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GAIA-RM: A Geographically Aware Intelligent Agents Framework for Rangeland Management

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1. Introduction

In this paper we present a spatially explicit agent-based model of land transformation processes in southwest Montana, a region that has experienced significant change over the past two decades. Southwest Montana was, and to a more limited degree still is, a landscape of agricultural production, with large family owned ranches dominating the region's social, political and economic activity. It is also a landscape that possesses spectacular scenery, significant national and international level exposure (it is adjacent to Yellowstone National Park), plentiful wildlife, and outstanding trout fisheries. For reasons both endogenous (e.g., its natural amenities and socio-demographic structure) and exogenous (e.g., global commodity markets, increasing affluence at the national and global scale) to the region, this landscape is being transformed into one increasingly characterized by second homes and hobby ranches. These drivers of change, coupled with the region's socio-political response to this change, produce a complex geographical system that continually adapts to changing social, political, and economic context. For the past three years an interdisciplinary team of researchers has been studying this dynamic process. A particular focus of this work is an investigation into how individuals form (or fail to form) consensus to manage the common pool natural resources that characterize this region in sustainable manner.

Agent-based models (ABM) provide a generative problem-solving approach that is well-suited to the modelling of complex geographical systems that exhibit emergence, self-organization, path-dependence, and adaptive characteristics (Epstein 1999, Parker et al. 2003, Brown et al. 2005). While ABM have been extensively applied to enhance our understanding of complex dynamics in geographical systems, few attempts have been made to model the influence of social organization, consensus building, and collaboration on land use dynamics from a behavioural perspective. This is particularly true in the context of common pool resources (CPR) and processes that may or may not avoid the tragedy of the commons (Hardin 1968).

To build the computational capability to model complex rangeland dynamics within the context of CPR we designed and developed GAIA-RM, a Geographically Aware Intelligent Agents (GAIA) framework for Rangeland Management. This modelling

system is an extension of the GAIA framework (Tang 2008, Bennett and Tang 2008), which is specifically designed to simulate complex adaptive spatial systems whose state is determined, at least in part, by individuals that are contextually aware, knowledgeable and goal driven, and adaptive. Individuals in these systems are represented as GAIA and characterized by three necessary components: context, knowledge structures, and learning mechanisms. The flexibility and generality of the GAIA framework allows for its extension to specific application contexts, for example, the spatiotemporal modelling of complex rangeland systems—i.e., GAIA-RM in this paper.

2. Framework

The current design of GAIA-RM is depicted in Figure 1. Land owners, modelled as agents, manage parcels and organize through social networks. The set of parcels comprises a spatially explicit environment within which land-owner agents interact. In its current state, parcel characteristics are generalized into, and represented by, two main state variables (natural and cultural amenities). Ownership changes of parcels (modelled using a transition matrix) cause changes in the production of natural and cultural amenities and drive rangeland dynamics. In particular, residential development leads to an irreversible decrease in natural amenity and degrades the resilience of rangeland systems.

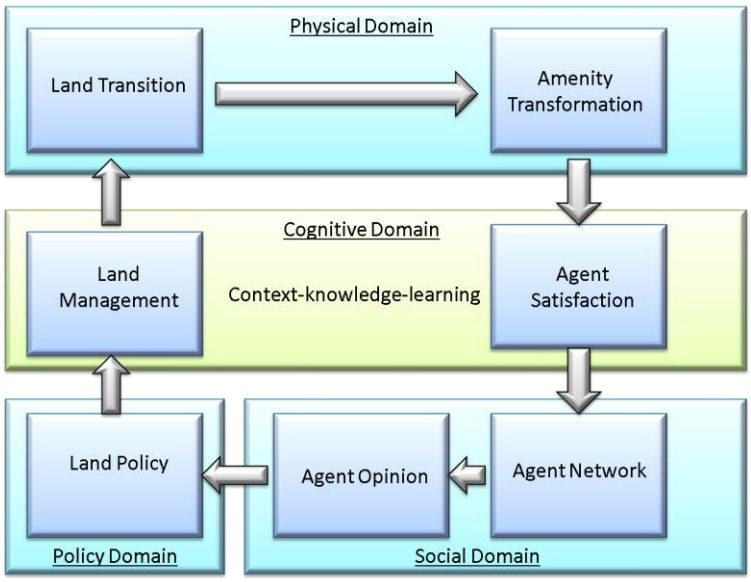

Figure 1. Illustration of the design of GAIA-RM.

Each land-owner agent is characterized by their current satisfaction with available natural and cultural resources and their opinions on land use policies (e.g., restrictive land use controls). Agent satisfaction is represented using sigmoid functions. Four types of land-owner agents are defined from land owner surveys: traditional ranchers, early arrival amenity buyers, late arrival amenity buyers, and developers. The population of agents interact to formulate land use policy. Coalitions are formed and opinions exchanged about alternative policies through social networking. Opinion dynamics are simulated using an opinion formation model proposed by Weisbuch et al. (2002).

