GIS and Spatial Agent-Based Model Simulations for Sustainable Development

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ABSTRACT

In recent years the interdisciplinary field of computational social science (CSS) has developed theory and research for developing spatial "agent-based" social simulation (SABSS) models of human societies situated in ecosystems that often comprise land cover and climate. This paper explains the needs and demand for GIS in these types of agent-based models, with an emphasis on models applied to Eastern Africa and Inner Asia and relevance for understanding and analyzing development issues. The models are based on MASON (Multi-Agent Simulator Of Networks and Neighborhoods), an open-source simulation environment in the Java language and suitable for developing ABSS models with GIS for representing spatial features.

Keywords: geographic information systems (GIS), spatial agent-based modeling (ABM), multi-agent systems (MAS), computational cartography, Inner Asia, Eastern Africa, Multi-Agent Simulator of Networks and Neighborhoods (MASON)

INTRODUCTION

Sustainable development—long-term growth with resource consumption that is trans-generationally neutral—is a complex process characterized by numerous requirements, interdependencies among social, technical and natural environments, and a great deal of uncertainty about the relevant dynamics. Simple economic models like Venn diagrams (Barbier 1987) have limited value or can be misleading. Advanced scientific methods and technologies from different fields are required for marking progress on multiple aspects of sustainable development, including analysis, design, decision making, implementation, and monitoring (Ostrom 2009).

Geographic Information Systems (GIS) and Agent-Based Models (ABM) used in the interdisciplinary field of computational social science (CSS) originated just a few decades ago and have since evolved in independent ways, including autonomous professional communities and organizations. However, an interesting feature of these two major methodological developments is that the intersection of GIS and ABM for social simulations enables new scientific and policy analysis advances that exploit the joint, synergistic capabilities of these advanced computational technologies. Modeling and analysis for improving sustainable development represents a particularly promising area for these joint methodologies. In this paper we show how some current advances are already providing answers to complex problems of sustainability that have resisted earlier approaches, and we argue that future coordinated developments in both methodologies promise even more transformative breakthroughs. This is especially so in critical areas of basic scientific research and applied policy analysis in sustainability and related topics in complex socio-techno-natural systems.

This paper consists of four sections. The first provides some essential background on both methodologies and the specific motivation for this paper in the context of sustainable development. The second section describes spatial agent-based models that are geospatially referenced, with emphasis on two recent models developed in the Java-based MASON toolkit; this is the core of the paper. The third section discusses current and future applications of GIS in social agent-based models. The fourth section presents our main conclusions.

Sustainable development is a complex problem requiring the use of advanced information technologies to support decision making. From a computational modeling perspective, GISs are generally composed of three main classes of layers of geospatially referenced data:

1. Natural features, such as physical terrain and hydrology, comprising an ecosystem;
2. Man-made artifactual systems, such as roads, parks, and other engineered structures; and
3. Social features, such as population concentrations, land-use patterns, and cultural attributes, which are the most important data layers for purposes of this paper.

We shall refer to this last category as "social GIS" (Cioffi-Revilla In press-a), to distinguish it from more traditional uses of GIS consisting of the first two categories. The defining characteristic of social GIS is the visualization and spatial analysis of spatial social data, including sociological, economic, political, cultural, military, or other human and social dynamics. Within this broad range of potential interactions, GIS is playing an emerging role in understanding both the scale and complexity of the social landscape.

The basic motivation for this paper is provided by current developments in GIS and ABM, given that the two methodologies (a) originated in autonomous ways; (b) have been and will continue to be heavily dependent on computational science and technology developments (for example, ABM is closely dependent on multi-agent systems, artificial intelligence, evolutionary computation, and other areas of computer science); and (c) have an area of overlapping interest specifically given by spatial agent-based modeling that are geospatially referenced.

Geospatially-referenced agent-based models (GABM) constitute a subset of agent-based models, because not all agent-based models have a spatial domain (for example, some are purely organizational), and even among spatial ABMs, not all of them are geospatially referenced with empirical data (e.g., Schelling's segregation model). In this paper we describe the two methodologies with a view towards illuminating their combined use through computational simulation models. We illustrate the present use of these complementary technologies through two modeling projects that are on-going and have significant potential for supporting analysis and planning of sustainable development. Additionally, we claim these technologies and modeling approaches enable the analysis of sustainability in new ways that have been unavailable through previous approaches.

