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An agent-based model for studying the effects of sustainable intensification on food security in the nation State

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Abstract

Growth in World's population, the expansion of human activities and the demand for land has and continues to damage the natural environment. Humans depend on the natural environment for essential life-preserving processes, for example food production. Damage to the environment has serious consequences for national (State) and human security and wellbeing. One concern is food security and, in particular, whether a growing World population will find enough food to eat. The consequences of using more land and resources to grow more food are an important area of research. The expansion of farming will leave less land for other important uses. A proposed solution to this land use problem is sustainable intensification: growing more food on less land with either the same, or a reduced environmental impact. On a purely technical level, sustainable intensification appears to offer a solution to food insecurity and environmental damage. However, the adoption of agricultural technologies such as sustainable intensification is influenced by 'social forces' which need to be considered. We are developing a hierarchical model that uses two 'social forces' as decision drivers: economics at the landowner level and security at the State level. In our prototype model, State security restricts the economic decisions of landowners. The purpose of the model is to understand the effect sustainable intensification has on land use patterns, when their distribution and quantity depend on State food-security in a global context.

***Keywords**:* Food security; land use; intensification; agent-based model

INTRODUCTION

Land is limited in both area and productive capacity. With global populations predicted to rise to 9.1 billion by 2050 (FAO 2009) and changes in dietary preferences due to increasing wealth, demands on the natural environment will increase. This can have negative consequences for both the environment and societies (Meadows 1972, Motesharrei *et al* 2014, Willenbockel 2015, Carolan 2016). Expansion of agriculture will inevitably lead to the reduction of other land uses and the loss of important ecosystems and habitats. There are also concerns over food distribution and security (Martindale 2015 and McMahon 2013). Tilman *et al* (2011) suggest, "*Global food demand is increasing rapidly, as are the environmental impacts of agricultural expansion*". Agriculture is the mainstay of food production around the world, but the ability of farmers to produce enough food without negatively affecting the environment and climate is sometimes questioned (Mueller *et al,* 2012). Johnston e*t al* (2014) suggest that in a resource-constrained world we will need to do more with less, intensifying crop production. Climate change will also affect food production (Olesen *et al* 2011) and food security (Dawson *et al* 2016). According to Tilman *et al* (2011), in scenarios where decisions are made to extensify agricultural, the environmental impact will be greater than if agriculture was intensified.

Sustainable intensification is technical solution, which is expected to alleviate gaps in food production. Security is a social issue. The object being secured depends upon the security paradigm used, but it can range from a single human (human security*)* up to and including the State itself. (State security*)*. In the model, we use a *realist* (State centred) paradigm. We use Thucydides' *tri-fecta* of fear, honour (prestige) and interest, as the motivations of the State (Kolodziej 2005; Rosen 2005). The *tri-fecta* is considered as having close links with behavioural biology (Rosen 2005). It also relates well to the UN's definition of *human security* (UNOCHA 2014), which is the freedom from wants, fear and the ability to live in dignity; where 'wants' translates as 'interest' and 'dignity' relates to 'prestige'. In the model, the State is concerned with food security i.e. having enough food to maintain either a healthy population or a functioning State. Food security is underpinned by a combination of crop and animal production. An adequate or excess supply of animal products such as meat or milk will not offset an inadequate supply of crops. The State will see this as a security issue and register fear. The State does not have degrees of fear but is characterised as either being fearful or having no fear. Fear develops because of an immediate threat rather than a gradual threat (Aronson 2012). The State may also become fearful if world prices are higher than domestic prices as this would mean that landowners would export crops or animal products. A fearful State will implement export restrictions on a product, which is in deficit.

In the model landowners react to supply and demand whilst The State reacts to insecurity. We can anthropomorphise States because they have agency (Wendt 2014). States seek security (Waltz 2008). States have attributes in common (Wendt 2014), for example governance and territory. The State is central because it agrees trade deals, holds territory and enforces the law within that territory. The State is also concerned with security issues (Kolodziej 2005) and is the central actor on the international (global) stage (Collins 2013 and Kolodziej 2005). Given commonalities, it should be possible to create a generic state, the value of whose attributes we can adjust to characterise any given State.

