Globalisation, Regionalisation and Behavioural Responses of Land Use Agents

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Abstract. The global land system is under intense pressure from human demands for a range of different services. Neo-classical 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.

Keywords: Globalization · Regionalization · Land use · Agent-based modelling · Supply and demand

1 Introduction

Land across the globe is under intense pressure from the demands of an increasing, and increasingly affluent, human population. Meanwhile, 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 and Meyfroidt 2011). Neo-classical economic theory suggests that this will result in an 'optimal' distribution of land uses that maximises productivity, productive efficiency, the land area available to different land uses, and the value of production that occurs in each country or region (McKenzie 1953; Pingali 2007).

Governments and international bodies sometimes pursue policies to this end (e.g. Burfisher *et al.* 2001; Kose *et al.* 2004; Subramanian and Wei 2007), but more often

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attempt to protect particular land users and to maintain stability in land systems (e.g. Potter and Burney 2002; Dibden and Cocklin 2009). They also increasingly promote ‘multifunctional’ land uses(Wiggering *et al.* 2006; Piorr *et al.* 2009). 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 and Swinton 2005; Godfray *et al.* 2010).

In reality, the behaviour and decisions of individual land managers can have strong and complex effects on policies concerning land use change (Starr and Adams 2003; Walford 2003; Potter and Tilzey 2005). These effects are extremely difficult to assess, depending upon a host of personal and cultural characteristics that may act and interact in unpredictable ways. However, the few quantitative analyses that have been undertaken suggest that human behaviour can entirely confound a policy or trend, and is certainly capable of altering its course (e.g. Weisbuch and Boudjema 1999). Despite this, the implications of individual behaviour for land use changes caused by globalisation or regional protectionism have not been fully investigated.

Agent-based models (ABMs) allow examination of how particular behaviours affect land use dynamics (e.g. Matthews *et al.* 2007; Rounsevell *et al.* 2012) and so are ideally suited to confronting the theoretical implications of globalisation with realistic behavioural responses. Nevertheless, 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 is one of the significant advantages of the ABM presented in this paper.

We use a newly-developed ABM framework, the CRAFTY model (Competition for Resources between Agent Functional Types; Murray-Rust *et al.* (2014) in review), to investigate the implications of globalization and 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 study 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 global scale encourages optimisation of land uses and that deviation from this is driven only by local agent behaviour;
  - That behaviour that constrains sensitivity to competition delays the establishment of this optimal 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 leaves the most productive land at risk of abandonment;
  - That behaviour that constrains sensitivity to competition or demand levels delays establishment of an optimal configuration but may also produce configurations that are globally more efficient;
- That varying land use intensity will lead to sub-optimal production at the global scale, but 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 increase global production above other regional cases.

2 Methods

2.1 An Overview of the Agent-Based Model

The CRAFTY model used here is designed to work at large (e.g. European) scale, and is described in detail in Murray-Rust *et al.* (2014) (*in review*). 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 model is based on demand and supply of services; demand is defined exogenously whereas supply is a function of agent behaviours and productive abilities, and location characteristics. Both are expressed in abstract 'units' of production representing the maximum possible yield of a service from a piece of land. We define productivity as the quantity of a service produced in a given area (agent productivity is the quantity that agents are capable of producing), and productive efficiency as the average productivity per unit of land. Land units are formed by the division of the modelled landscape into grid cells, and each is assigned values for the levels of capitals (e.g. economic, natural productivity, infrastructure) at that location. Agents use these capitals to produce services according to a production function that can apply at the individual or typological level. 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 (used to represent a single year, but practically representing the timescale at which agents respond to demand levels) the level of service production achieved by an agent is given a utility value that depends on 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. Especially important are 'giving-up' and 'giving-in' thresholds that describe 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 (this is

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.

Timestep	Allocate Land
1. For each agent ∈ Agents a. Update competitiveness based on residual demand **b. If competitiveness < giving-up threshold, leave system** **2.** For each region ∈ Regions **allocate-land** **3.** For each agent ∈ Agents Update supply of services **4.** For each region ∈ Regions Update supply and demand	**1.** For each agent type t ∈ Agent Types, undertake n search iterations of m cells **2.** For every searched cell, calculate t's competitiveness **3. If *t's* competitiveness > cell owner's giving-in threshold, owner relinquishes cell** **4.** Agent of type t takes cell over

equivalent to an agent changing land uses) (Table 1). Behavioural parameters are all subject to random or systematic variation at individual or typological level, and we do not attempt here to accurately parameterise them for any particular system.