GEO-REFERENCED SPATIAL AGENT-BASED MODELS

Overview

Agent-based modeling (ABM) is a computational methodology for formalizing and analyzing complex social systems on many scales, ranging from small groups of individuals to organizations and much larger systems, such as national, regional, or international systems (Axelrod 1997; Gilbert and Conte 1995; Cioffi-Revilla 2002; Epstein 2008; Gilbert 2009; North and Macal 2007). Complex social systems that are modeled by ABMs typically exhibit features such as: (i) many autonomous or semi-autonomous actors (called "agents") making interdependent decisions; (ii) high-dimensionality (many variables or attributes); (iii) environments (artifactual and/or natural) where agents are situated; (iv) nonlinear dynamics that govern interactions among actors and environments; and, consequently, (v) emergent ("bottom-up") macroscopic properties generated by micro-level agent-to-agent and agent-environment interactions. Such features typically defy the modeling capability of earlier formal methods, such as dynamical systems of differential equations or game-theoretic models. ABM methodology is part of the computational simulation modeling approach in the social sciences, which also includes other types of simulation models, such as system dynamics, cueing models, micro-simulations, and cellular automata (Gilbert and Troitzsch 2005).

A subset of ABMs has spatial features for modeling human or social dynamics in a given landscape; these are called "spatial ABMs" and they are often applied in areas such as land-use and cover change (LUCC; Parker et al. 2003). The landscape itself may be simple or complex, depending on the purpose of the model and its level of abstraction. For example, the classical

Schelling segregation model represents only a simple grid of city blocks (Schelling 1971), whereas a model such as MASON Wetlands represents terrain in addition to vegetation and weather (Cioffi-Revilla et al. 2004).

A subset of spatial ABMs has geospatially referenced features corresponding to a given region of the real world, based on GIS data. It is these GIS-based spatial ABMs that we are concerned with in this paper (Castle et al. 2007).

MASON and GIS

ABMs are developed either in native code or by using one of the existing toolkits (Nikolai and Madey, 2009), such as the MASON system (Luke et al., 2005) and other similar toolkits (Swarm, Repast, Cormas, and others). MASON (Multi-Agent Simulator of Networks or Neighborhoods), developed as a joint project by the Department of Computer Science and the Center for Social Complexity at George Mason University, is an academic license free multi-agent simulation toolkit flexible enough to use for wide variety of agent based related application. Its applications include modeling social complexity, physical and artificial intelligence, and machine learning. It is fast, easily extendible and less dependent on other external libraries.

Architecturally, MASON comprises two major parts, for model computation and visualization, as well as a utility layer. The model layer is specialized for event scheduling tasks and can run in the command line independently of the visualization layer. The visualization layer is the GUI interface, which is responsible for manipulating the model object, portraying it on the screen, and inspecting its content. The utility layer is tasked for taking care of any other purpose facilities, such as the random number generator, data structures, creating movies, and snapshots. MASON includes an extensive tutorial guide and online support for users. Additionally, MASON includes specialized functionality and extensions with tutorials for Social Network Analysis (SNA; Wasserman and Faust, 1994), evolutionary computation (EC; De Jong, 2006; Luke et al., 2009), physics modeling, charting, and parameterization. Currently MASON is expanding its GIS facilities to include the import of vector data for spatial reasoning, distance calculations, determining coverage, and other functionality.

The MASON HouseholdsWorld Model

HouseholdsWorld in MASON (Cioffi-Revilla, Rogers, and Latek 2010) is the ABM developed to explore a wide range of social and environmental interactions, including the emergence of social complexity, the adaptive capacity of different types of social systems, and the impacts of climate change related to pastoralism in Inner Asia (defined as northern China, Mongolia, southern Siberia, and portions of Kazakhstan). As a simulation of socionatural systems, HouseholdsWorld is informed by empirical data from ethnology, archaeology, paleoclimatology, historical ecology, and experimental results from studies in rangeland and herd management (e.g., Kohler and Gummerman, 2000; van der Leeuw and Redman, 2002). It uses the relatively egalitarian social landscape of the Bronze Age, ca. 1000 B.C. in Inner Asia as the target system (Askarov, Volkov, and Ser-Odjav, 1999). Beginning in 2001, archaeological teams from the Smithsonian Institution identified and excavated sites in Mongolia to strengthen the empirical data and spatio-temporal framework used in creating the simulation.