Within a State, we can apply an intensification scenario. This allows us to model the impact of agricultural intensification on land use by landowners under the influence of supply and demand and constrained by the security interest of the State. Our intention is to use a series of single State models, which will form the basis of a global model. This global model will adopt a similar structure to the GLOBFOOD model (Jiang 2014) and will use similar land use determinates as those described by Meiyappan *et al* (2014). We use an agent-based approach because this offers a mechanism for incorporating both social and economic factors affecting decision-making as well as interactions between actors and with their environment (Matthews *et al* 2007). Our models are State security-centred and are less focused on individual farmer decision-making than, for example, PALM (Matthews 2006) or *Aporia* (Murray-Rust *et al* 2014). Competition for resources inevitably creates security pressures. The models allow us to examine the effect of sustainable intensification on land use change under these pressures.

PROTOTYPE MODEL DESCRIPTION

General

The purpose of the prototype State model is to test and prove the general functions and behaviours of landowners, under a limited (export only) State security control. We expect to see land use changes similar to those in the real world i.e. the expansion of farming, the contraction of forest and the expansion of woodland onto abandoned land. The quantity and pattern of these changes is expected to differ between intensification and non-intensified options and to differ with a State's security reactions. If a State does not act to control exports and imports, we expected it to have a higher risk of becoming food insecure. Our aim is to first model specific States and then to create a multi-State global model. Each time step represents a year within the model. We intend to run the simulated model scenarios for a period of 200 years. The model runs a sequence of events where sub-models calculate yields, weather impacts, State interests, World prices, population changes, domestic demand, harvest production, export controls, exports, imports, domestic supply, State food security, domestic prices, landowner incomes and land uses.

Environment

In the model, the environment consists of two parts, the physical and the social environment. The physical environment consists of the land, represented in the model by NetLogo *patches*. Land productivity is determined by land 'grade' or quality, which in the model ranges from grades 1 to 6, the most productive land being grade 1. During the set up of the prototype model, land use types are stochastically generated. Exogenously modelled weather events change crop yields on a yearly basis; these weather events are stochastic in nature. Real world cropping and animal rearing is complex, with different varieties, species and management practices within regions and nations around the world. In the model, crop production is based on wheat equivalents and animal products on livestock units. Each land grade produces a specified yield of crop or animal products. Apart from land grade and weather, the only other influence on yield is intensification. In our current model this only applies to crops and is based on predicted improvements and historical data. In the model, we assume equal technical competency of landowners. Currently all the 'farms' are of equal size. For the prototype model we calculated crop and animal production from *Whole farm Data* (SAC, 2014), with additional data from Martindale (2015) and Defra (2016). Yield improvements were estimated using Defra data. Forest yields and harvesting periods were calculated using *Forest Management Tables* (Hamilton *et al* 1971) using Matthews *et al* (2006) and Rollinson (1971). We intend to use Food and Agricultural Organisation (FAO) data for future models.

Crop and animal product yields and incomes are calculated annually. Incomes are net of costs, except for transport, which varies depending on distances to markets and ports. Forest incomes are more complex. In the model, it is assumed that young forests (below 25 years of age) produce no yields, while those over this age produce yields from thinning every 5 years and at clear-fell on year 50. For the purposes of the model, woodland timber production is based on Yield Class, defined as the maximum mean annual increment (Rollinson 1971), which remains constant for all ages, but varies with land grade. Weather has less of an impact on forest yields.

