ABM, to identify any divergence caused by human behaviour. The empirical basis for behaviour in the model this will be a meta-analysis of behavioural drivers of agricultural land use change (see Section 2). At EU scale, our treatment of behaviour will inevitably lack the detail and complexity that is possible in smaller-scale studies, but in any case it is necessary to consider what the essential behavioural characteristics are for a model of the given scale and resolution. We have designed the model to capture the effects of many different processes in a simple framework, but also to treat factors such as:

- Agent age, which is known to be a strong determinant of land use change, intensity and responses to policy interventions, particularly among farmers (Section 2);
- The effects of spatial and non-spatial peer groups on land use and probability of change (and, perhaps, the effects of historical and current family groups);
- Variation in productivities and behaviours across the study area. These are particularly relevant at large scales and, while comparative studies are rare, national or regional-scale research is common and provides good coverage in combination;
- Further variation within agent types. This is expected to scale strongly with spatial resolution – where individual agents are distinguished by the model, their personal characteristics are as relevant as those of their wider type, and methods of efficiently representing these are likely to be required (Matthews et al. 2007). At the same time, it is important to consider the number and positions of divisions between types in order to minimise such intra-type variability.

Many of these factors are already treated in the model, but some require further work. The effects of these will be approximately calibrated using the meta-analysis presented in Section 2 where possible, and some (e.g. individual variation) will be varied in order to explore the effects of different behaviours on land use outcomes. Behavioural variations within types will be described via variables and interchangeable mathematical functions that are recognised as being appropriate for this purpose (e.g. Berger 2001; Polhill et al. 2001; Gotts et al. 2003; Gorton et al. 2008).

Another important consideration is the role of institutions in driving land use change (or preventing it), and the ability to model this role is one of the distinguishing characteristics of the Euro-ABM. Institutional support is particularly important in the EU, where large international subsidies support agriculture and are used to affect land use intensities and multifunctionality (Potter & Tilzey 2005; Piorr et al. 2008). A range of local, regional, national and international bodies intervene in land uses through a range of mechanisms and to a number of different ends; these can be modelled as described above and may justify the use of an institutional agent typology (Rounsevell et al. 2012).

There are, of course, a number of limitations to our approach, as there are to any that attempts to achieve similar capabilities while retaining generality and flexibility. One relates to the expression of diverse behaviours and characteristics in a small number of
numerical values such as giving-up and giving-in thresholds. While these are believed to offer a robust description of individual variations between land managers, it is difficult to establish their absolute values for any given agent or type. 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, we are susceptible to an acknowledged bias in the literature towards marginal regions where rapid land use change has occurred (Section 2). We also make the unrealistic assumption that single agents manage single cells, and that land use change occurs only when a different agent takes a cell over. While this is equivalent to more complex agent dynamics in most cases, there may be circumstances in which the effects of this assumption are not valid. Finally, the scope and accuracy of the model is inevitably limited by data availability, and while an increasing amount of relevant data is freely available both within and outside the VOLANTE project, this is certain to remain a significant constraint.

Some of these issues are mitigated by our separation of code and data, so that no case-specificity is built into the model, and richer data can easily be incorporated. This also allows different users to focus the model on a wide range of applications. Further model development and usage is likely to generate further improvements. In any case, the Euro-ABM provides a powerful tool for modelling land use change in theoretical and real-world settings, and is an appropriate tool for use at European scale.

1.6 Conclusion

In this Section we have argued that a simple, flexible ABM framework capable of modelling land use change in considerable detail and/or at very large scales could make a valuable contribution to land use science. We have developed such a framework and described its structure in detail, along with its potential applications. We have shown that the model is currently able to reproduce a number of important land use processes using simple settings, and outlined the steps necessary to apply the model to our own intended study and to others.

The future development of the EURO-ABM will focus on its application to large scales and its ability to accurately describe and simulate human behaviour. This will allow us to generate examples of future land use change in Europe under a range of political, social, economic and environmental scenarios, and provide results for comparison with top-down land allocation models. It will also make the model a valuable tool for modelling large or small-scale processes of land use change and, we hope, enable research into topics that have previously been too large or complex for study using land use ABMs.
1.7 References – Section 1


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SECTION 2: Meta-analysis of drivers for agricultural land changes in Europe

Abstract
In this Section we present a meta-analysis of studies of agricultural land use change in Europe, intended to identify the main drivers of such change and inform the development and calibration of the model presented in Section 1.
2.1 Aim and rationale

Agent based models allow simulation of the behaviour of actors, such as farmers or foresters, to be carried out explicitly. This makes agent based models inherently very suitable to assess land use changes that are a direct result of human decisions (An, 2012; Matthews et al., 2007). However, the design of an agent based model is rarely based on empirical data or real world observation (Valbuena et al., 2008). At the same time it is not clear a priori what mechanisms underlie the decisions of land managers, nor is it clear which data feed into these decisions (whether spatial, or non-spatial, internal or external to the land manager themselves). Therefore the design of spatial agents and their parameterisation remains a challenge for the EuroABM described in Section 1 as well as for many other agent-based land use models (Filatova et al., 2013).

This meta-analysis aims to find underlying drivers of land use changes, in order to improve the design of the EuroABM and provide a justification for the decisions made in this design. For this we collected and analysed local case studies that report on drivers underlying land use changes, based on interviews, questionnaires and surveys of land managers. This latter qualification allowed us to assess the role of spatial agents explicitly as a link between drivers and changes (Hersperger et al., 2010).

This meta-analysis focuses on drivers underlying changes in agricultural land use, because agricultural land covers a large portion of the European union, because it is subject of many policies as well as changes in its context such as globalisation, and because the agents that are the decision makers underlying agricultural land changes are typically clearly identifiable as the families or persons running the farm. Specifically, we identified four primary types of land use change: abandonment, expansion, intensification and extensification. Abandonment and expansion deal, respectively, with conversion from agricultural to non-agricultural land and the opposite process. Hence they indicate changes in acreage. Extensification and intensification indicate changes in land management for land that remains agricultural. Extensification and intensification are interpreted broadly, as long as the changes relate to the management of the land. Such changes could for example include the introduction of hedgerows and green elements (extensification) or the construction of irrigation facilities (intensification). The classification of the primary types of land use change is based on our interpretation of the reported changes, as some are used interchangeably by other authors (for example, abandonment of individual plots leads to an extensification on a landscape scale; in this analysis this is considered abandonment).

2.2 Methods and data

Study selection

Because case studies for agricultural land use change are published under a wide variety of names, a systematic query of databases containing scientific publications did not yield a satisfactory result. Therefore studies for this meta-analysis were selected using snowball sampling, starting from a number of seed-studies. Specifically, for each study that was included in the meta-analysis, we checked all other studies referred to, and all studies that refer to this study (using Google Scholar as well as the references listed in the study). Seeds originated from different fields (rural sociology, physical geography, human geography), to avoid a narrow focus. Studies were first selected for inclusion based on the title, subsequently based on their abstract, and eventually on the complete paper. We used the following criteria for inclusion in this meta-analysis:
- The study is published in a peer-reviewed journal, in or after the year 2000. The rationale behind this start year is two-fold: First, we want to include land changes that are as recent as possible, to ensure its relevance for simulating future land use changes. Second, a thorough review of the abandonment of marginal agricultural areas in Europe (discussing both abandonment and extensification) was published in 2000 (MacDonald et al., 2000), which offers a nice starting point for a follow-up while avoiding redundancy.

- The study describes changes in agricultural land use that occurred in case study areas in Europe after 1945. Consequently, cluster analysis for one moment in time and other similar typologies are not included. In addition, ideas about future changes (such as stated preference studies), were not included in this study.

- The study is based on primary research and describes drivers that underlie the observed land use changes. An additional requirement is that drivers are related to land managers directly, i.e. by means of farm surveys, interviews or even participatory observation.

- The study explores or analyses a range of drivers; hence single relation investigation (The effect of X on land abandonment) were excluded.

**Case definition**

A study can contain one or several cases; a case is defined as each unique combination of:

- Case regions or combinations of case regions that are analysed separately.

- Observed land use changes (one of four primary types):
  - Expansion (permanent conversion of non-agricultural land into agricultural land);
  - Abandonment (permanent conversion of agricultural land into non-agricultural land). The introduction of fallow land as part of a crop rotation is not considered abandonment, since the land remains under rotating cultivation. This is extensification instead.
  - Extensification (persisting agricultural land with a decrease in land use intensity, for example the introduction to organic farming, on-farm diversification, the introduction of natural elements, structural changes, introduction of fallow land under crop cultivation)
  - Intensification (persisting agricultural land with an increase in land use intensity, for example the removal of natural elements, the introduction of drainage or irrigation measures, increase in production by means of fertilizer of mechanisation)

- Time periods, in the case where time periods are analysed separately. Only time periods that start in or after 1945 were included.

**Coding categories**

For each case, the underlying drivers were coded.

- Case description: Study; Primary land use change type; Start year and end year; Case study area (description, and X and Y coordinates); Size of the study area.

- Primary data sources underlying the case study: Spatial data (including remote sensing, aerial photographs, topographic maps, DEM); Interviews, questionnaires and surveys; Non-spatial data (including statistics, census data, agricultural census); Direct observation.

- Types of agriculture: Livestock in rangelands; Livestock in managed grasslands and meadows; Arable land; Permanent crops; Mixed farms; Undefined agricultural land
Drivers underlying land use changes (drivers were coded when the original study mentioned them as drivers, to ensure a consistent interpretation in the meta-analysis). These drivers were not identified a priori, but instead identified based on those reported in the case studies.

