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A multi-agent model system for land-use change simulation

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ABSTRACT

This paper presents a multi-agent model system to characterize land-use change dynamics. The replicable parameterization process should be useful to the development of simulation frameworks, important to environmental policy makers to analyze different scenarios during decision making process. The methodological two-fold approach intends to form a solid backbone based on: (i) the systematic and structured empirical characterization of the model; and (ii) the conceptual structure definition according to the agent-based model documentation protocol – Overview, Design concepts and Details. A multi-agent system for land-use change simulation was developed to validate the model, which is illustrated with a case study of the Brazilian Cerrado using LANDSAT ETM images. The simulation results prove the model importance with a figure of merit greater than 50%, what means the amount of correctly predicted change is larger than the sum of any type of error. The results are very good compared with nine popular peer-reviewed land change models.

Software availability

Name of software: MASE – Multiagent System for Environmental Simulation
Developer: Cássio Giorgio Couto Coelho (InfoKnow-Computer Systems for Information and Knowledge Treatment Group, ComNet – Computer Networks Lab)
Contact address: Computer Science Department, University of Brasília, Campus Universitário Darcy Ribeiro - Asa Norte – Edifício CIC/EST, Caixa postal 4466 – CEP 70.910-900 Brasília – DF – Brazil Email:ghedini@cic.unb.br, Ralph.Roberts@ars.usda.gov, cassiocouto88@hotmail.com
Availability online for free download at: https://sourceforge.net/p/mase-unb
Year first available: 2013
Hardware required: Dual-core Processor 2 GB RAM – 1 GB HDD (minimum)
Software required: JRE 7.0 or superior (tested on Windows 7 Home Premium 64bit)
Programming language: JAVA 7.0
Agent Development Framework: JADE – Java Agent Development Framework, version 4.0, release date 04/20/10
Executable and Libraries: 32.2 MB
Resources (images): 181 MB

1. Introduction

Brazil is a nature privileged country. It houses various biomes including the Amazon, the largest tropical rainforest in the world and the largest biome in Brazil, occupying almost half (49.29%) of the country (4,196,943 km^2) (IBGE, 2004). Despite this privilege, historically environmental information in Brazil has not been taken into account during planning and decision making processes. This common critique is usually addressed to traditional solutions in the way decision makers treat Land Use/Cover Change (LUCC), among other environmental issues. Recent changes in the Brazilian Forest Code, demonstrates the effects of policies on the environment are barely identified, assessed or even discussed by the competent authorities in the decision making process.

A clear example of this gap between environmental information and political action is the Brazilian Cerrado (woodland savanna). Cerrado is the second largest biome in South America and covers approximately 22% of the Brazilian territory, or 204.7 million hectares

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(Sano et al., 2010; Oliveira, 2002). According to Cavalcanti and Joly (2002) and Myers et al. (2000), the Cerrado harbors outstanding biodiversity, being included in the world's 25 principal hotspot areas, with great endemism and less than 30% remaining natural vegetation. Unfortunately, the biologically diverse, more than 12,356 catalogued plant species as presented in Rezende et al. (2008), is poorly protected. Only 2.2% of Cerrado's original area is protected by formal reserves (Klink and Machado, 2005). The Cerrado savanna of central Brazil has been undergoing rapid transformation to cattle ranching and more recently to soy production, requiring urgent action for the conservation of biological richness in the face of threats of destruction (McAlpine et al., 2009). For the cited reasons, the Federal District was selected for our case study since it is the single state of Brazil fully covered by the Cerrado biome.

Changes in LUCC are relevant not only for the Cerrado Biome, since they are amongst the most pervasive and important sources of recent alterations of the Earth's land surface (Houet et al., 2010; Smith et al., 1998). According to Vitousek (1997), LUCC is one of the most profound human-induced alterations on the environment. Its research aims to support insightful management of land resources in order to avoid irreversible damage (Le et al., 2008). There is now more than a decade of international research on land-use processes, and as a result, a much clearer understanding of these processes and a much better appreciation of their complexity and comprehensiveness (Schaldach et al., 2011; Lambin and Geist, 2006). LUCC can be summarized as a complex process caused by the interaction between natural and social systems at different temporal and spatial scales (Valbuena et al., 2008; Rindfuss et al., 2004; Lambin and Geist, 2001).

Environmental policy and management demand the integration of cross-disciplinary knowledge of socio-ecological processes, where agent-based model (ABM) has become a popular investigatory technique to simulate LUCC dynamics (Matthews et al., 2007; Verburg et al., 2004; Parker et al., 2003). ABM use is driven by increasing demand from decision makers to provide support for understanding the potential implications of decisions in complex situations (Smajgl et al., 2011). ABM explicitly represent human decision making processes by means of agents, presented as autonomous computer entities interacting directly with themselves and the environment, in order to achieve goals (Naivinit et al., 2010). Agents in the model can represent individuals or group of people and also can be designed with heterogeneous, autonomous and dynamic characteristics. For this inherent possibilities, ABM explicitly deal with the diversity of land-use decisions (Valbuena et al., 2008).