2.2 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 and each agent may manage only one cell. 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. We include crop and forest productivity capitals that take perpendicular gradients across the world, with forest productivity being maximised along the top of the arena and crop productivity along the right. We make farmer agents sensitive to crop productivity and forester agents sensitive to forest productivity. These agent types are chosen only to represent producers of distinct services; their identities are otherwise arbitrary.

At first, agent behaviour is kept to a minimum, so that the dynamics of the system resemble a process of optimisation. Each agent type undertakes 5,000 search iterations at every timestep, in each of which the types' competitiveness scores on 10

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. 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.

Ex.	Farmer GU; GI	Forester GU; GI	Farmer Prod.	Forester Prod.	Search its.	Cells/search it.	Utility function	Agent types
1.1	0.0; 0.0	0.0; 0.0	1.0	1.0	5000	10	$y=3x$	2
2.12	**0.2**; 0.0	0.0; 0.0	1.0	1.0	5000	10	$y=3x$	2
2.17	0.0; **0.1**	0.0; 0.0	1.0	1.0	5000	10	$y=3x$	2
2.19	**0.2**; 0.0	**0.2**; 0.0	1.0	1.0	5000	10	$y=3x$	2
2.110	**N(0.2, 0.0)**; 0.0	0.0; 0.0	1.0	1.0	5000	10	$y=3x$	2
2.111	0.0; **N(0.1, 0.0)**	0.0; 0.0	1.0	1.0	5000	10	$y=3x$	2
2.112	0.0; 0.0	0.0; 0.0	**N(1.0, 0.1)**	1.0	5000	10	$y=3x$	2
2.114	0.0; 0.0	0.0; 0.0	**N(1.0, 0.1)**	**N(1.0, 0.1)**	5000	10	$y=3x$	2
2.115	0.0; 0.0	0.0; 0.0	1.0	1.0	**100**	10	$y=3x$	2
2.116	0.0; 0.0	0.0; 0.0	1.0	1.0	5000	**1**	$y=3x$	2
2.119	0.0; 0.0	0.0; 0.0	1.0	1.0	5000	10	$\boldsymbol{y=e^x}$ **(farmer)**	2
2.120	0.0; 0.0	0.0; 0.0	1.0	1.0	5000	10	$\boldsymbol{y=e^x}$ **(both)**	2
2.121	0.0; 0.0	0.0; 0.0	1.0	1.0	5000	10	$y=3x$	**4**
2.122	0.0; 0.0	0.0; 0.0	1.0	1.0	5000	10	$y=3x$	**3**

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 initially 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 $y = x$, with negative values set to zero. The form of these functions 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 demand applied at the global level, and subsequently divided equally between four and nine regions that together cover the entire modelled world.

Experiment 2

We now introduce variation between agents to the model 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, and used to capture the effect rather than the magnitude of real behaviour), in productivities within types, in agents' abilities to search and compete for cells, and in the service utility functions (to represent real-world utility, which may remain positive even where overproduction occurs). Finally, we divide the agent typology further by land use intensity and introduce an additional, multifunctional agent type (see Tables 2 and 3). Our objective is to identify the general effect of broad variations in individual behavior. Because stochastic variation within types may provide a more robust description of real-world behaviours than a complex model requiring detailed calibration (Bell 1974; Siebert *et al.* 2006; Helbing 2010), we investigate behavioural trends through inter-type variations, and individual divergence through intra-type variations.

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

Agent type	Sensitivity to CROP PRODUCTIVITY	Sensitivity to FOREST PRODUCTIVITY	Food production	Timber production
Farmer	1.0	0.0	1.0	0.0
LIFarmer	0.9	0.0	0.9	0.0
Forester	0.0	1.0	0.0	1.0
LIForester	0.0	0.9	0.0	0.9
AgroForester	0.5	0.5	0.5	0.5

3 Results

3.1 Experiment 1

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

3.2 Experiment 2

Giving-up and Giving-in Thresholds

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

Giving-in thresholds have a different effect, preventing the development of superior land use configurations 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 efficiency) of 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. 2e).

Introducing random variation to the thresholds alters the equilibrium distribution of land uses, with agents persisting or relinquishing land where they otherwise would not. Production by agents with 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 land that is less productive for that agent type is more likely to be taken over by the other agent type.