HouseholdsWorld is part of a suite of MASON simulations developed at George Mason University in conjunction with additional research on the rise and fall of polities in Inner Asia (Cioffi-Revilla et al. 2007; Rogers 2007; Rogers and Cioffi-Revilla 2010). Specifically, the model is informed by multiple sources of archaeological, historical, and contemporary data. The main agent classes are Households and Camps, where Households also belong to Clans (Figure 1). Additional characteristics of the computational model are described in Cioffi-Revilla, Rogers, and Latek (2010).

HouseholdsWorld, as a dynamic model, pays close attention to both spatial and temporal resolution as these define the scale of abstraction by which phenomena can be analyzed (see Castle and Crooks 2006). In many ways HouseholdsWorld is about how pastoralists adapt to landscape, weather and social variability. We have analyzed the intersection of these sources of variability to study the sustainability of pastoralism both from the perspectives of herd dynamics in rangeland management and in terms of policy decision making.

Households function on realistically rendered landscapes calculated at 1 km resolution, termed landscape scenarios (S1-S8). These landscapes were selected in order to sample environmental variability, but also to overlay with empirical landscape use patterns under study by archaeological teams as part of the overall project. Each landscape is either 10,000 or 40,000 sq. km. In addition to geomorphological characteristics, these landscapes use normalized difference vegetation indices (NDVI) (Hansen et al. 1998, 2000). NDVI rasters were computed for each month of the year from atmospheric corrected bands in 500 m resolution. This allows the modeling of seasonal weather as it affects vegetation. Additionally, weather events--snow storms and droughts--modeled on 19th and 20th Century weather data are incorporated to produce additional dynamic characteristics. The landscapes are classified into 14 land cover types and approximations are calculated for edible biomass for herd animal consumption. Coefficients for calculation of edible biomass are drawn from Kawamura et al. (2005).

Research has focused on 5 areas: north Xinjiang (S3), south Hovsgol Aimag (S5), north Hovsgol Aimag (S6), Egiin Gol (S7), and Baga Gazaryn Chuluu (S8). The S3 landscape is currently under study. It is in the Xinjiang prefecture of northwest China, between Kazakhstan and Mongolia. This is a region of moderate to low biomass density with a diversity of land cover combinations characteristic of large portions of Inner Asia. The analysis presented here is supported by a considerable quantity of rangeland management research conducted throughout northern China (Committee on Scholarly Communication 1992; Humphrey and Sneath 1999).

The contemporary pastoralists in many regions of northern China have experienced a decline in the quality of rangelands, due to overgrazing (Figure 2). There are various studies and management interventions proposed to improve livelihood, however, sustainability is usually considered in conjunction with improving the short-term economic conditions of the herders. By running our simulation for hundreds of years we are able to show that concepts of carrying capacity based on grassland conditions at any one time are likely to be very misleading.

Sustainable and resilient solutions are instead likely to depend on the use of non-equilibrium ecological models that incorporate pastoralist mobility and an understanding of local social limits.

The MASON HerdersAndFarmers Model

The herders of the Mandera Triangle region, located along the border of Ethiopia, Kenya and Somalia, have developed adaptive responses that are resilient to their changing and harsh environment. They constructed an elaborate social alliance structure to cope with different environmental shocks, such as drought or flooding. However, the relatively recent division into states, the introduction of new actors, and the occurrence of frequent and lengthy drought, create stresses on the availability of resources, such that these can have a crippling effect on the coping mechanism of herders in the region. This complex socio-natural system has become highly conflict ridden.

HerdersAndFarmers is an agent-based model to simulate herders' behavior in response to the introduction of new actors—farmers--and the feedback of these groups through the natural environment and the resulting source of tension and conflict (Rouleau et al. 2009). Our herder and farmer model focuses on two major issues. First based on the current situation, we focus on escalation of conflict raised either between herder and herder or between herder and farmers. Second, we focus on conflict raised by environmental stress and ineffective land management.

