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An open framework for agent based modelling of agricultural land use change

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ABSTRACT

There is growing interest in creating empirically grounded agent based models (ABMs) to simulate land use change at a variety of spatio-temporal scales. The development of land use change models is challenging, as there is a need to connect representations of human behavioural processes to simulations of the biophysical environment. This paper presents a new agent-based modelling framework (Aporia) that has the goal of reducing the complexity and difficulty of constructing high-fidelity land use models. Building on earlier conceptual developments for modelling land use change and the provision of ecosystem services, Aporia was designed to be modular, flexible and open, using a declarative, compositional approach to create complex models from subcomponents. The framework can be tightly or loosely coupled with multiple vegetation models, it can be set up to evaluate a range of ecosystem service indicators, and it can be calibrated for a range of different landscape-scale case studies and modelling styles. The framework is released under an Open Source licence, and can be freely re-used and modified to form the basis of new models. We illustrate this with two case studies implemented using Aporia, exploring different socio-economic scenarios and behavioural characteristics on the land use decisions of Swiss and Scottish farmers. We also discuss the benefits of frameworks in terms of their flexibility, expandability, verification and transparency.

Software availability

Name of software: Aporia
Developer: Dave Murray-Rust
First available year: 2011
Software requirements: Java, Eclipse, Repast Simphony
Programming language: Java
Program availability and cost: Free, GPL, http://www.wiki.ed.ac.uk/display/aporia
Contact person: Dave Murray-Rust
E-mail: aporia@mo-seph.com

1. Introduction

Agent based models (ABMs) are increasingly used to model human–environment interactions (Rounsevell et al., 2012a,b). The degree to which these models have been empirically grounded (Janssen and Ostrom, 2006; Robinson et al., 2007) has also steadily increased from simple theoretical models to high fidelity models (e.g., Transims; Toroczkai and Eubank, 2006). In many cases, higher-fidelity ABMs are the result of coupling among models that enable dynamic feedback responses to human decision-making from human, natural, or both systems. For example, when examining the effects of land management decisions, ABMs have been coupled to biophysical models that simulate processes such as plant phenology, crop vegetation growth, and water cycling (Bithell and Brasington, 2009; Luus et al., 2013; Monticino et al., 2007). From design through to implementation, the construction of land-

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use ABMs often involves developing avenues to link with dynamic vegetation models (DVMs) and individual based models (IBMs) to estimate the impacts of human behaviour on ecological systems (Murray-Rust et al., 2011).

The conceptual and computational challenges associated with developing complex and/or interconnecting multiple models puts a huge burden on researchers and modellers, who are often not trained in computer science or do not have in-depth programming experience. However, a collection of tools exist that can aid researchers "dealing with complexity, re-using modules for different models, and providing support for commonly needed services" (Evert and Holzworth, 2005). Each tool or modelling approach chosen or developed forces the researcher to make a number of trade-offs (e.g., Parker et al., 2003). Ideally our tools should be used to construct models that "maximize generality, realism, and precision toward the overlapping, but not identical goals of understanding, predicting, and modifying nature" (Levins, 1966, p. 422).

Generic toolkits such as Repast (North et al., 2005) and Swarm (Minar et al., 1996) have been widely used and offer the greatest flexibility for researchers to develop ABMs (see Parker et al. (2003) and Nikolai and Madey (2009) for reviews). These toolkits enable the construction of a complete range of models that start with simple toy models (e.g., Boids; Reynolds, 1987). Simple toy models have the benefit that they do not require data, they can be rapidly developed, and they can demonstrate that a set of rules, mechanisms, or processes can produce observed phenomena (i.e., a proof of existence; Waldrop, 1990). Additional data, detail, and complexity can be incorporated systematically at a later stage to increase the degree of realism and precision of a real-world system at the expense of general applicability.