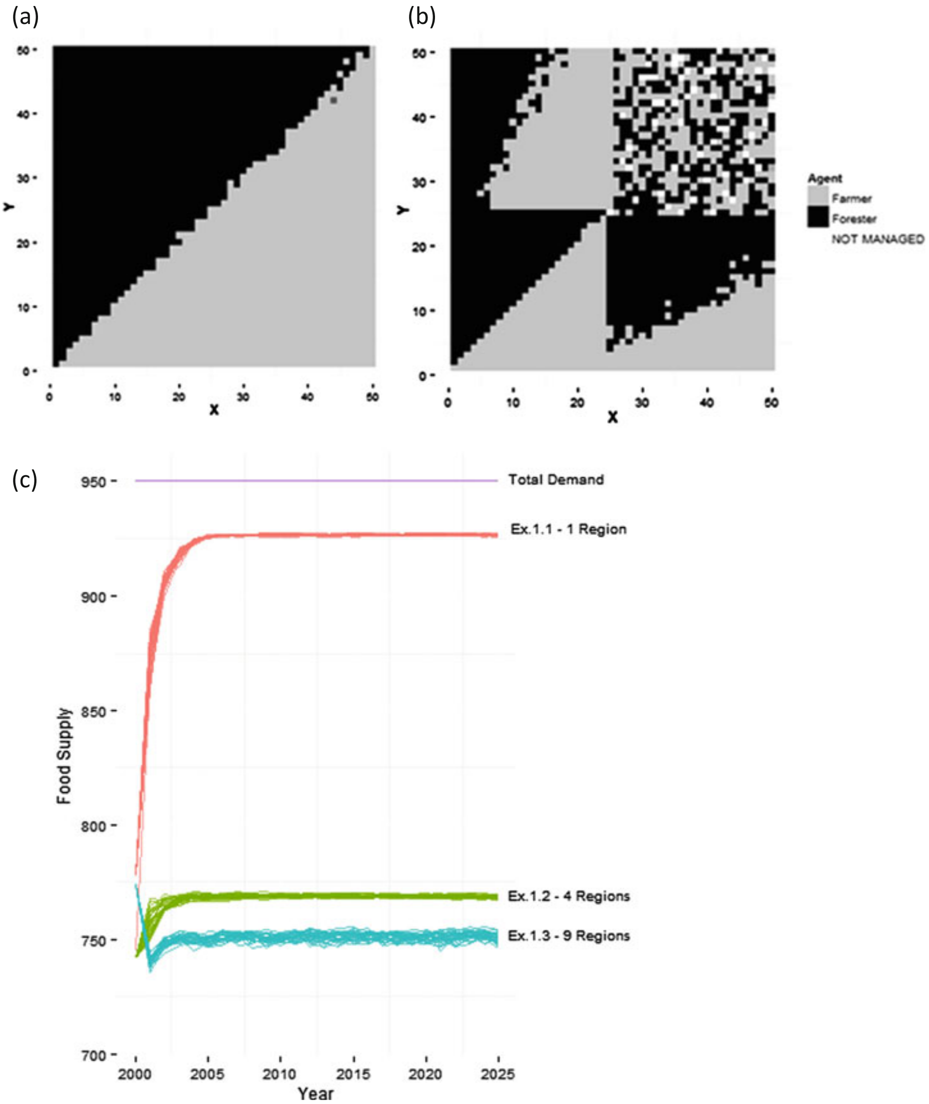

Fig. 1. Map of the simulated world after 25 timesteps with demand at global level (a) and divided across four regions (b). The overall levels of demand and supply for food in all three regionalisations (1, 4 and 9 regions) are shown in (c) (data for all realisations are shown, giving 30 curves for each regionalisation).

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.