- Location factors: Plot accessibility; Productive capacity (or any factor related to this, such as soil type or precipitation); Land characteristics for mechanisation
- Farmer characteristics: Age; Successor is identified or available; Education; Farming tradition; Farmer’s motivation for environmental sustainability; Farm income
- Farm characteristics: Farm size; Ownership security; Labour requirements
- Regional characteristics: Region accessibility; Regional demand for agricultural products; Regional demand for other ecosystem services; Demands for regional tourism (not on the farm itself); Availability of off-farm employment (in the region); Availability of agricultural specialist services; Land consolidation
- Global, continental or national developments: Availability of technology (Machinery, fertilizer); Policies that aim to manage land sustainably (pillar 2, LFA, direct payments); Production support subsidies; Change occurs as a result of globalisation of agricultural markets and changes in global demands for products.
- Finally, we coded two additional variables which appeared frequently in the case study descriptions, and whose importance has become clear from the respective case studies: The farm or region is located in a post-socialist country; The farm or region is located in a marginal area.
- Type of farmer: Full-time commercial farmer; Part-time commercial farmer; Hobby farmer; Retired farmer; Subsistence farmer
- Direct changes to agricultural lands: Urbanisation; Nature development (as an act of converting land, not as a result of land abandonment); Outmigration of farmers (for example because they find jobs elsewhere)
- Neighbourhood characteristics: Clustering of similar changes; Land change is typical for fragmented patches

**Coding practices and further analysis**

Drivers were coded when the analysis or discussion of results indicated that those drivers contributed to the observed change. A value of 1 means that this driver, or a high value of this driver, contributed to the change, while a value of -1 indicates that a low value or the absence of this driver contributed to this change. A value of 0 indicates that the driver was found to have no influence, or that the driver was not mentioned. In the case where statistical tests were performed, relationships with p > 0.05 were considered relevant, while other values were considered not to demonstrate any influence. When several models were built for use with the same dataset, the most significant relationship was selected (hence, if one model finds a significant relationship, and the other does not, the relationship is coded as significant). When several drivers were tested that all belong to one and the same coding category and one of them was significantly related, this category was coded as being related.

Papers that were not based on statistical tests were coded according to the interpretation of the original authors: when they indicated a driver as related, it was coded (in order to interpret results as little as possible). Drivers were only coded when they were 1] based on the data that underlay the original study, and the original authors’ interpretation thereof, and 2] their relations were indicated as causal or typical (hence a sample that only includes large farms is not coded as "large farm", because this...
is a characteristic of the sample, not a driver for the observed changes - unless, of course, the authors indicate elsewhere that the fact that farms are large is a driver for observed changes).

Finally, since many drivers do not act independently, but instead are part of a typical pathway (Lambin et al., 2011), we analysed cases for these typical pathways. This analysis is based on our interpretation of the cases and therefore separate from the meta-analysis itself which is based on the original authors’ interpretation of the case study.

### 2.3 Results and discussion

**Case characteristics**

The meta-analysis contains 105 cases, originating from 53 publications. Figure 2.1 provides an overview of the geographic location of these cases. It should be noted that some case study areas include more than one case, because locations typically face a combination of primary land change types (such as intensification and abandonment). For that reason the map shows fewer than 105 dots.

While the map shows some distribution it is clear that the selected cases are not necessarily representative of the whole of Europe. A large portion of the cases are located in mountainous areas or areas that are otherwise marginal. This is also illustrated in table 2.2, which shows that 37 cases are in locations indicated as marginal. A likely explanation is that these areas have faced much land use change over the last few decades (see for example Hatna and Bakker, 2011; MacDonald et al., 2000; Strijker, 2005), and therefore qualify as interesting case study areas. On the other hand, many productive areas in Europe are hardly investigated, or not investigated at all, probably because these areas just show a persistence of (intensive) agricultural land use (such as central France and central Germany).

Moreover, there is a clear overrepresentation of cases in a limited number of countries, particularly Denmark, Greece, Spain and Switzerland. Since often these cases are reported by a small group of researchers, this concentration might simply be due to their ties with these case study areas. At the same time, some other countries (Iceland, Norway, Finland) have no cases at all. These biases might influence the representativeness of the meta-analysis. On the other hand, cases are well distributed in terms of variation in economic situation, variation in climate, and differences in political systems (including post-socialist countries, which are represented by 19 cases). Therefore we feel that the case study evidence underlying this meta-analysis could be used to extract drivers for land change in Europe meaningfully.
Preliminary results

Table 2.1 presents the counts of drivers influencing all agricultural land use changes combined. It becomes clear that farm economics is the driver that has been mentioned most frequently (43 times); this also explains the relatively high counts for land management subsidies (31) and production subsidies (11): both provide financial incentives to change land management. Similarly, location characteristics like plot accessibility (24), land productivity (24), as well as technology (24) can be linked to economic incentives as accessibility relates to transport costs, productivity relates to yield and consequently farm income, and technology relates at least partly to the amount of labour required to manage the land.

A number of other drivers are clearly not related to farm economics directly. As many farms are still family run businesses, family characteristics, such as the age of the head of the family (29) and the identification of a successor (16) have an important influence on agricultural land dynamics. Young farmers were frequently found to make changes to their farm, as they have an incentive to adjust the newly acquired business to meet their ideas, while older farmers typically continue their business as it is, without making any major changes (or investments). Additionally, many cases directly or indirectly refer to the succession cycle in farming, confirming the importance of succession as a driver for agricultural land change (Inwood and Sharp, 2010). Specifically, changes often take place at the moment a farmer retires. Either his (younger) successor changes the business, or the land becomes available to other farmers or for abandonment.

Moreover, a number of drivers explicitly show the importance of non-monetary influences, such as productivist attitude (26) and environmental stewardship (10). In
fact these drivers were typically mentioned to indicate why farmers made decisions that were not rational from an economic point of view. For example, a productivist attitude was mentioned as a reason not to participate in agri-environmental schemes, while environmental stewardship was indicated as a reason to lower the productivity (and hence farm income) to improve the environmental situation of the farm. These findings confirm the role of cognitions in actors’ decision making (Meyfroidt, 2012). These motivations also explain the cases where land management subsidies (1) and production subsidies (5) were not found to influence land changes.

Finally a number of direct causes of agricultural land change were identified, mostly relating to land abandonment. These are urbanization (11) and nature development (13), where the latter refers only to purposeful development of natural areas, as opposed to the re-naturalisation of abandoned agricultural lands. In both cases land use changes are not directly the result of the farmer’s decision, but instead caused by other actors such as policy makers or real estate developers. Although the amount of urban land is relatively small in Europe, the area required for expansion is considerable, as scenario studies have shown already (Verburg et al., 2010) Rural depopulation, and especially the outmigration of (former) farmers causes direct land use changes as these farmers simply stop farming. Frequently the availability of jobs elsewhere (typically in urban areas) are the underlying reasons, which makes this driver again part of the farm economics, although social reasons (unwillingness to live in remote places) were indicated as well.

In addition, changes were assessed per type of land use change separately. Results of these analyses are provided in table 2.2, where positive values indicate positive relations (for example a high plot accessibility is related to land intensification), while a negative values indicate a negative relation (for example a productivist attitude prevents land abandonment and a low productivity is generally associated with land extensification).

Table 2.2 shows that while farm economics are equally important for all types of land use changes, the underlying causes differ. Land productivity plays an important role for extensification and land abandonment, but not for intensification and expansion. Clearly the productivity of land is sometimes a constraining factor on the living made from farming (MacDonald et al., 2000). Another important financial incentive is subsidies: Land management subsidies (in the form of the CAP reform and agri-environmental schemes) mostly yielded the expected outcomes: an extensification, or sometimes partly an abandonment of the land. However, it also shows how unintended side-effects can emerge, for example as reported in case [31] where land management subsidies allowed farmers to invest in mechanization, which led to a more intensive use of the land. Similarly some other financial drivers can have counterintuitive effects, depending on the context. The clearest example is the availability of nearby off-farm employment. In most cases this yielded a more extensive use of the land, as farmers had fewer hours to spend on their farm, in other cases it led to agricultural abandonment as it provided an alternative source of income (for example Garcia-Martinex et al., 2009), while there are also 3 cases that indicate that off-farm employment provided the necessary resources to expand the farming business (Ciadella et al., 2009). Hence the same driver could yield opposing changes in agricultural land.
<table>
<thead>
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</tr>
<tr>
<td>Productivity / fertility</td>
<td>24</td>
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<td>Land improvement technology (drainage, terraces)</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Farmer’s age</td>
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<tr>
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<tr>
<td>Education of the farmer</td>
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<tr>
<td>Productivist attitude</td>
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<td>Farming tradition</td>
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<td>Regional demand for recreation and tourism</td>
<td>8</td>
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<td>Off farm employment</td>
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<td>Land consolidation</td>
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<td>Global (or national) influences</td>
<td></td>
<td></td>
</tr>
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<td>Technology (availability, existence)</td>
<td>24</td>
<td>0</td>
</tr>
<tr>
<td>Land management subsidies</td>
<td>31</td>
<td>1</td>
</tr>
<tr>
<td>Production subsidies</td>
<td>11</td>
<td>5</td>
</tr>
<tr>
<td>Globalization (input side)</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Globalization (output side)</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Direct changes</td>
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<td></td>
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<td>0</td>
</tr>
<tr>
<td>Urbanization</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Nature development / protection / restoration</td>
<td>13</td>
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<td>Neighbourhood characteristics</td>
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<tr>
<td>Fragmentation</td>
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</tr>
</tbody>
</table>

TABLE 2.1: Drivers for agricultural land use changes in Europe for all types of change combined (n=105).