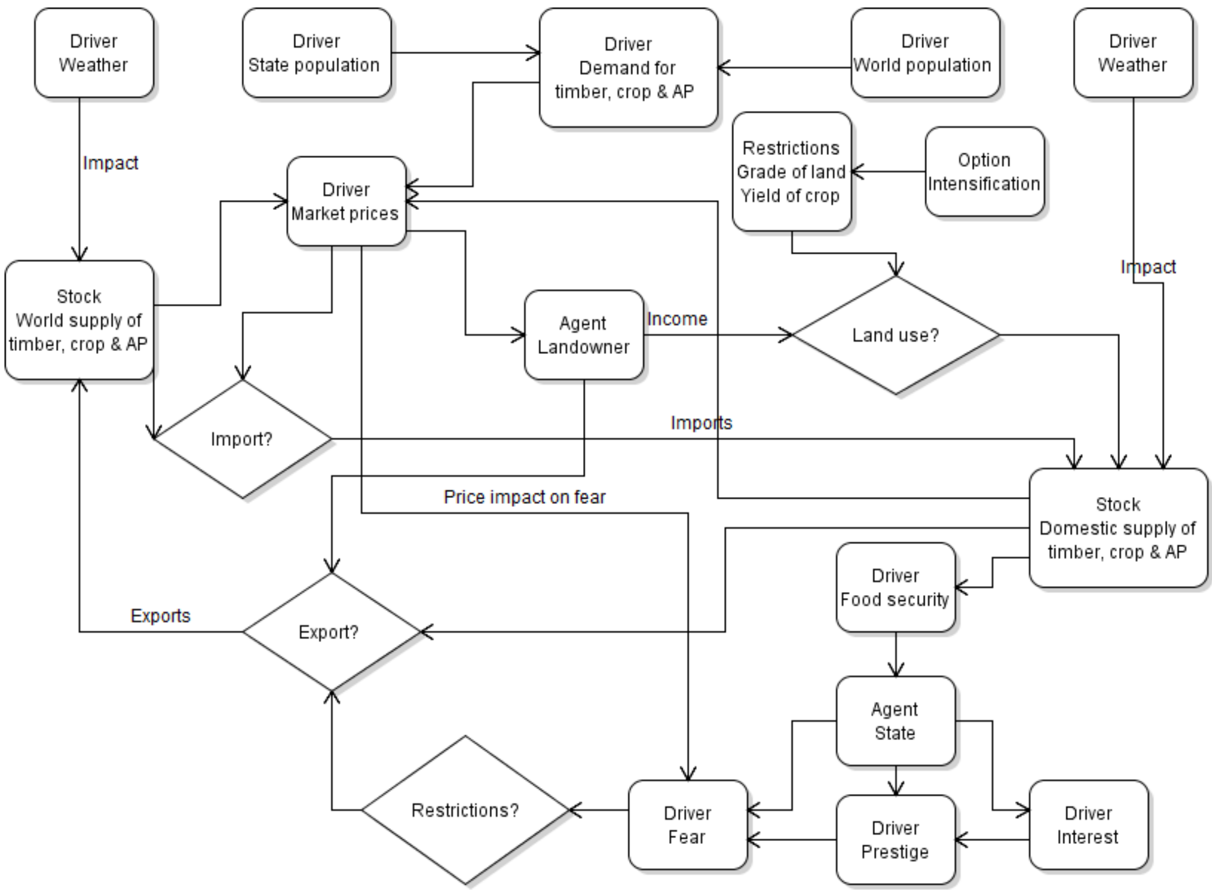

Figure 1. Prototype model of landowner and State agent behaviour and decisions. The boxes represent sub-models, arrows show the flow of information and the diamonds signify decisions. Timber, crop and animal product (AP) are measured in tonnes.

Agents

States make decisions determined by their interest in a position they wish to maintain (i.e. level of food security). Changes in land use and exports will produce changes in domestic production and domestic supply and can result in State food insecurity. The State measures food security and reacts to 'external shocks' such as a rise in world prices or a fall from a desired level of food security by restricting exports. The speed at which the State reacts depends on its level of prestige. This is a measure of its reputation and influence, which we link to its economic power. We apply the ideas of Aronson (2012), citing Leventhal *et al* (1980) linking prestige with reaction time. Low prestige results in slower reactions to external shocks. In the prototype model, the State takes a single action; when faced with food insecurity it restricts exports. Imports are under the control of 'the market', which increases imports when domestic supply is limited or when domestic prices are high.