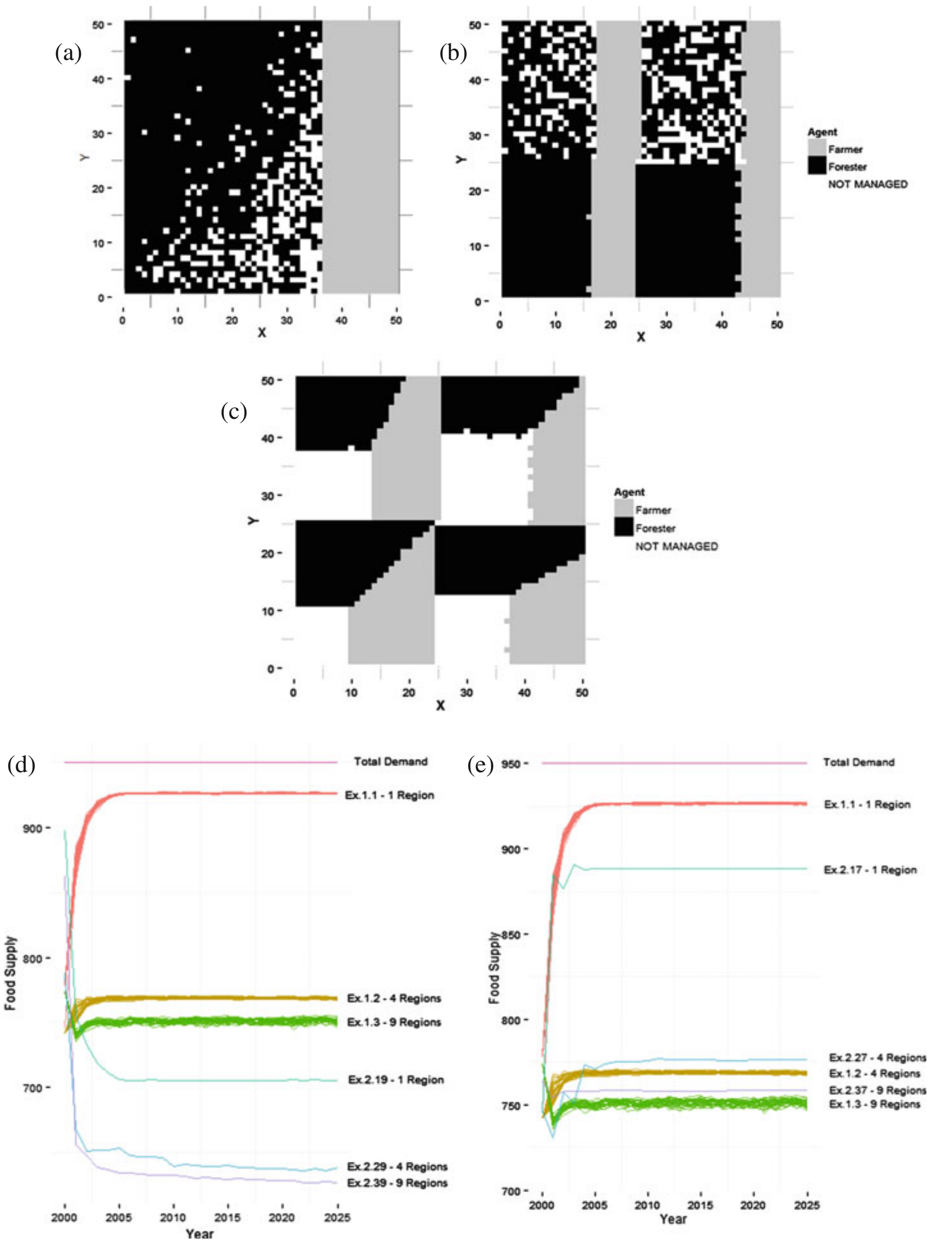

Fig. 2. Maps of the simulated world for experiments 2.12 (a), 2.22 (b), and 2.29 (c), food demand and supply for all 2.*x*9 regionalisations where both agent types have higher giving-up thresholds (d), and food demand and supply for all 2.*x*7 regionalisations where farmer agents have a higher giving-in threshold (e). Demand and supply plots include Experiment 1 runs for comparison.

Productivities

Where random variation in agent productivities applies only to one agent type, unproductive agents tend to be lost from the system, while highly productive agents can retain land and increase overall production slightly. Where both types are subject to variation, however, neither receives a net benefit and production does not change.

Search Abilities

Decreasing the number of search iterations at each timestep delays but does not alter the eventual configuration of land uses, and average and total production gradually rises to its level in Experiment 1. Decreasing the number of cells considered at each search iteration means that agents of a single type that do not already 'own' a cell will often compete for the same cells (through increased proportional resampling) rather than finding other cells which they may be able to take over, which also delays the development of the equilibrium configuration.

Utility Functions

Switching one of the two utility functions to an exponential curve, in which overproduction of a service still provides a positive utility, benefits the agents that produce that service. 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 production are both considerably higher in the system as a whole than under linear utility functions.