Non-economic incentives typically yield the changes that can be expected: environmental stewardship leads to a more extensive land use, for example because greening elements were added to the landscape, or because of changes towards organic production systems. Similarly, a productivist attitude leads to land intensification, or at least prevents land abandonment and land extensification.

The differentiation of drivers also indicates that some can have two opposing effects. Good examples are plot and region accessibility, both of which can be positively and negatively related to land abandonment. A closer look at the case studies reveals that these are two different mechanisms: low accessibility is a direct driver because land is abandoned when it is distant from markets, generating high transport and processing costs; while high accessibility typically relates to indirect effects because these locations are the most suitable for urbanisation, and not because they are unsuitable for agriculture.
Additionally to the coding of drivers, cases were coded for the type of farmer involved in the respective agricultural land changes. Results of this analysis are shown in Table 2.3 below. Again, positive values indicate that this type of farmer was positively related to the respective land use changes, while negative values indicate the opposite. This analysis clearly shows that different types of farmers make different types of decisions. For example, and not unexpectedly, retired farmers typically reduce the amount of labour they need to put into their farm, resulting in extensification or, more typically, abandonment (Nikodemus et al., 2005). Similarly, hobby farmers typically have other jobs that require most of their time and resources, and therefore they generally seek to extensify their land use (Busck, 2002), while a similar observation can be made for part-

<table>
<thead>
<tr>
<th>Location characteristics</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot accessibility</td>
<td>3/-10</td>
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<td>1/0</td>
<td>0</td>
<td>2/0</td>
<td>0</td>
<td>8/0</td>
<td>1</td>
</tr>
<tr>
<td>Productivity / fertility</td>
<td>0/-12</td>
<td>1</td>
<td>2/0</td>
<td>0</td>
<td>2/0</td>
<td>1</td>
<td>1/-7</td>
<td>1</td>
</tr>
<tr>
<td>Land improvement technology</td>
<td>0/-4</td>
<td>0</td>
<td>1/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
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</tr>
</tbody>
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<table>
<thead>
<tr>
<th>Household characteristics</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farmer's age</td>
<td>10/-1</td>
<td>0</td>
<td>1/-2</td>
<td>0</td>
<td>1/-3</td>
<td>0</td>
<td>11/0</td>
<td>1</td>
</tr>
<tr>
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<td>0</td>
<td>3/0</td>
<td>0</td>
<td>1/-1</td>
<td>0</td>
<td>0/-2</td>
<td>0</td>
</tr>
<tr>
<td>Education of the farmer</td>
<td>0/1</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>8/-1</td>
<td>1</td>
</tr>
<tr>
<td>Productivist attitude</td>
<td>0/-7</td>
<td>1</td>
<td>0/0</td>
<td>0</td>
<td>4/0</td>
<td>1</td>
<td>2/-13</td>
<td>3</td>
</tr>
<tr>
<td>Farming tradition</td>
<td>0/-1</td>
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<td>1/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>1/0</td>
<td>0</td>
</tr>
<tr>
<td>Environmental stewardship</td>
<td>0/1</td>
<td>1</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>1</td>
<td>9/0</td>
<td>2</td>
</tr>
<tr>
<td>Farm economics</td>
<td>2/-11</td>
<td>0</td>
<td>3/0</td>
<td>0</td>
<td>12/0</td>
<td>0</td>
<td>13/-2</td>
<td>1</td>
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</tbody>
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<table>
<thead>
<tr>
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<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Farm size</td>
<td>1/-3</td>
<td>0</td>
<td>3/0</td>
<td>0</td>
<td>8/0</td>
<td>0</td>
<td>3/-7</td>
<td>0</td>
</tr>
<tr>
<td>Ownership security</td>
<td>2/-4</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>2/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
</tr>
<tr>
<td>Labour requirements</td>
<td>2/-1</td>
<td>0</td>
<td>0/-1</td>
<td>0</td>
<td>1/0</td>
<td>0</td>
<td>2/-1</td>
<td>0</td>
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<table>
<thead>
<tr>
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<th>Driver</th>
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<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Region accessibility</td>
<td>3/-3</td>
<td>1</td>
<td>0/-1</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>4/-1</td>
<td>0</td>
</tr>
<tr>
<td>Regional demand for farm products</td>
<td>0/-2</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>1/0</td>
<td>0</td>
<td>2/-0</td>
<td>0</td>
</tr>
<tr>
<td>Regional demand for recreation / tourism</td>
<td>3/-2</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>3/0</td>
<td>1</td>
</tr>
<tr>
<td>Off farm employment</td>
<td>5/-1</td>
<td>1</td>
<td>3/0</td>
<td>0</td>
<td>0/0</td>
<td>1</td>
<td>12/-1</td>
<td>0</td>
</tr>
<tr>
<td>Land consolidation</td>
<td>2/-7</td>
<td>1</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>1</td>
</tr>
<tr>
<td>Availability of specialist services</td>
<td>0/-1</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>1/0</td>
<td>0</td>
<td>0/-1</td>
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<table>
<thead>
<tr>
<th>Global (or national) influences</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
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</thead>
<tbody>
<tr>
<td>Technology (availability, existence)</td>
<td>1/-5</td>
<td>0</td>
<td>3/0</td>
<td>0</td>
<td>13/0</td>
<td>0</td>
<td>0/-2</td>
<td>0</td>
</tr>
<tr>
<td>Land management subsidies</td>
<td>2/-7</td>
<td>1</td>
<td>3/0</td>
<td>0</td>
<td>4/0</td>
<td>0</td>
<td>14/-1</td>
<td>0</td>
</tr>
<tr>
<td>Production subsidies</td>
<td>1/-1</td>
<td>1</td>
<td>1/0</td>
<td>0</td>
<td>2/1</td>
<td>2</td>
<td>3/-2</td>
<td>2</td>
</tr>
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<td>Globalization (input side)</td>
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<td>0</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
</tr>
<tr>
<td>Globalization (output side)</td>
<td>2/1</td>
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<td>2/0</td>
<td>0</td>
<td>3/0</td>
<td>0</td>
<td>1/0</td>
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</tbody>
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<table>
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<tr>
<th>Direct changes</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
<th>Driver</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outmigration</td>
<td>8/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>1/-1</td>
<td>0</td>
</tr>
<tr>
<td>Urbanization</td>
<td>9/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>2/0</td>
<td>0</td>
</tr>
<tr>
<td>Nature development / protection</td>
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<td>0/0</td>
<td>0</td>
<td>0/0</td>
<td>0</td>
<td>4/0</td>
<td>0</td>
</tr>
</tbody>
</table>

**Table 2.2:** Drivers for agricultural land use changes in Europe per type of land use change. Negative values indicate a negative relation. The “No” columns indicate the number of cases that explicitly indicate a driver has no influences, or no statistically significant influence.
time commercial farmers: in a need to reduce the amount of work on the farm they move to more extensive land management systems. On the other hand, since they do want to farm they sometimes prevent the land from abandonment (Gellrich et al., 2008). The distribution of types of farmers can therefore be an indication of the types of agricultural land use changes that are happening, as can be expected.

<table>
<thead>
<tr>
<th>Farmer type</th>
<th>Aban (n=36)</th>
<th>Expan (n=10)</th>
<th>Inten (n=20)</th>
<th>Exten (n=39)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Driver</td>
<td>No</td>
<td>Driver</td>
<td>No</td>
</tr>
<tr>
<td>Hobby farmer</td>
<td>5/-3</td>
<td>1/0</td>
<td>1/-1</td>
<td>12/0</td>
</tr>
<tr>
<td>Subsistence farmer</td>
<td>2/-2</td>
<td>1/-1</td>
<td>0/-1</td>
<td>1/0</td>
</tr>
<tr>
<td>Full time commercial farmer</td>
<td>1/-3</td>
<td>3/0</td>
<td>9/0</td>
<td>7/-2</td>
</tr>
<tr>
<td>Part time commercial farmer</td>
<td>2/0</td>
<td>1/0</td>
<td>2/0</td>
<td>8/0</td>
</tr>
<tr>
<td>Retired farmer</td>
<td>6/0</td>
<td>0/0</td>
<td>0/0</td>
<td>1/0</td>
</tr>
</tbody>
</table>

**TABLE 2.3:** Relation between farmer types and land use changes.

**Discussion of the preliminary results**

The results as presented above reveal some clear, and logically expected, relationships between drivers of land changes and observed land changes. For example, it is no surprise that of all farmer types, full-time farmers are the ones that are most strongly related to land intensification, while hobby farmers generally seek to extensify their land management. However, the results also show that not all relations are unidirectional, and that some drivers might yield changes in opposite directions or that opposite values can lead to the same land use change. For example, off-farm employment can yield land abandonment as farmers choose other careers to generate their income, or it can lead to expansion of agricultural land as it provides additional income required to finance this expansion. Frequently, such conflicting results are actually caused by the wider context within which these changes take place, or the specific combination of drivers that act in a regions. The most obvious example being accessibility, which can be a direct cause of land abandonment in remote places or an indirect cause of land abandonment in exactly those places that are very well accessible. Therefore, understanding land use changes requires the consideration of a combination of drivers rather than single cause-effect relations (Lambin et al., 2001).