Landowners inhabit the State and determine land use by their choices. There are four possible land uses: forest, arable, pasture or abandoned, which reverts to scrub-forest after 15 years. Pasture also includes land used for cropping for animal feed and bedding. Landowners will choose a land use that produces an acceptable income for their particular grade of land. Landowners commit to a land use for a period of years depending on use: 5 years for arable, 10-15 years for pasture and 50 years for forestry. The period replicates simplistically real world investment decisions, which are constrained by the physical attributes of the land, the capital investment required and the available skills and labour in time. At the end of the 'period', landowners calculate trends in prices. Downward trends prompt landowners to look for alternative uses.

In the real world, land is controlled by businesses, individuals and collectives. In the model we amalgamate these into a single agent class 'landowners'. The landowners are land use decision-makers. The landowners' reactions to a stimulus (price and income) determines land use, changes supply and impacts on food security. Their decisions are based on returns per unit area of land. If these returns are rising, landowners will maintain their current land use. If returns are static or falling, landowners will mimic their highest returning neighbour. This mimicry behaviour replicates that observed by Weir and Knight (2000) in the adoption of agricultural technologies. We use this behavior as an heuristic (Wilkinson & Klaes 2012 and Eslter 2015) but it could also represent a norm, where landowners follow a pattern of behaviour (Morris *et al* 2015). If a landowner cannot find a neighbour with a better income, then they will calculate the best alternative use. The use of heuristics will mean that landowners do not always maximize their income, as they will only calculate the full range of options when they are not satisfied and have no higher income neighbours to mimic. Landowners calculate the full range of options using yields, average prices and relevant costs. The options are calculated as a net present value, averaged over the period of intended use. This approach is an adaptation of investment calculations outlined by Millington (2006), Prag (2003), Price (1989) and Williams (1988). Landowners can choose to sell their products domestically within the state, or to export them depending on price and cost.

External drivers

The model runs with growing populations. These populations create demand for crop products, animal products and timber. The larger the population, the greater the total demand. The model assumes an average person; there is no distinction at this stage for age or gender. We recognise that the nutritional value of food is critical to health (Sahn 2015), but for the purposes of this version of the model and this paper, we assume that all the food produced has adequate nutritional value. All members of the State and World Populations have equal access to finance. An individual within the population represented in the model will demand a given amount of crop, animal products and timber each year. These demands form the basis for State security. In the conceptual model, the initial demand figures are derived from data in Rice (1995) for timber and for food from the FEEDME model, Dawson *et al* (2016) and UNFAO (2016). Both the State and the World Population have budgets, which are representations of their relative economic performance, calculated from the country's Gross Domestic Product (GDP) and indexed. Supply and demand curves influence prices of individual products. The elasticities of the demand curves are calculated using data from Norton *et al* (2015). Landowners will supply or export products based on price and change land use if overall income remains static or falls. The model has an option to improve arable crop yields. We equate improved crop yields to sustainable intensification.

The Agent Based Model has multiple variables. Some of these variables are exogenous and are adjusted to fit the State being modelled. Examples include the distribution of land grades, the rate of population growth and the physical position of markets and ports. Other variables, for example prices, yields, land use patterns and food security, emerge from the model.

Scenarios

In the prototype model, we modelled a conceptual State and we observed differences in the land use patterns and land use areas under non-intensified and intensified options. We expected to see a reduction in both arable and pasture land use under intensification and an improved State security position. The landowners on the better quality land were expected to produce sufficient food to meet demand. We also expected to see a greater proportion of low-grade land abandoned under intensification. In both scenarios, pasture use mirrored changes in arable use and changes in forest use were mirrored by changes in scrub woodland. Figure 2 below shows these patterns. These mirroring patterns are similar to those recorded between arable and pasture use in England and Wales between 1870 and 1932 (Venn 1933). In both modelled scenarios, the domestic production of livestock rose while that of crops reduced. In all simulations, forest production ceases altogether in favour of timber imports, while the majority of land graded 5 and below is abandoned. The small spikes in forest activity on scrubland (abandoned land) are likely caused by brief increases in timber prices but this requires further investigation and possibly adjustments to the model. Neither scenario appeared to affect the amount of land abandoned.