In the study of land-use change, most ABMs are constructed solely from generic toolkits and represent highly specific case-study systems. For example, ABMs representing land-use change have been developed for Altamira, Brazil (Deadman et al., 2004); south-central Indiana, US (Evans and Kelley, 2004); Koper, Slovenia (Robinson et al., 2012); Mayuge District, Uganda (Berger and Schreinemachers, 2006; Schreinemachers and Berger, 2006); San Mariano, Isabela, Philippines (Huigen, 2004); Mae Salaep village, Chiang Rai, Thailand (Barnaud et al., 2005); Washington D.C., US (Irwin and Bockstael, 2002); EU Special Protection Area number 56, central Spain (Millington et al., 2008); and Denton County, Texas, US (Monticino et al., 2007) among many other locations. Few, if any, of these and other ABMs of Land Use and Cover Change (LUCC) have been applied across multiple study areas, which may be attributed to "a lack of funds or labour resources to go beyond core scientific objectives of the research; scientists who are often not software engineers by training and may be hesitant to release models that are inelegantly coded; and/or the extensive time and effort to develop models, which often suggests that individuals optimise their use of a model for specific publications …" (Evans et al., 2013).

To enable others to use and apply a site specific model to other locations requires an investment in time that is likely to have little payoff for small research projects. If resources and time are available to produce a well-constructed model framework, then the trade-offs among generality, realism, and precision can be balanced and a number of benefits ensue, such as re-usability of code, comparability of results and extensibility of models. In this context, a framework is a collection of building blocks (i.e., coded methods) and generic land-use system structure (i.e., abstract classes representing actors in the system, how they can interact and behave, as well as scheduling actions) that enable researchers to focus on conceptual representations of the study system, justification of model parameterisation, and calibration rather than developing a model from scratch. Frameworks are significantly more refined than general ABM toolkits, as they integrate domain knowledge and preassemble building blocks that facilitate domain-specific research questions (e.g., land-use change). Furthermore, a well-defined and designed *framework* can extend the application of a model to multiple case study locations and enable non-programmers to initialise the model for specific contexts, scenarios, or computational experiments (Schweitzer et al., 2011).

This paper presents a new state-of-the-art framework (Aporia) that was developed to aid the creation of agent-based land-use models, at multiple locations with unique socio-economic contexts, by local experts and academics without extensive coding and software engineering experience. Through the configuration of Aporia, researchers can investigate a variety of research questions, such as: How does the relative influence of social factors versus economic and environmental factors guide on-farm crop rotation selection and the provision of ecosystem services? What is the degree of subsidy adoption among farm households and how effective are subsidies in achieving their economic or environmental goals? And, under what conditions is marginal land taken out of (or put into) agricultural production? To answer these types of questions and enable others to also do so, the creation of Aporia focused on the agricultural land-use system.

While other ABM frameworks are available (e.g., MameLuke; Huigen, 2004) that allow for a range of actors to be modelled, and offer a strong theoretical basis on which to build decision-making by creating sets of rules for agents, Aporia, does not impose a specific decision architecture on agents – however, this comes at the cost of requiring increased coding effort if one wants to move beyond the architectures already implemented. Similarly, some frameworks are focused on capturing the dynamics of coupled human–environment systems, in particular human adaptation to changing biophysical factors (LUDAS; Le et al., 2008, 2012). Others (e.g., PALM; Matthews, 2006; SLUCEII; Robinson et al., 2013) have a greater focus on land use change and subsistence agriculture or exurban growth more specifically. Aporia differs from these existing developments in that it provides substantial detail in terms of representing the attitudes of agents, the complex interplay of factors that are prevalent in more intensively farmed areas, and a modern software engineered approach that facilitates the easy integration of geospatial data, a progression from simple to more complex models, and a detailed view of farming practices and their socio-political context, that can all be configured or assembled without computer programming (i.e., through extensible mark-up language [XML]).

We designed Aporia to provide 1) an off-the-shelf framework for researchers to easily create models; 2) comprise a suite of output metrics that when applied across multiple study sites can foster comparison, synthesis, and generalisation of research findings; and 3) a baseline for extension and improvement to support model innovation and to answer novel research questions. To demonstrate these design criteria, the remainder of this paper provides an overview and description of Aporia components. An example of a simple stylised model that is extended by adding Aporia components to increase the complexity of representation of the land system. Then two empirically-grounded case study applications are presented, Aarau, Switzerland (Karali, 2012; Karali et al., 2013) and the Lunan area of Scotland, UK (Guillem and Barnes, 2012; Guillem et al., in review). We also discuss the framework and how it compares to other land-use-modelling frameworks.