Farm economics, or factors that influence farm economics directly such as subsidies, accessibility or land productivity, are the most important drivers of agricultural land change reported in case studies. This confirms the earlier observation that it is increasingly difficult to continue farming in a profitable way (Cocca et al., 2012). For the same reason, (a lack of) farm income is an important factor determining abandonment of agricultural areas, for example caused by globalisation of food markets. However, results also show that there are several different and opposing routes to either remain in business or to improve farm economics; while some farmers choose to supplement farm income with off-farm employment and consequently extensify to facilitate off-farm diversification, others attempt to gain benefits of scale by intensification or expansion. This observation again illustrates that agricultural changes are not unidirectional, but that instead similar circumstances can lead to opposing land use changes.

Finally, family tradition (including the associated investment in knowledge and specialised equipment), culture of farming, and the succession cycle are factors that considerably slow down the rates of change in agricultural lands. Family traditions generally make farmers continue their business despite decreasing profitability, while a culture of productivity motivates farmers to produce food while ignoring demands for
other goods and services provided by farms and farmland. Instead, the moment a farmer retires is frequently cited as the moment when the farming system is changed, either by the successor moulding the business in his desired direction, by abandonment of the land, or by leasing or selling the land to neighbouring farmers. These processes cause agricultural land to respond relatively slow to changing circumstances such as modifications in agricultural subsidies or globalisation of world food markets.

Results from this meta-analysis inform about the drivers of recent agricultural land use changes, and can therefore inform the design of agent-based land-use models such as the VOLANTE EuroABM described in Section 1. It informs about the different agents involved in agricultural land use changes, their decision-making processes and the factors that influence these decisions. Section 3 elaborates how exactly this meta-analysis informs the EuroABM.
2.4 References – Section 2


2.5 Appendix to Section 2
The following papers have been included in this meta-analysis:


SECTION 3: Model Inputs

Abstract
In this Section we list the inputs required by the model presented in Section 1, and detail how empirical data and the meta-analysis in Section 2 will be used to satisfy these at European scale. We identify data sources where possible, and discuss the future model development necessary for the establishment of the final VOLANTE ABM.
3.1 Introduction
This section provides details of the model inputs outlined in Section 1. We present the data sources to be used for the establishment of the full Euro-ABM, where these have been identified, and discuss methods for dealing with inputs for which data is unavailable. Some inputs and data are not required at this stage, and will be dealt with more fully at a later date as the model is extended; we identify these here for completeness. Where possible we have included data redundancy so that any problems that arise with particular sources can easily be resolved.

The model inputs that we include here are:

- Capital levels (current)
- Land cover (current)
- Demand levels for each service (current and predicted)
- Agent typology (type identities)
- Agent production functions (typological)
- Agent variation (within types)
- Agent-capital feedbacks
- Institutional identities / typology and actions
- Utility functions

3.2 Capital levels
As discussed above, we initially include seven capitals: human/social, infrastructure, economic, grassland productivity, forest productivity, crop productivity and nature value (these capitals can be altered or extended as required). Definitions and data sources for these capitals are given in Table 3.1. The requirements for data are that they must be available and consistent, preferably at 1 km² scale, across the whole of the EU, while capitals themselves must relate meaningfully to the production of services by agents.

Our use of these capitals follows the established methodology of Scoones (1998), and is also partially supported by the results of the meta-analysis presented in Section 2. Infrastructure is represented in the meta-analysis by the accessibility of a region or plot of land, both of which appeared to be important. Moreover, land improvement includes irrigation and, consequently, depends on the availability of irrigation infrastructure, the deterioration of which was cited as a reason for land abandonment. Similarly, the productivity of the land for respective uses was mentioned frequently as a driver for land use change, typically to indicate that marginal areas were being abandoned or managed less intensively, but also to indicate that expansion and intensification take place in locations that are productive. Natural value influences agricultural land changes indirectly, as regions with more diverse and natural landscapes are attractive for rural tourism, which again is one of the drivers for extensification. The dependency of land uses on these capitals will therefore be parameterised on the basis of these findings, where relevant.
<table>
<thead>
<tr>
<th>Capital</th>
<th>Definition</th>
<th>Input data (scale)</th>
<th>Data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Human/social</td>
<td>Levels of skills, education, health, labouring abilities and the effects of peer, familial or geographical social networks in supporting land uses (by increasing productivity or agents' tolerances of competition or low utility levels).</td>
<td>1. Several possibilities and combinations including life expectancy (NUTS2), tertiary educational attainment (NUTS2), income inequality (NUTS0) and community cohesion (NUTS0).</td>
<td>1. Eurostat</td>
</tr>
<tr>
<td>Infrastructure</td>
<td>Proximity to transport networks and central markets.</td>
<td>1. Travel time to the nearest city with population &gt; 100 000 (also possible combinations of cost-distance to harbors, airports, or cities of other sizes). 2. Road, rail and waterway networks (NUTS 2)</td>
<td>1. IVM 2. Eurostat</td>
</tr>
<tr>
<td>Economic</td>
<td>Level of financial assets (i.e. personal savings, local GDP, debt levels, external financial support) that support land management activities.</td>
<td>1. Regional GDP (NUTS3) downscaled to 1km² by population density (per km²). 2. Household income (NUTS2) 3. Household financial assets (NUTS 0) 4. Produced economic capital stock (NUTS0)</td>
<td>1. IVM 2. &amp; 3. Eurostat 4. World Bank</td>
</tr>
<tr>
<td>Grassland productivity</td>
<td>Baseline productive potential for grassland, dependent on temperature, water availability, sunshine etc.</td>
<td>1. Grassland production potential (1km²)</td>
<td>1. IVM</td>
</tr>
<tr>
<td>Forest productivity</td>
<td>Baseline productive potential for forestry, dependent on altitude, temperature, water availability, sunshine etc.</td>
<td>1. Suitability index for various European tree species (1km²)</td>
<td>1. EFDC, JRC</td>
</tr>
<tr>
<td>Crop productivity</td>
<td>Baseline productive potential for crops, dependent on temperature, water availability, sunshine etc.</td>
<td>1. Production potential for range of crops (e.g. wheat) (1km²)</td>
<td>1. IVM</td>
</tr>
<tr>
<td>Nature value</td>
<td>The 'degree of naturalness', biodiversity levels, natural resource stocks (soil, water, air, genetic resources etc.) and environmental services (hydrological cycle, pollution sinks etc.)</td>
<td>1. Potential for nature conservation (1km²) (composite of presence of important species, fragmentation &amp; human intervention). 2. Index of Naturalness (10'x10') 3. Water exploitation index (10'x10')</td>
<td>1. IVM 2. &amp; 3. UEDIN</td>
</tr>
</tbody>
</table>

**TABLE 3.1:** Identities and data sources for model Capitals. IVM is the Institute for Environmental Studies at Vrije Universiteit Amsterdam, a VOLANTE and WP6 partner which holds several alternative datasets (not listed) for each Capital. EFDC is the European Forest Data Centre, managed by the Joint Research Centre (JRC), another project partner. UEDIN is the University of Edinburgh. NUTS refers to the Nomenclature of Territorial Units for Statistics regions. Data held by the World Bank are accessed via [http://data.worldbank.org/](http://data.worldbank.org/). Data held by EUROSTAT are accessed via [http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/](http://epp.eurostat.ec.europa.eu/portal/page/portal/eurostat/home/). Data held by EFDC / JRC are accessed via [http://forest.jrc.ec.europa.eu/efdac/](http://forest.jrc.ec.europa.eu/efdac/). Multiple sources may be used independently or combined as appropriate.
The influences of economic and human capitals are less clear from the meta-analysis results. While farm economics are the most important driver for agricultural land changes, they are primarily the result of the farm’s situation and its interplay with agricultural markets and subsidies; regional economics do not seem to play a large role in here. Hence we focus on local or individual economic data (Table 3.1). Regional economics do play another role in agricultural change (which cannot be deduced directly from the results presented above as it was not analysed directly): extensification processes such as conversion to organic farming, adding greening elements, active reforestation or renaturalisation and environmental stewardship are primarily, but not exclusively, found in the wealthier regions of north-western Europe. Also, the availability of off-farm employment plays an important role in agricultural land change as it provides either an alternative livelihood for farmers who stop farming or a supplementary income to farmers that continue. Hence, regional economics plays an important but complex role in agricultural land change, with influences that are not clear a priori. The calibration of agent sensitivities to regional economics must therefore be approximate and subject to further research.

Similarly, the influence of human/social capital as a driver for land use change is not directly clear from the meta-analysis. The education of the farmer is a driver for extensification, mostly through environmental awareness, but the education levels of most farmers depend more on their family background than their own educational history. On a regional scale, education levels might underlie the demand for regional goods and services including food, but also other ecosystem services. Another related factor which strongly influences land changes is the farming tradition of the farmer’s family, or the strength of their productivist attitude. While these properties might be personal, they are certainly stronger in some regions than in others. However, it is not directly clear how to express these relations in terms of dependency on human or social capital, instead being more appropriate to description via agent typologies and variation.

Finally, it should be noted that the services that are produced based on these capital levels are not independent. Obviously, agricultural land produces food, feed and fibre. But the meta-analysis demonstrated that the provisioning of recreation and tourism services is strongly related to such production, at least in terms of rural tourism and recreation of people in their own region: the agricultural landscape is what attracted tourists in the first place. Consequently the (extensive) production and tourism or recreation services seem to be symbiotic: the first provides the setting, and the second provides supplementary income.

While the meta-analysis therefore supports the use of the above Capitals, it also illustrates that the calibration of agent sensitivities to them (and productivities using them) must be carried out carefully and, in some cases, requires further research. This will form part of the development of the full Euro-ABM.