In both scenarios and with sufficient world supplies of crops, animal products and timber, the State maintained food security using only export controls. A food security surplus of 0.03 tonnes per person (t/Per) was generated under intensification. When not intensified the land generated a higher food security surplus 0.04 t/Per. The modelled scenarios probably developed as they did because the physical constraints placed on land use strongly influence land economics. On the better grades of land, only arable and pasture are competitive. Time discounting disadvantages land uses whose returns are intermittent and occur in the far future, which explains the absence of forest planting.

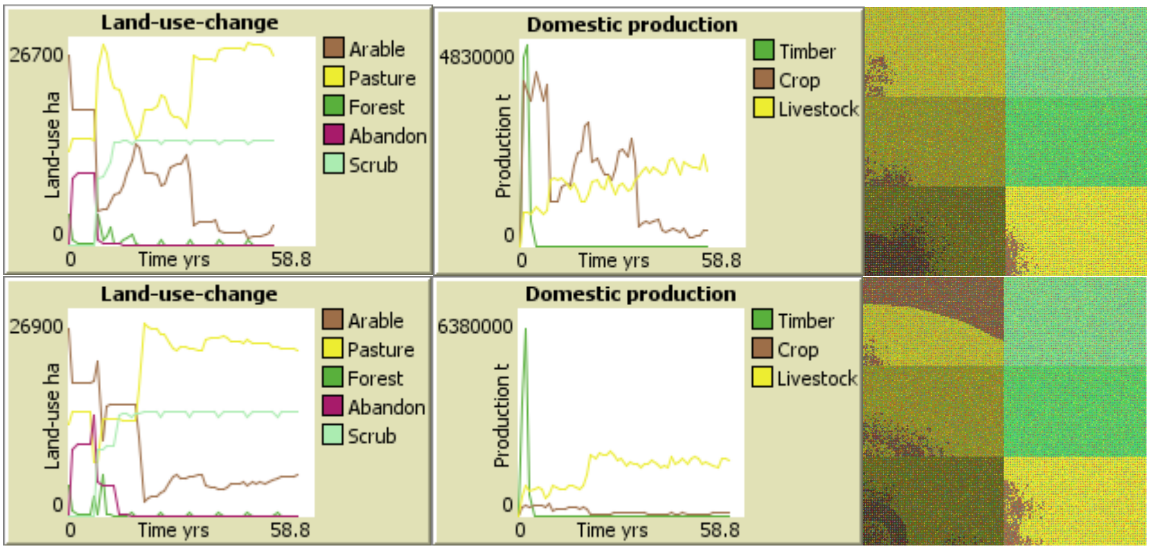

Figure 2. Running the prototype model. Changes in land use, production and land use patterns without intensification (top) and with (bottom). Our model uses four land use types: arable, pasture, forestry and abandoned with original distribution stochastically generated. The pasture represents not just grassland, but cropland used for animal feed. Examples include hay, silage, cereal and root crops. Land use is colour coded, brown represents arable, yellow pasture, pink recently abandoned and green, forest or scrub woodland. The colours are shaded so land grades can be distinguished. In the prototype model (above), land grades are divided equally into six rectangular areas. In modelled States, land grades will be mapped to represent their actual distribution. Land use is measured in hectares, production in tonnes and time in years.

The model trends follow those we expected to see, with deforestation and the adoption of arable and pasture farming, land abandonment and its reversion to scrub woodland. The arable/pasture and forest/scrub mirroring pattern previously described was unexpected. Its cause is not yet established and further investigation is required. The model shows a more consistent separation between arable and pasture use under intensification, but is more cyclic under the non-intensified scenario. In both scenarios, a greater proportion of land is devoted to livestock than arable production. This is probably a result of higher prices being paid for animal products over arable products. Intensification may have improved the efficiency of crop production to such an extent that it freed up more land for livestock production. That the State was able to maintain food security under both intensive and non-intensive cropping is probably due to there being sufficient World food supply. Whether this position can be maintained by States in a competitive environment is not yet known.

