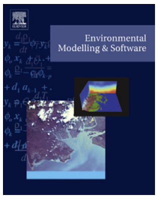
Environmental Modelling & Software 59 (2014) 187–201

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft



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

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ARTICLE INFO

Article history:
Received 13 September 2013
Received in revised form
16 May 2014
Accepted 26 May 2014
Available online

Keywords:
Agent based model
Land use change
Agent functional types
Ecosystem services
Socio-ecological systems

ABSTRACT

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

Software availability

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

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

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

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http://dx.doi.org/10.1016/j.envsoft.2014.05.019

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

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

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

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

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

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

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

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

2. Materials and methods

2.1. The CRAFTY framework

2.1.1. Design criteria

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

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