### 3.3 Land cover

Land cover maps are needed to establish current agent locations from which to start simulations. Once again, these data must be available and consistent at 1km² scale for the EU. We will subsequently apply a single translation to convert land cover into agent types that are drawn from our typology.

We use CORINE Land Cover data, which provides raster data between 2000 and 2006 for the land cover in Europe for a mapping scale of 1:100 000 (the surface area of the
3.4 Demand levels

Demand levels are exogenous to our model and, while agents and institutions may be able to alter them, they are initially defined prior to model initialisation. Demand levels are also where the VOLANTE scenarios inform the ABM, and so we use scenario-dependent demand levels generated by top-down models in VOLANTE Work Package 7 (Lotze-Campen et al. 2012), which take account of predicted climatic, population, economic and environmental changes.

The ABM does not explicitly treat urban land uses, and so we do not include any quantification of demand for housing or other urban or industrial developments. Instead, we make the assumption that demand for urban areas will always be met, even at the expense of other land uses, and incorporate externally-generated predictions of urban expansion as exogenous conditions of the model. These predictions are made by the MOLAND (Monitoring Land Use / Cover Dynamics) model running at the Joint Research Centre (Engelen et al. 2007).

3.5 Agent typology, production functions and variation

The design of the agent typology, production functions and intra-type variations will be based on modelling requirements (i.e. the need for flexibility and efficiency; see Section 1), the meta-analysis (Section 2), and further research and experimentation. As noted earlier, the division of agents into productive types has an empirical basis (e.g. Rounsevell et al. 2012) and will be chiefly informed by the meta-analysis (in the case of agricultural agents). Furthermore, the ability to group agents while retaining individual behaviour is one of the principal advantages of ABMs (Bonabeau 2002), and so intra-type variation will also be included. This may be aided by the division of agent characteristics into those that are internal and external to the agent, with internal factors determining whether the agent will take certain decisions, and external factors determining the scope of these decisions (Siebert et al. 2006; Lambin et al. 2001; Valbuena et al. 2010).

We include a similar division between factors that affect an agent’s access to capitals and production of services (production factors), and those that affect their willingness to persist with their land use or relinquish their land for use by another agent (persistence factors) (these are effectively equivalent to Siebert et al.’s (2006) division of agents’ ‘ability’ and ‘willingness’ to make changes). The latter group of factors is largely beyond the scope of empirical calibration at EU scale, and will be described using established mathematical functions (e.g. Gaussian distributions for particular variables, with parameters informed by the meta-analysis). Particularly important characteristics that the meta-analysis provides input for are:

- The effect of agent age, especially retirement and succession cycles;
- The sub-division of agricultural agent types by income. The meta-analysis identified at least five groups of farmers with distinctively different behaviour and motivations: subsistence farmers, retired farmers, hobby farmers, full time commercial farmers and part time commercial farmers;
- The effects of spatial and temporal peer (or family) groups on land use and probability of change, including cultural and traditional views of productivity and environmental issues;
• Variation in productivities and behaviours across the study area;

It is important to note, however, that while the meta-analysis provides information about the importance of drivers of land use change and the nature of changes that they cause, these relationships and their descriptions in case studies are qualitative. Therefore these results cannot be used directly to parameterise the ABM or to design production functions and assign variations to these functions. Instead, the drivers identified are used to inform particular facets of the model (e.g. capital levels or individual variation) and to provide approximate, directional relationships between these and land use changes (Table 3.2).

<table>
<thead>
<tr>
<th>Category</th>
<th>Accessibility</th>
<th>Regional socio-cultural factors</th>
<th>Farm economics</th>
<th>Farm characteristic</th>
<th>Farmer characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Factor</td>
<td>Far from town</td>
<td>Low/high population density</td>
<td>Financial capital</td>
<td>No option for expansion</td>
<td>Desire to expand farm</td>
</tr>
<tr>
<td></td>
<td>Close to city</td>
<td>Religion</td>
<td>Labour investment</td>
<td>Located in less productive environment</td>
<td>Unwillingness to purchase inputs</td>
</tr>
<tr>
<td></td>
<td>Presence/absence of public transport</td>
<td>Historical land uses</td>
<td>Soil conditions</td>
<td>Soil conditions</td>
<td>Education level</td>
</tr>
<tr>
<td></td>
<td>Networks</td>
<td>Politics</td>
<td>Farm size</td>
<td>Farm size</td>
<td>Age</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Tenanted/owned</td>
<td>Tenanted/owned</td>
<td>Attitude to risk</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Level of specialisation</td>
<td>Level of specialisation</td>
<td>Attitude to environment</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Level of farming experience</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Previous diversification experience</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Gender</td>
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<td></td>
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<td></td>
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<td></td>
<td>Attitude to government</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Competitiveness</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Succession perspective</td>
</tr>
<tr>
<td>Description in VOLANTE ABM</td>
<td>Infrastructure capital</td>
<td>Social capital</td>
<td>Financial capital; individual variation</td>
<td>Natural capital; Individual variation</td>
<td>Individual variation</td>
</tr>
</tbody>
</table>

**TABLE 3.2:** Factors related to farming intensity and diversification found by a meta-analysis. Factors are grouped and their potential means of description in the VOLANTE ABM given.

### 3.6 Agent-capital feedbacks

Capital levels may undergo temporal change during simulations as the result of modelled or exogenous environmental processes, institutional intervention or scenario
development, and can also be directly affected by land use. The latter effect is particularly relevant to the effects of land uses on productivity and natural capitals. In each application of the model, the nature and magnitude of any feedbacks will be based on relevant literature, but because it is impossible to accurately parameterise these for all modelled land uses at the EU scale, we will also treat these as experimental variables and investigate their likely effects on model outcomes.

### 3.7 Institutional identities, typology and effects

Institutions of various kinds - from informal and local to governmental and international - have a critical effect on land use and land use change (e.g. Prishchepov et al. 2012; Section 1), and the ability to model their effects is one of the distinguishing characteristics of the ABM. The actions of institutions are partially constrained here by scenarios that define future policies, and also by separate top-down modelling that defines demand levels. While these exogenous institutional effects are simply converted to cell-level changes, there remains a need for additional institutional activity to be modelled within the ABM.

We will include institutional agents that can influence land use change by altering the levels of capitals (e.g. increasing social capital through education), enhancing the ability of particular agents to access capitals (e.g. through subsidies), or by altering the value of, or demand for, services (e.g. through subsidies or taxes). Modelled institutions will have a fixed area of influence (generally regional or country-wide), a single goal and a single mechanism to achieve that goal. The strength of this mechanism depends upon the institution’s defined level of power, and will operate with a time-lag to account for the time taken for policies to take effect (see Section 1).

Rounsevell et al. (2012) proposed a typology of institutions similar to that of agents, in which institutions would be grouped by the type and the scale of their effects. For example, formal or informal organisations dedicated to the maintenance of agricultural or conservationist practices are common at the local level, and may have relatively consistent effects on land use patterns and change (Berkes et al. 2000; Armitage 2003). It is also important to note that the actions of institutions at different levels may interact; national (or higher) level demands can override local opposition or suitability (e.g. Bonaiuto et al. 2002; Verburg et al. 2002), but local institutions can also filter or effectively prevent national policies from having any real effect (e.g. Agarwal & Yadama 1997; Skinner et al. 2001).

We do not attempt to accurately model all of the effects of institutions within the EU, but will develop an institutional typology, with associated effects, based on expert opinion and further review of the literature. This will form the basis for further experimentation, in which institutions and their effects will be varied to examine their influence on model results. The primary input required is a survey of the main institutional types operating in Europe.

### 3.8 Utility functions

Utility functions in the ABM are not intended to describe the monetary value of service production, but its broader ‘worth’ to society. As such, their relative values and forms are more important than absolute quantities, and these will estimated by literature surveys and expert opinion. Inputs to these functions therefore take the form of comparative assessments of the benefits and forms of demand for different services.
3.9 References – Section 3


Lotze-Campen, Herman & Alex Popp, Peter Verburg, Markus Lindner, Hans Verkerk, John Helming, Andrzej Tabeau, C.L., 2012. Deliverable No: 7.2 Description of the linked modelling system of sector models and multi-sector assessments,


Appendix A1: Globalisation, regionalisation, and the behavioural responses of land use agents

Abstract
This appendix presents an example application of the ABM presented in Section 1, to the theoretical effects of globalisation, regionalisation and the effects of land use agent behaviour on these.

The global land system is under intense pressure from human demands for a range of different services. Economic theory suggests that globalised free trade is the most efficient way of handling these demands, allowing maximum productivity and specialisation of supply. However, political responses are often protectionist in nature, designed to ensure continuity of land uses and the regional production of multiple services. We investigate the implications of both globalisation and regionalisation of demand for the efficiency and productivity of land uses and, using an agent-based model of land use change, how realistic forms of human behaviour can strengthen, weaken or alter these implications. We show that ‘rational’ productive agents tend towards optimal land use configurations under globalised systems, but that ‘irrational’ behaviour yields superior results under regionalisation. Finally, the adoption of multifunctional land uses is found to be a strong and effective emergent property of agent populations under regional demand.
Introduction

Land across the globe is under intense pressure from the demands of an increasing, and increasingly affluent, human population. Resource extraction, food production, nature conservation, urban development and other land uses compete for increasing areas of a finite land resource (Bouma et al. 1998; Godfray et al. 2010; Smith et al. 2010). Wealth inequalities and economic liberalisation drive globalisation of demand and supply, and lead to dramatic land use transitions, especially in the developing world (Lambin et al. 2001; Lambin & Meyfroidt 2011).