Simulation models of LUCC in space and time can inform policy setting and decision making processes on the use and management of land resources (Le et al., 2008). By mimicking the causal mechanisms and feedback loops of LUCC, these models can be learning tools for understanding the dynamics and driving forces of the land-use system and show how landowners' choices might affect the direction the future may take (Verburg, 2006). To successfully achieve these ambitions, environmental models and software need to be scientifically and technically sound, reliable, usable and cost effective (Mcintosh et al., 2011).

However, LUCC modeling involves the complexity of human drivers and natural constraints, since land-use change emerges from the interactions of these components (Le et al., 2008). To overcome limitations of classical mathematical models, in the Computer Science field, the sub-area of Artificial Intelligence (AI), considering AI modern approach of Russell and Norvig (2009) where agents are the focus, specifically the Multi-Agent Systems (MAS) approach, as studied by Wooldridge (2009), emerges as a candidate technique for solving this class of problems. MAS can be defined as a collection of autonomous entities, called agents, interacting with each other and with their environment (Ferber, 1999). Contrary to traditional modeling techniques, MAS are not expressed in terms of variables, functions and equations, but in terms of agents, objects and environments. They provide the software resources necessary to implement in software ABM descriptions, capturing emergent phenomena resulting from the interactions of individual entities.

This paper presents the use of an ABM and a MAS methodology to characterize LUCC dynamics that can be used in the development of different simulation frameworks. The methodology validation was done through the development of MASE, a Multi-Agent System for Environmental LUCC simulation. MASE aims to assist analyzing LUCC dynamics using technical information to aid the decision making process. MASE was used to simulate a LUCC model of the Brazilian Cerrado. The rest of the paper presents: in Section 2, the empirical characterization, the conceptual structure and MASE overview; in Section 3, the case study with simulations and results; in Section 4, a short discussion of the adopted method and MASE results; and finally, in Section 5, the conclusions and future works.

2. Methods

In this section, we describe the multi-agent model system used to characterize LUCC dynamics, focusing the parameterization process to help in the development of simulation frameworks. We present the validation of the model defined with the development of MASE, including the architecture and implementation aspects of the application.

2.1. Empirical characterization

The purpose of a LUCC simulation framework based in ABM is to represent and simulate the human decision-making processes through the use of agents behavior, the physical environment and the understanding of how the policy decisions affect the dynamics of LUCC. By observing how these variables interact, it is possible to explore causes, consequences and formulate useful scenarios during the decision-making process and planning. The results should not be used predictively, but as a tool to develop sustainable strategies for land use.

The implementation of human decision-making processes is the main strength of ABM, but the behavioral response functions that represent these processes require knowledge support from qualitative and quantitative empirical sources. Unfortunately, there are no standard approaches to documenting empirical support that underlies modeling and design decisions in agent-based models (Robinson et al., 2007; Berger and Schreinemachers, 2006). Thus, in this work we have used a set of specific methods, commonly used in practice, based on the methodological parameterization process for human behavior in ABM proposed by Smajgl et al. (2011).

According to Smajgl et al. (2011) there are two fundamental steps in which empirical data are required: the development of behavioral categories and the scaling to the whole population of agents. The challenge involves the representation of larger populations, identifying suitable empirical methods for eliciting behavioral data, where the sample-based data need to be translated into behavioral representations for the whole population (up-scaling). For this challenge, we have used a proportional up-scaling approach assuming that the sample of agents represent the whole population.

Smajgl et al. (2011) build a comprehensive framework with the set of the most commonly used methods for the challenge of parameterize behavioral responses of humans empirically: (i) expert knowledge, (ii) participant observation, (iii) social

Table 1
IBGE agricultural census of 2006.

Seq.	Producer legal status	Amount	Units or hectares
1	Individual owner – No. establishments	3407	Units
	Individual owner – Area establishments	182,031	Hectares
2	Condominium, trust or company – No.	426	Units
	Condominium, trust or company – Area	33,564	Hectares
3	Cooperative – Number establishments	3	Units
	Cooperative – Area establishments	1092	Hectares
4	Corporation or limited liability – No.	93	Units
	Corporation or limited liability – Area	21,432	Hectares
5	Public utility institution – No.	5	Units
	Public utility institution – Area	1087	Hectares
6	Government (federal, state, municipal) – No.	7	Units
	Government (federal, state, municipal) – Area	11,536	Hectares
7	Other conditions – No.	14	Units
	Other conditions – Area	578	Hectares
	Total No. establishments	3955	Units
	Total Area establishments	251,320	Hectares