DISCUSSION

To calculate food security, we compared supply with the needs of the population. Changes in demand do not currently alter the food security interest, which remains constant for a given population, although in future implementations of the model, food security interest could be related to a change in demand. The State's prestige, which is a function of its economic power, affects how quickly the State reacts. In an interactive (State on State) model, this one decision might produce emergent dynamics, which we will compare with real world events. Future developments will allow the States to recognise trends (i.e. learn), be proactive and have more than one choice of action; for example, holding reserves of food. We could investigate whether a State holding food reserves for its own security could cause food insecurity in other States.

We have maintained the State as being central to world power and influence, although there are arguments for the inclusion, for example, of corporate businesses and non-governmental groups (Carolan 2016). In the model, they could be represented by the market, but this would require further development. We assume a 'standard' person in the State population with identical needs and incomes. This is a reasonable simplification when modelling at a global scale. However, State security decisions may differ if the modelled populations were assigned demographic profiles and different income distributions. Inclusion of income distributions could also lead to a bias in food choice, because of wealth (Carolan 2016) or culture (Johnston 2014).

In the model, land use decisions are made on the basis of income and landowners hold the same attitudes. Landowners could also hold different views and have different attitudes or values independent of income; for example, a preference for forestry, even if incomes are lower. The landowners use memory (the time period can be varied in the model) to calculate trends in prices, but they calculate these trends by comparing averages. There is evidence to suggest that people's decisions may be biased through placing greater weight on 'bad events' and those that are closer to the present (Elster 2015). Skewing the mean price of products and weighting losses over gains might be one way to replicate this effect. The landowners use copying behaviour as an heuristic when deciding on new land uses, but norms might also be important (Morris *et al* 2015). Landowners seek to maximize their incomes, but in the model their behaviour is bounded; they only make a 'economically rational' business decision when prices are falling and they cannot find a neighbour to copy. These 'economically rational' decisions use net present values and all the landowners use the same discount rate, but in reality landowners might use differing rates.

Land grades mark the quality or productivity of land. In the conceptual model we based the land grades on those in the UK. The calculation of land grades around the world will differ and we will adjust these to a common standard. Land grades are not static and can be altered by climate change. These temporal and spatial changes in land quality are not included in our model, but to gain a better understanding of future land use distributions, these changes could be included.

A sensitivity test of the ABM will be undertaken to evaluate a number of system states, for example varying farm sizes, the scale of weather impacts, security sensitivities and reactions of the State. The model will explore a number of scenarios with and without intensification. Several avenues of exploration will be investigated to address a number of interesting questions. For example, if a State takes a 'free market approach' (no restriction of exports), what is the resulting security situation and land use pattern? How do export restrictions influence land use patterns and how does this affect food security? How important is farm size and does the pattern of land use under extensification (increasing farm size) differ from intensification?

CONCLUSION

Food-security is often cited in discussions on agriculture and food production, quality and distribution. It seems fitting that we develop a land use model, in which the context of behaviour is driven by security. Our model has a structure, which is similar to other land use models. It recognises land quality and climate as influencing factors on yield, and ultimately on scarcity and excess. In the model, prices are influenced by supply and demand using standard economic theories. Landowners make decisions about land use based on income. There is a world within which the landowners and the State interact, through exporting and importing. Where our model differs is in the choice of motivational behaviour and the role of the State. We have chosen a security paradigm that has applicability from human to State level. A model that uses interest, prestige and fear as motivational influences offers an opportunity to view land use and agricultural intensification or non-intensified options in the often-presented context of food security. Understanding how security-seeking behaviour might influence the distribution of food and land use might have other applications in, for example, the study of environmental impacts or population migration.

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