In theory, globalisation underpinned by free trade will produce an optimal distribution of land uses, so that goods and services are produced wherever it is most efficient – and cheapest – to do so (van Ittersum et al. 1998; Pingali 2007). Where true, this would maximise productivity, productive efficiency, the land area available to different land uses, and the value of production that occurs in each country or region (e.g. McKenzie 1953). Some governments have pursued policies to this end, and international bodies often promote free trade and economic liberalisation. Examples include the European Common Market (Sleuwaegen 1988), North American Free Trade Agreement (Burfisher et al. 2001; Kose et al. 2004) and the activities of bodies such as the WTO (Subramanian & Wei 2007).

However, it is more common for governments and other institutions to enact policies designed to protect particular land users in particular areas and to maintain stability in their land systems (e.g. Potter & Burney 2002; Baldwin 2006; Dibden & Cocklin 2009). Such policies may attempt to balance the interests of productive and economically important industries, protection of biodiversity, and democratic planning control (Lambin & Meyfroidt 2011), or they may simply be examples of protectionism (Potter & Burney 2002; Dibden & Cocklin 2009). Increasingly, they are used to promote ‘multifunctional’ land uses (Wiggering et al. 2006; Piorr et al. 2008). The European Union’s Common Agricultural Policy (CAP) has several such objectives (Sampson & Yeats 1977; Potter & Tilzey 2005). Originally intended to maintain a level of self-sufficiency in food production in Europe, it was criticised for its tendency to stimulate overproduction and environmentally damaging intensification of agriculture (e.g. Rabbinge & van Latsteijn 1992; Stoate et al. 2001), which later modifications have sought to resolve (Piorr et al. 2008). In contrast to globalisation, policies of this kind should lead to relatively inefficient land uses distributed via policy mechanisms rather than optimal allocation (Lambin et al. 2001) - although neither extreme can be reliably linked with true efficiency because of other externalities (e.g. Robertson & Swinton 2005; Godfray et al. 2010).

In reality, free trade and protectionism occur in far more alloyed forms than their theoretical counterparts. One of the most important reasons for this is that the behaviour and decisions of individual land managers can have strong and complex effects on land use change (Potter & Tilzey 2005). For example, numerous studies have looked into whether and how farmers’ individual characteristics affect (the heavily-legislated) process of agricultural land use change. These have identified a host of personal or cultural factors that can have a decisive effect on land use decisions (e.g. Macy & Willer 2002; Siebert et al. 2006; Gorton et al. 2008; Valbuena et al. 2010; Meyfroidt 2012). Such factors may prompt land managers to resist policies that are not consistent with their own beliefs or desires (e.g. Walford 2003), or simply engage in unrelated behaviour that undermines their effects (e.g. Burton & Walford 2005). Individual preferences can also produce emergent societal influences such as support for local food or recreation (e.g. Starr & Adams 2003), or, indeed, opposition to globalisation expressed through democratic processes (e.g. Mughan et al. 2003).
The effects of individual characteristics and behaviours of this kind are extremely difficult to assess. However, the few quantitative analyses that have been undertaken suggest that human behaviour can entirely confound a policy or trend, with uptake of particular schemes, for example, varying between 0% and 100% (Weisbuch & Boudjema 1999). Despite this, the implications for land use changes caused by globalisation or protectionism have not been fully investigated, so the likely effects of these processes in the real world, where they are subject to filtering through land users’ responses, remain to some extent uncertain.

Increasingly widely used in studies of land use change, agent-based models (ABMs) allow examination of how particular behaviours affect land use dynamics (e.g. Berger 2001; Parker et al. 2003; Matthews et al. 2007; Rounsevell et al. 2012) and so are ideally suited to confronting the theoretical implications of globalisation with realistic behavioural responses. However, while multifunctional land use and density gradients have been explored for urban land uses (Van Vliet et al., 2012), we are not aware of any application that comprehensively includes multifunctional land uses or gradients of land use intensity, both of which are important in this context and common in the real world (Lambin et al. 2000). The ability to include these in models is one of the significant advantages of the ABM presented in this paper.

We use a newly-developed ABM framework to investigate the implications of regionalisation of demand for land use productivities and competition, and how these change under modelled human behaviours. The ABM applies exogenous demand levels which agents attempt to meet according to behavioural rules and service productivity. Where individual behaviour is absent, agents effectively optimise their land uses according to supply and demand levels, but as the variety and strength of behaviours increase, these become a dominant factor in determining land use change. Our framework allows the adoption of different land uses, variations in the intensity of land uses, diversification into multifunctional land uses, land abandonment and competition for available land. In this paper we investigate the effects of these in a simulation setting designed to isolate particular processes, according to a number of hypotheses concerning processes and drivers of land use change. These are:

- That demand expressed at the global scale allows optimisation of productive land uses so that supply meets demand using the most efficient configuration of land uses, and that deviation from this optimal configuration is driven only by local agent behaviour;
  - That behaviour that constrains sensitivity to competition delays the establishment of this configuration;
  - That behaviour that limits sensitivity to demand levels can prevent establishment of an optimal configuration;
- That demand expressed at regional scales leads to (globally) sub-optimal production and spatial configurations, with production occurring at reduced efficiencies and the most productive land at risk of abandonment;
  - That behaviour that constrains sensitivity to competition or demand levels again delays establishment of an equilibrium land use configuration but may also produce configurations that are more efficient from a global perspective;
- That allowing land managers to vary land use intensity will produce sub-optimal production at the global scale as above, but that it will allow agents to match land uses to regional characteristics more effectively, so increasing efficiency of production;
• That allowing agents to adopt multifunctional land uses will similarly allow agents to match land uses to regional characteristics, and may additionally increase global production (while remaining inferior to the globalised case above).

Methods

An overview of the agent-based model

The ‘EURO-ABM’ model that we use here is designed to allow land use changes to be modelled at the European scale, and is described in detail in Murray-Rust et al. (2011) and Murray-Rust et al. (in prep). Forming part of the EU FP7 ‘Visions of Land Use Transitions in Europe’ (VOLANTE) project, the model will be used to investigate the effects of human behaviour on land use transitions in Europe under a range of socio-economic and environmental scenarios. The EURO-ABM is designed to be flexible, capable of handling a large variety of data, and applicable in a wide range of empirical or theoretical settings.

The model is based on demand and supply of particular services; demand is defined exogenously whereas supply is a function of agent behaviours and productivities, and location characteristics. Both are expressed in abstract ‘units’ of production that can be thought of as the maximum possible yield of a service from a piece of land. The modelled landscape is divided into grid cells, and each is assigned values for the levels of capitals (e.g. economic, human, natural productivity, infrastructure) at that location. Agents use these capitals to produce services, and their ability to do so is controlled by a production function that can apply at the individual or typological level (Fig. 1). The model is intended to operate with an agent typology based on the Human Functional Type concept (Rounsevell et al. 2012).

At each modelled timestep, the level of service production achieved by an agent is given a utility value via a function that relates production levels to unmet demand. Agents compete for land on the basis of these utility values, and this competition is also affected by individual or typological behaviour. Behaviour can be modelled via a number of parameters that control agents’ productivities, sensitivities to demand and utility, and abilities to search for new land. Giving-up and giving-in thresholds describe, respectively, the minimum utility level an agent will accept before abandoning land, and the minimum value by which a competitor’s utility must exceed an agent’s own before that agent relinquishes its land (Table 1). Several studies have suggested that a wide range of behaviours are reducible to a few dimensions of this kind (e.g. Berger 2001; Polhill et al. 2001; Siebert et al. 2006; Gorton et al. 2008; Murray-Rust et al. 2011). Behavioural parameters are all subject to random or systematic variation at individual or typological level.

Figure 1: Schematic description of the structure of the EURO-ABM
Table 1: Basic simulation schedule showing the role of the giving-up and giving-in thresholds. Timestep actions occur at every modelled timestep, and the Allocate Land actions follow from one of these. Capitalised terms refer to a complete set, and parameters $n$ and $m$ are given in Table 2.

<table>
<thead>
<tr>
<th>Timestep</th>
<th>Allocate Land</th>
</tr>
</thead>
</table>
| 1. For each agent $\in$ Agents  
   a. Update competitiveness based on residual demand  
   b. If competitiveness $< \text{giving-up threshold}$, leave system  
2. For each region $\in$ Regions  
allocate-land  
3. For each agent $\in$ Agents  
   Update supply of services produced  
4. For each region $\in$ Regions  
   Update supply and unmet demand | 1. For each agent type $t \in$ Agent Types,  
   undertake $n$ search iterations of $m$ cells  
2. For every searched cell, calculate $t$'s competitiveness  
3. If $t$'s competitiveness $> \text{cell owner's giving-in threshold}$, owner relinquishes cell  
4. Agent of type $t$ takes cell over |

Experimental Setup
We begin with a simple modelled world to investigate the effects of regionalisation in the absence of any confounding processes, and gradually add complexity to this world. In all experiments, the world is represented by a 50 by 50 cell grid, where each cell may be managed by a single agent. Agents are distributed randomly across the world at the start of the simulation, and are allowed to compete for land over the course of 25 timesteps. In each case, we keep track of the distribution of agents relative to capital levels and the supply and average productivity of services. We run 30 realisations of each basic model configuration and a single realisation of each configuration that includes agent behaviour, to see whether this falls within the envelope of results from the equivalent basic model. Parameter settings used in each case are given in Table 2.