The model is developed within the MASON simulation environment with three major components: agents, environments, and their rules of interaction. Within the model, there are two types of agents: herders and farmers. The herders are the major focus of the model. Herders feed and manage their herd. They move from one parcel to another in search of pasture or water. Trespassing across already owned parcels occurs if herders are desperately in need of food due to lack of a viable parcel. Such trespassing results in the onset and escalation of conflict.

The environment, with spatial extent of 150 Km X 150 Km, consists of parcels and local weather. Each parcel has 1km by 1km spatial resolution (Figure 3). Land parcels are spatially heterogeneous in quality, which is represented by the maximum amount of vegetation they can support in the absence of grazing and under optimal weather conditions. We represent weather with the single variable of monthly rainfall. We also introduced drought periodically as a parameter in the model simulation.

At this level, our model incorporate GIS as a loose coupling with the ABM. The location of the space where agents are acting is spatially referenced. Even if initially both herders and farmers are located in the landscape randomly, they move, explore, and act on the landscape in a spatially explicit way. Agents have spatial knowledge or vision, which is express in proximity and experience of exploration of the surrounding environment, to search for pasture and water. We estimated the maximum amount of vegetation for each parcel using GIS data on land use and slope.

Our initial model intends to demonstrate the fundamental behaviors needed to replicate conflict dynamics in the Mandera Triangle area. We have found that much of the macro-patterns of conflict in Mandera can be simulated with a set of relatively simple actors with competing agendas. This model is still being developed and will have several extensions. The future direction of the model is to develop an extended versions that incorporate population dynamics, land use change, degradation, climate change and deeper GIS integration to handle vector data formats.

CONCLUSIONS

There are many fields of application that currently utilize GIS and ABM. The application and abstraction of a model and integration of the two methodologies depend on the objective of the research model and field of study. Most spatial oriented fields such as in quantitative geography, ecology, or urban systems place greater emphasis on the use of spatial information but give less weight to incorporating the social information through ABM, while the social science fields such as economics and political science take the opposite approach.

Gimblett (2002) emphasizes the need to integrate GIS and ABM and raises several conceptual and technical issues concerning current practice. Parker (2004) discusses the current practice of ABM based on the level of GIS integration and categorizes a range of models, from those utilizing abstract space to models with an interface that integrates both ABM and GIS into one system. In between these two extremes, the majority of the models utilize GIS data as model initialization or model visual output.

Currently there is no clear principle concerning which level of integration or coupling (loose or tight) is best and achievable (Brown et al 2005, Parker et al., 2003). For instance, Torrens and Benenson (2005) suggested building a new system or a separate framework approach that would be initially constructed with the functionality of the two systems together. They provide the architecture of Geographical Automata System (GAS) linking automate urban system with GIS, which can be run on different platforms. The other alternative suggested by

Brown et al (2005) is a compromise solution for bridging the gap between ABM and GIS fields by building on the existing system. Their application "builds on existing platforms and involves the development of software to handle the identity and causal relationships between the agents within an ABM environment and spatial features within a GIS environment, as well as the temporal and topological relationship issues that arise in the model". In both approaches, progress is not sufficiently well advanced and many flaws remain. The development of object orientation and simulation and the high demand for the integration of ABM and GIS in social and spatial fields provides a glimpse of hope for reducing current gaps.

In terms of future developments, we view the following as significant:

1. Increasingly sophisticated visualizations of agents on landscapes.
2. The development of linkages between various sources of remote sensing data to allow easier integration into the modeling environment.

3. The development of proxy measures of environmental variability that allow easier integration into the modeling environment.
4. The incorporation of dynamic analytical capabilities into GIS-based software.

ABM allows for the most advanced integration of environmental and social modeling. This type of interdisciplinary integration has the most potential to offer new insights to complex problems.

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Figure Captions

Figure 1. Unified Modeling Language chart illustrating the relationship between the major components of the HouseholdWorld model.
Figure 2. The border between Northern China and Mongolia showing extensive overgrazing on the southern side of the border (China). (Landsat image)
Figure 3. Example of landscape visualization used in the HerdersAndFarmers model.