Land Use Intensities and Multifunctionality

Allowing the intensity of land use to vary by introducing lower intensity foresters and farmers to the simulation prevents a clear convergence from occurring. In each regionalisation, the four agent types remain mixed across the arena, but low intensity agents clearly dominate in the areas of lowest capital. 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. Nevertheless, less of the highly productive land is abandoned in this case.

Introducing multifunctional 'AgroForester' agents (Table 3) has a similar effect in preventing a stable equilibrium arrangement of land uses from developing. However, the multifunctional agents clearly dominate in less productive areas, especially under regionalisation (Fig. 3a). 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 production of both services (Fig. 3b).

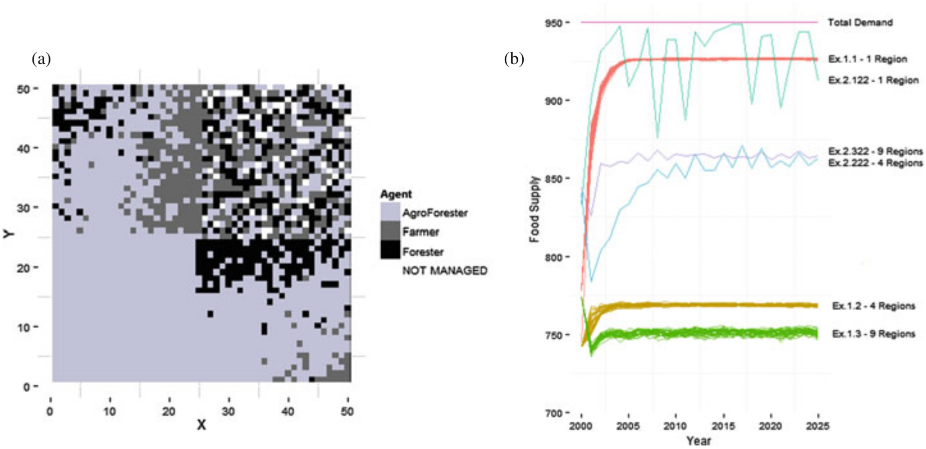

Fig. 3. Map of the simulated world after 25 timesteps with multifunctional AgroForester agents included, in four regions (a), and the resulting changes in food supply and demand in all regionalisations, with Experiment 1 results for comparison (b).

4 Discussion

Our results clearly demonstrate that expression of demands at the global scale does, in principle, allow an optimal configuration of land uses to develop, with services 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, behavioural agents that are (partially) insensitive to demand levels may be preferable.

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 and Boudjema 1999; Potter and 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 agents' willingness to abandon or relinquish land, and the utility functions of different land uses. Agent types with lower sensitivities to demand or competition were able to maximise production levels at the expense of the other 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 a systematic difference between types. Utility functions that rewarded overproduction of a service were, unsurprisingly, found to favour that service at regional and global 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.

We also found that varying the intensities and specialization of land uses had strong effects on the system as a whole. Disequilibrium followed, as intermediately productive land changed hands between equally-competitive land users. This limited land abandonment in productive areas, but also caused fluctuations and, sometimes, declines in productivity. Multifunctional land uses, though, generated 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 conclude 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 investigated 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. In particular, land managers are known to be very unwilling to convert to different land uses (e.g. Siebert *et al.* 2006), suggesting that the small variations we model in giving in thresholds understate the effects of real behavior. Processes of intensification and diversification of land uses are also apparent throughout the world's land systems, and numerous policies have been enacted to encourage or discourage these (e.g. Piorr *et al.* 2009). Overproduction does occur, and leads to regional over-supply even as global shortages persist (e.g. Stoate *et al.* 2001); regional demand can cause the abandonment of productive land in the same context (Bouma *et al.* 1998).

These results underline the difficulty of applying theoretical principles to the land system. A 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 and Burney 2002), or may emerge from the population, particularly where the effects of globalisation are thought to be disadvantageous (Mughan *et al.* 2003; Starr and Adams 2003). 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.

It is also apparent that rising food demands pose a serious challenge to terrestrial and aquatic ecosystems (Godfray *et al.* 2010), and that globalisation leads to job insecurity in the developed world (e.g. Burfisher *et al.* 2001), and may have considerable negative effects in under-developed countries (e.g. Fujita and Hu 2001; Pingali 2007). An important recent response to these issues is the promotion of multifunctional land uses (Robertson and Swinton 2005; Pretty 2008). We find that these can increase productivity and respond more effectively than intensification to regional demand. Global markets are of course highly complex, containing, for example, numerous 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.

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