Experiment 1
Initially, we model only two agent types – farmers and foresters, producing only food and timber respectively – competing to satisfy demands expressed at the global level. These demands remain constant and homogeneous throughout the simulation. We include crop and forest productivity capitals that take perpendicular gradients across the world, with forest productivity being maximised at the top of the arena and crop productivity on the right. We make farmer agents sensitive to crop productivity and forester agents sensitive to forest productivity.

At first, agent behaviour is kept to a minimum, so that the dynamics of the system resemble a process of optimisation. No variation occurs within agent types, so that differences in competitiveness at a particular time point are a function only of demand levels and underlying capitals. Each agent type undertakes 5,000 search iterations at every timestep, in each of which the types' competitiveness scores on 10 randomly-selected cells are calculated. Agents of that type then attempt to take these cells over, and succeed if they are currently unoccupied or if the current occupiers relinquish the cells (Table 1). Agents abandon cells when their giving-up threshold is not met and relinquish cells when their giving-in threshold is exceeded. Both thresholds are here set to 0.0, so that agents abandon a cell when they do not have a positive competitiveness score, or when another agent has a higher competitiveness score. Therefore, for each agent type, 50,000 cells are sampled with replacement at every timestep and assigned to the most competitive agent type, making it unlikely that inferior agents would persist.
Agent competitiveness is calculated on the basis of a utility function that relates supplies produced to residual (unmet) demand levels. In this case, utility functions for food and timber are identical, being linear functions of the form $y = 3x$, with negative values set to zero. While the exact values used in these functions are arbitrary, their form ensures that when demand for a service is met an agent gains no competitiveness from further production of that service, but as unmet demand for a service increases, the competitive value of providing that service grows rapidly. Using these settings, the model is run with constant demands for 950 units of food and timber. These demands are initially applied at the global level, and subsequently divided equally between four and nine equally-sized regions that together cover the entire modelled world.

**Experiment 2**

In the second experiment, we introduce typological and individual agent variation to the settings used in Experiment 1. We include heterogeneity in giving-up and giving-in thresholds between and within agent types (which is systematic and stochastic in form, respectively), in productivities within types, in agents' abilities to search and compete for cells, and in the service utility functions. Finally, we divide the agent typology further by land use intensity and introduce an additional, multifunctional agent type (see Table 2).

Our objective is to identify the general effect of broad variations in individual behavior. In fact, the nature, number and complexity of relevant behavioural factors preclude the identification of unique links between them and model parameters (e.g. Winch 1958; Rounsevell et al. 2012). This means that stochastic variation within types may provide a more robust description of real-world behaviours than a complex, inexactly calibrated model structure (Bell 1974; Siebert et al. 2006; Helbing 2010). We therefore investigate general behavioural trends through inter-type variations, and individual divergence through intra-type variations.

In the first case, we systematically vary giving-up and giving-in thresholds by agent type. We then allow stochastic variation, which is Gaussian in form, in these thresholds within types. Secondly, we introduce variation in productivities within types that is also Gaussian in form. Following this, we vary the number of search iterations and cells considered by agents at each timestep. We then alter utility functions so that overproduction retains some utility value by introducing an exponential utility function. This is intended to more accurately represent real-world utility, where overproduction of a service can still benefit the producer, even if the utility (or price) drops as a result.

For the final sub-experiments of Experiment 2, we introduce additional agent types. We first divide the existing farmer and forester agents into low- and high-intensity producers. These differ in two respects: low-intensity producers are less sensitive to the relevant capital (crop or timber productivity) than high-intensity producers, and are also capable of producing lesser quantities of food or timber where capital levels are maximised (Table 3). We then introduce a multifunctional agent type, which has a relatively little sensitivity to both capitals and produces relatively small levels of both services.
Table 2: Parameter settings used in Experiments 1 and 2. Settings that are altered relative to Experiment 1 in each case are in bold. Experiments a.2b and a.3b follow a similar pattern for 4 and 9 regions respectively. Productivities are the units of service produced under perfect conditions (capital levels). \( N(y,z) \) denotes a Gaussian distribution with mean \( y \) and standard deviation \( z \).

<table>
<thead>
<tr>
<th>Ex.</th>
<th>Farmer GU ; GI</th>
<th>Forester GU ; GI</th>
<th>Farmer Prod.</th>
<th>Forester Prod.</th>
<th>Search its.</th>
<th>Cells/search it.</th>
<th>Utility function</th>
<th>Agent types</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.0 ; 0.0</td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
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<td>2.11</td>
<td><strong>0.1</strong> ; 0.0</td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
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<td>2.12</td>
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<td>1.0</td>
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<td>10</td>
<td>( y=3x )</td>
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<td>0.0 ; 0.0</td>
<td><strong>0.1</strong> ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
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<tr>
<td>2.15</td>
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<td><strong>0.2</strong> ; 0.0</td>
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<td>10</td>
<td>( y=3x )</td>
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<tr>
<td>2.16</td>
<td>0.0 ; 0.0</td>
<td><strong>0.3</strong> ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>10</td>
<td>( y=3x )</td>
<td>2</td>
</tr>
<tr>
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<td>0.0 ; <strong>0.1</strong></td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
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<tr>
<td>2.18</td>
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<td>0.0 ; <strong>0.1</strong></td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
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<tr>
<td>2.19</td>
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<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
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<td>10</td>
<td>( y=3x )</td>
<td>2</td>
</tr>
<tr>
<td>2.110</td>
<td><strong>N(0.2,0.0)</strong>; 0.0</td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
</tr>
<tr>
<td>2.111</td>
<td>0.0; <strong>N(0.1,0.0)</strong></td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
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<tr>
<td>2.112</td>
<td>0.0 ; 0.0</td>
<td><strong>N(1.0,0.1)</strong></td>
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<td>10</td>
<td>( y=3x )</td>
<td>2</td>
</tr>
<tr>
<td>2.114</td>
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<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
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<tr>
<td>2.115</td>
<td>0.0 ; 0.0</td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>100</td>
<td>10</td>
<td>( y=3x )</td>
<td>2</td>
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<tr>
<td>2.116</td>
<td>0.0 ; 0.0</td>
<td>0.0 ; 0.0</td>
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<td>1.0</td>
<td>5000</td>
<td>1</td>
<td>( y=3x )</td>
<td>2</td>
</tr>
<tr>
<td>2.119</td>
<td>0.0 ; 0.0</td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3e^x ) (farmer)</td>
<td>2</td>
</tr>
<tr>
<td>2.120</td>
<td>0.0 ; 0.0</td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3e^x ) (both)</td>
<td>2</td>
</tr>
<tr>
<td>2.121</td>
<td>0.0 ; 0.0</td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>4</td>
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<tr>
<td>2.122</td>
<td>0.0 ; 0.0</td>
<td>0.0 ; 0.0</td>
<td>1.0</td>
<td>1.0</td>
<td>5000</td>
<td>10</td>
<td>( y=3x )</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 3: Capital sensitivities and production levels of each agent type used in the experiments

<table>
<thead>
<tr>
<th>Agent type</th>
<th>Sensitivity to CROP PRODUCTIVITY</th>
<th>Sensitivity to FOREST PRODUCTIVITY</th>
<th>Food production</th>
<th>Timber production</th>
</tr>
</thead>
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<tr>
<td>Farmer</td>
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<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>LiFarmer</td>
<td>0.9</td>
<td>0.0</td>
<td>0.9</td>
<td>0.0</td>
</tr>
<tr>
<td>Forester</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>LiForester</td>
<td>0.0</td>
<td>0.9</td>
<td>0.0</td>
<td>0.9</td>
</tr>
<tr>
<td>AgroForester</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Results

Experiment 1
In the globalised case, the two agent types rapidly achieve an equilibrium distribution, with both specialising to areas of high productivity for the service that they produce (Fig. 2a). This distribution is near-optimal for this modelled world, and allows supply levels to be equal and close to overall demand. Under regionalisation, however, agents attempt to meet demands in each region and therefore are forced to use less productive land for their particular service (Fig. 2b). In less productive regions, the areas occupied by the different agents remain distinct, but in highly productive areas they are less clear and some of the best land is left unmanaged because regional demands can be met using fewer cells. Productivities decline sharply as a result (Fig 2c).

Experiment 2
Giving-up and giving-in thresholds
Variations in agents’ giving-up and giving-in thresholds cause substantial differences in dynamics and productivities that are consistent across regionalisations. When the giving-up threshold of a single agent type is increased, agents of that type abandon less productive land, which is occupied by agents of the other type until demand for their service is satisfied (Fig. 3a). Under regionalisation, much of this abandoned land is located in the most productive regions of the arena (Fig. 3b). When both thresholds are increased together, a larger portion of the arena remains unmanaged, but this is predominantly located in the less productive areas (Fig. 3c). As a result, the increase in the threshold of a single agent type leads to dramatic drops in overall productivity of that type’s service relative to Experiment 1, and an increase in both types’ thresholds produces further drops in productivity because both agent types compete more strongly for areas of high productivity (Fig. 3d).

Giving-in thresholds have a different effect, preventing the ‘optimal’ land use configuration from developing as agents fail to relinquish land on which another type is more competitive. This decreases overall production of both services in the global case because agents that persist in unproductive areas cause others to abandon land in more productive areas when demand is met. However, it slightly increases production (and production efficiency) by agents with the higher threshold under regionalisation, as regional demand is difficult to meet in all but the most productive regions, and land abandonment therefore occurs less frequently (Fig. 3e).