Agent motivation to become engaged in opinion and policy formulation is considered to be a function of perceived change in the environment and how satisfied an individual is with that change. As land is transformed from one state to another (e.g., traditional ranches to hobby ranches, hobby ranches to small ranchettes), natural resources are consumed and thus satisfaction levels change. Cultural amenities are assumed to increase as population increases. Agents must, therefore, make tradeoffs between natural and cultural amenities—an increase in their satisfaction of supplied cultural amenities requires a decrease in natural amenities. Coalitions of agents develop through social communication in an attempt to set land-use policies that maximize their satisfaction level (e.g., prevent the overuse of natural resources, increase cultural amenities). The level of cultural and natural amenities, together with land use policy, produces a feedback process that affects the kinds of agents that migrate into the systems. This set of interactions, agent motivation to promote policy change being contingent on the rate at which satisfactions levels change through time and the feedback processes that affect the opinion preference set of new agents, suggest that there may exists a limited window of opportunity to pass policies that sustain a particular level natural amenities (Figure 2).

Figure 2. Satisfaction, willingness to engage in political action and resource levels are interrelated.

These GAIA-type land-owner agents acquire information through direct interaction with their external environments and communication with other agents. Depending on model parameters and simulated interactions, consensus can form, stakeholder groups can emerge, or chaos can ensue (see Figure 3).

Information about the level of natural and cultural amenities and the characteristics of socially networked peers is collected. This information is maintained as context within each land owner agent and matched to knowledge stored in knowledge structures. Learning algorithms have been developed that allow land-owner agents to improve their perceived level of satisfaction. Specifically, land-owner agents learn to interact, cooperate, and compromise to maximize their satisfaction with resource levels over time. We apply an evolutionary algorithm for multi-objective optimization to represent the collective learning process of these agents. The evolutionary algorithm allows for the adjustment of agent opinion preference in response to changes in resource levels and, thus, simulates adaptive behavioral response to complex rangeland dynamics.

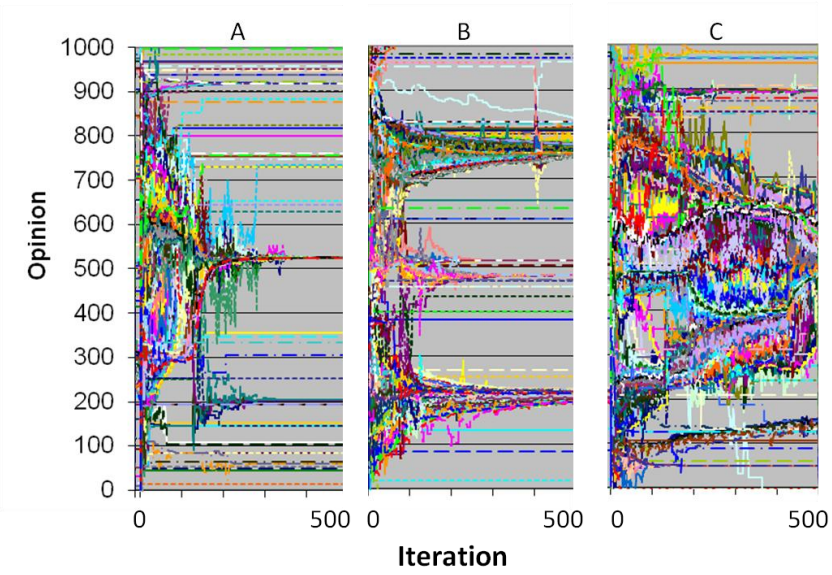

Figure 3. GAIA-RM output showing the formation of consensus (A), the emergence of stakeholder groups (B), and chaos (C); outcomes dependent on system dynamics and initial conditions; agent opinions are scaled to [0,1000].

3. Hypotheses and Experiments

It is hypothesized that threshold states exist that require a rapid formation of consensus to protect natural resources. These threshold states represent a form of emergent phenomenon. Furthermore, the intensity and spatial heterogeneity of land development may play an important role in guiding the development of land-use policies because of their associated effects on the perception of key stakeholders. Gradual or spatially concentrated land development, for example, may not trigger the same perceptual response as rapid more widespread development. This may produce delayed response times and missed opportunities for the formation of policies that promote the sustainable use of natural amenities.

Based on hypotheses concerning land use change, experiments were designed and conducted to explore the precursors of consensus and sustainability, and of social fractionalization and the tragedy of the commons. Our experimental results show that GAIA-RM is well-suited to capturing the complexity of rangeland systems in our study area.

3. Concluding Discussion

GAIA-RM provides an integrative framework for the spatiotemporal modelling of complex rangeland systems. Land owners are represented as GAIA who can learn to adapt their cognitive behaviour in response to landscape change in rangeland systems. Multi-objective evolutionary algorithms enable the explicit representation of collective learning of land owner agents to adaptively form coalition for sustainable resource use. The resulting ABM facilitates investigations into rangeland systems and offers insight into the modelling of other complex adaptive spatial systems.

4. Acknowledgements

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