Introducing random variation to agents’ giving-up or giving-in thresholds alters the equilibrium distribution of land uses, with agents persisting or relinquishing land where they otherwise would not. Production by the agent type with a randomly varying giving-up thresholds increases slightly, presumably because agents of the same type (with different thresholds) tend to keep taking over productive land when it is abandoned, while less productive land is more likely to be taken over by the other agent type. Random variation in giving-in thresholds has a similar effect because land that is relinquished will tend to be re-taken by the original type when it holds a competitive advantage there, while land that is retained may be at any point along the relevant capital gradient.
**Figure 2:** Map of the simulated world after 25 timesteps with demand at global level (a) and divided across four regions (b). The overall levels of demand and supply for food in all three regionalisations (1, 4 and 9 regions) are shown in (c) (data for all realisations are shown, giving 30 curves for each regionalisation).

**Figure 3:** Maps of the simulated world for experiments 2.12 (a), 2.22 (b), and 2.29 (c), food demand and supply for all 2 x 9 regionalisations where both agent types have higher giving-up thresholds (d), and food demand and supply for all 2 x 7 regionalisations where farmer agents have a higher giving-in threshold (e). Demand and supply plots include Experiment 1 runs for comparison.
Productivities
Random variation in agent productivities has similar effects to the random variation in thresholds above. Where the variation applies only to one agent type, unproductive agents tend to be lost from the system, while highly productive agents can retain land that competitors might otherwise take, so increasing overall productivity slightly. Where both types are subject to variation, however, neither receives a net benefit and productivities do not change.

Search abilities
Decreasing the number of search iterations delays but does not alter the eventual configuration of land uses, and average and total productivities gradually rise to their levels in Experiment 1 (Fig 4). Decreasing the number of cells considered at each search iteration means that agents of a single type will often compete for the same cells (through increased proportional resampling) rather than finding other cells which they may be able to take over. This also has the effect of delaying the equilibrium configuration from developing and slowing the increase in productivities.

Utility functions
Switching one of the two utility functions to an exponential curve, in which overproduction of a service still provides a positive utility, predictably benefits the agents that produce that service in all regionalisations. This leads to substantial overproduction of that service and corresponding underproduction of the other. It also means that the overproducing agent type is more competitive in areas where both capital levels are high, and that type’s average productivity increases dramatically as a result, while the other type’s declines.

When both utility functions are exponential, the dynamics under global demand are similar to those in Experiment 1, but the system converges to a near-optimal configuration more quickly. Under regionalisation, however, the system converges to a point that balances regional and global (total) demands because agents in particularly
productive land still benefit from competitive advantage even where they are regionally overproducing. As a result, average and total productivity are both considerably higher in the system as a whole than under linear utility functions (Fig. 5).

**Land use intensities and multifunctionality**

Allowing the intensity of land use to vary by introducing lower intensity foresters and farmers to the simulation increases the complexity of results and prevents a clear convergence from occurring. In each regionalisation, the four agent types remain mixed across the arena, but with low intensity agents clearly dominating in the areas of lowest capital (Figs. 6a, b, c). Outside these areas, land changes hands repeatedly as low- and high-intensity producers compete, giving productivity a cyclical form that rarely achieves the levels seen with two agent types (Fig. 6d). Nevertheless, the existence of low-intensity producers means that less of the highly productive land is abandoned. Introducing multifunctional 'AgroForester' agents (Table 3) has a similar effect in preventing a stable equilibrium arrangement of land uses from developing in the global case. However, the multifunctional agents clearly dominate in less productive areas, especially under regionalization (Fig. 7a). Productivities fluctuate under competition, but are similar to those without multifunctional agents in the global case. Under regionalisation, however, the presence of multifunctional agents dramatically increases productivity for both services (Fig. 7b).

**Figure 6**: Maps of the simulated world after 25 timesteps with low intensity farmers and foresters as additional agent types, under global demand (a), four regions (b) and nine regions (c). Overall levels of demand and supply for food in all three regionalisations are shown in (d) with Experiment 1 runs included for comparison.
Discussion

Our results clearly demonstrate that the expression of demands for land services at the global scale does, in principle, allow an optimal configuration of land uses to develop, under which services are produced to mutually maximal levels using the most productive land. Regionalisation of demand, in contrast, encourages land users to produce services inefficiently, using unproductive land and abandoning the most productive areas. As a result, fully ‘rational’ and equivalent land use agents that compete on the basis of their ability to satisfy regional demand create a markedly sup-optimal land system. Instead, highly behavioural agents that are insensitive to demand levels may be more beneficial under regionalisation.

Human behaviour causes substantial deviations from economic or productive rationality in the real world, and has the potential to confound drivers of land use change (Weisbuch & Boudjema 1999; Potter & Tilzey 2005). We investigated several forms of behaviour through their effects on agents’ productivities, sensitivities to demand, and abilities to compete for land and to intensify or diversify land uses. We found that some of these had dramatic effects on land uses and, while none were capable of entirely masking the consequences of regionalisation (at the strengths we modelled them), they did substantially alter them.

Among the strongest effects were those of altering the thresholds that describe agents’ willingness to abandon or relinquish land, and altering the utility functions which agents use to determine the competitiveness of their land use in a particular area. At the typological level, the agent type with the lower sensitivity to demand and competition was able to maximise production levels at the expense of the other agent type. Random variation within types (which may provide an accurate description of real-world variation) did not produce a clear effect unless it led to such a systematic difference between types. Utility functions that rewarded overproduction of a particular service were, unsurprisingly, found to favour that service at regional and national levels. However, where both services had functions of this form, the effects of regionalisation were dampened, with productive efficiency and overall production levels both increased at global scale.
These clear results are important because they speak to the effects of real-world variation between land users and utilities. For instance, it is known that many agriculturalists persist with a land use for a number of personal reasons, making them relatively insensitive to competition or to demand levels (e.g. Walford 2003; Siebert et al. 2006; Jongeneel et al. 2008). It is also true that the effective utility of service production rarely tracks demand exactly, and that overproduction usually has some utility for the producer – especially under policies that artificially inflate demand (e.g. Stoate et al. 2001).

We also find that varying the intensities and specialization of land uses have strong effects on the system as a whole. Disequilibrium follows, as intermediately productive land changes hands between equally-competitive land users. This has the advantage of limiting the extent of abandoned land in productive areas, but also causes fluctuations and, sometimes, declines in productivity. Multifunctional land uses, though, generate dramatic increases in productivity. These can be attributed to the efficiency of using marginal areas to produce small quantities of multiple services and reserving highly productive areas for intensive use. We find that the adoption of multifunctional land uses is therefore a strong emergent trend of a system dedicated to matching supply to demand levels.

Although we investigate these processes in a simple, theoretical setting, it is unlikely that the complexity of the real world entirely confounds the effects we identify. Much of the human behaviour identified as important in the literature is expressible through the parameters that we use in this model, as detailed above. Processes of intensification and diversification of land uses are also apparent throughout the world’s land systems, and a large number of policies have been enacted at various levels to encourage or discourage these processes (e.g. Piorr et al. 2008). Overproduction is known to occur, and leads to regional over-supply even as global shortages persist (e.g. Stoate et al. 2001; Walford 2003); regional demand can cause the abandonment of productive land in the same context (Bouma et al. 1998; Lambin & Meyfroidt 2011).

These results reinforce the difficulty of applying theoretical principles to the land system. A fundamental tenet of classical economics is that free trade and globalisation leads to specialisation and maximisation of production (McKenzie 1953). In reality, demand is not and cannot be truly globalised. Pressure for regional production may originate with governments or institutions (e.g. Potter & Burney 2002), or may emerge from the population, particularly where the effects of globalisation are known or thought to be locally disadvantageous (Mughan et al. 2003; Starr & Adams 2003). The internationalisation of political institutions may itself be viewed as harmful to democratic choice and accountability, and be democratically opposed as a result (Zürn 2004; Nanou & Dorussen 2013). Under such circumstances, free trade between rational agents does not produce the best result in terms of production levels or efficiency. Instead, human behaviour that limits apparent ‘rationality’ may be preferable at regional and global scales.

Of course it is not necessarily true that the most productive or efficient land use configuration is ‘best’. The economic notion of global welfare, maximised under free trade (e.g. Sampson & Yeats 1977), does not easily translate to human systems. Environmental effects of production must also be taken into account. It is increasingly apparent that rising food demands pose a serious challenge to terrestrial and aquatic ecosystems and the services they provide to humanity (Tilman et al. 2002; Robertson & Swinton 2005; Pretty 2008; Godfray et al. 2010). It has also long been recognised that globalisation and free trade lead to job insecurity in the developed world (e.g. Dietzel
1905; Burfisher et al. 2001), and may have considerable negative effects in under-
developed countries (e.g. Fujita & Hu 2001; Fortin 2005; Pingali 2007).

An important recent response to these issues is the promotion of multifunctional land
uses, intended to safeguard environments and ecosystem services while feeding a
growing population (e.g. Robertson & Swinton 2005; Pretty 2008; Dibden & Cocklin
2009). We find that this can lead to increased productivity, and appears preferable to a
system of intensification under regional demand in terms of production of services.
Global markets are of course far more complex than our model, containing, for example,
umerous demands at different levels and ‘spaghetti bowls’ of (restricted) free trade
between specific partners (e.g. Baldwin 2006), and being a mix of ideologically
dominant free trade and practical protectionism. Nevertheless, our findings suggest that
human characteristics have strong and sometimes counter-intuitive effects at the global
scale, and that agent-based modelling is a highly relevant and useful tool for their
investigation.
References


Lambin, E., Rounsevell, M.D., Geist, H.: Are agricultural land-use models able to predict changes in land-use intensity? Agriculture, Ecosystems & Environment. 82, 321–331 (2000).


