Complexity theory and spatial simulation models to assess population-environment interactions in the Galapagos Islands

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Abstract

The intent of this research is to develop a spatial modeling and data visualization approach to study population-environment interactions, i.e., alternate household livelihood strategies, household decision-making, and land use change, with an emphasis on invasive species, on Isabela Island in response to a dynamic environment and changing employment opportunities in fisheries, tourism, and agriculture. A base model of land use/land cover change and household livelihood dynamics is developed and then perturbed by creating three alternative scenarios: (1) an increase in agricultural subsidies, (2) a decrease in global fisheries, and (3) a decline in tourism. The ABMs used in this study allowed us to develop explanations for those scenarios, and examine endogenous factors and exogenous shocks that can alter trajectories of change resulting in possible shifts in system behaviors and dynamics.

Introduction

The ABMs used in the present study represent the primary livelihoods of the population in the Galapagos Islands – tourism, fisheries, and agriculture – and shifts in household employment patterns in those sectors over time. Population-environment interactions are examined using the NetLogo software platform (version 4.0.4), a user-friendly ABM software system that integrates a graphical user interface with an intuitive scripting syntax based on the LOGO language (Papert 1972). The general goal is to explore the utility of Agent-Based Models (ABMs) for hypothesis generation and testing though plausible scenarios that alter the interactions between population and environment (Malanson 1999, Malanson et al. 2006). In this research, the decision - making processes of households associated with economic diversification from agriculture to tourism and fisheries (and back again) are examined through scenarios that involve the interplay, for instance, of possible labor shortages on the farm and demand for mainland immigrants and land abandonment and decline in management of invasive plant species, using guava (*Psidium guajava*) as the examplar species (Walsh et al., 2008a). El Niño events that influence terrestrial, marine, and social sub-systems and assumptions about social and spatial interactions of people and environment are also integrated to address "what if" scenarios within a spatial modeling and visualization approach Walsh et al. 2008b).

Methods

ABMs consist of human agents (e.g., individuals or households) who are autonomous decision-making entities. ABMs use a bottom-up approach to test alternative theories of specific observable patterns (Grimm et al. 2005). In this research, empirical data are used to establish the initial conditions of the system, including the initial attributes of the agents from

Ecuadorian census data to describe, for instance, demographic characteristics, intrinsic behavioral rules, modes of communication and learning, and internally-stored information about itself and other agents (Tesfatsion 2003). The ABMs are executed using a spatially gridded and stylized environment that mimics the fundamental characteristics of Isabela Island, using a satellite land use/land cover classification to set the initial conditions (Walsh et al. In Press). A conceptual framework was developed to identify key population-environment interactions and to organize the computer simulations (Figure 1). This framework includes selected landscape, agent, and system characteristics. Agent characteristics affect livelihood options and decision- making, and interact with the environment in complex ways. Alternate household livelihood strategies are limited to include the central occupations associated with tourism, fisheries, and agriculture. Livelihood decisions feed back into agent characteristics and also affects land use/land cover patterns. Land use feeds back into the system by affecting various aspects of the local landscape, particularly, the areal expansion and /or constriction of invasive species on farms and in the nearby Galapagos National Park. Exogenous factors include global markets, public policies, and environmental variations. Subsidization of farmers may take the form of greater access to agricultural information and technologies, creation of crop price-supports, or improving farmer incomes through a greater focus on local commercial agriculture, possibly including a greater emphasis on organic farming. Environmental policies governing the land use in the agricultural zone and the community boundaries of Puerto Villamil are included in the model. The exogenous factors are considered as separate perturbations that are modeled as scenarios of change. For instance, El Niño is conceptualized as an exogenous factor that is indirectly incorporate into the baseline model.

Results

From the base model, the number of people working in fisheries remains relatively stable, while the number of farmers initially declines as they transition to the tourism sector. After this initial change, the populations in the tourism industry as well as in farming remain relatively stable during the observation period, except for small changes during El Niño years. The workers in the tourism industry increase during some El Niño years, perhaps due to farmers and a smaller number of people in fisheries switching livelihoods during these years. A small number of farmers also exit the system due to low accumulated wealth and an inability to switch to alternate employment sectors. Guava area initially decreases and then begins to increase, and by the end of our observation period, the guava area is virtually the same as its initial conditions. This finding was unforeseen, because the total number of farmers decreases with time and we anticipated that the area of guava would increase as a result. Three scenarios were developed to explore how an agricultural subsidy might affect the system. An increase in yearly income of $2,000 or $3,000 was examined — as well as a subsidy in the form of eliminating the costs associated with eradicating guava by farmers. The $3,000 yearly income subsidy had the largest effects on the population of farmers and on the total area in guava. In this scenario, the number of farmers initially increases and remains relatively high compared to the baseline model for the remainder of the observation period. Under a fishery collapse scenario, the farm workers and workers in fisheries decrease, while workers in the tourism industry increase and the median income in the fisheries industry decreases. Surprisingly, the median income from farming also substantially decreases. It appears that agents with sufficient wealth switch from farming to the tourism sector, while farmers with relatively low patch value remain in the farming sector, further depressing median incomes. The median wealth in the fisheries sector also decreases, while median wealth in the other two sectors was very similar to the baseline model. The amount of guava slightly decreases from its baseline levels in this scenario, despite the decrease in the number of farmers. Finally, a simulation of a decline in tourism was developed. Under this scenario, the number of workers in tourism declines and the number of farmer agents increase during this same period. As the tourism industry recovers from the economic crisis, the number of tourism workers increases, while the number of farming agents decreases to approximately its baseline level. In turn, the guava coverage shows a slight decrease during and after the tourism decline.

Discussion & Conclusions

Models generated through agent-based approaches can be used to explain patterns and to relate them to processes. Thresholds and feedback mechanism are key considerations, as are endogenous factors and exogenous shocks that combine in complex ways to perturb systems and to alter future trajectories. A challenge is to develop and encode rules and pattern-process relations in the models that address fundamental issues of ecosystem functions and services, population-environment interactions, and scenarios of landscape change that are framed within a policy-relevant context (Messina and Walsh 2001, 2005). Complexity offers a theoretical framework to study the interactions among people, place, and environment (Walsh et al. 2008b). Comparisons made across settings, systems, scales, and processes can be embodied in coupled human- natural systems, and the system can be constructed to examine the integrated effects of social, terrestrial, and marine sub-systems in the Galapagos Islands.

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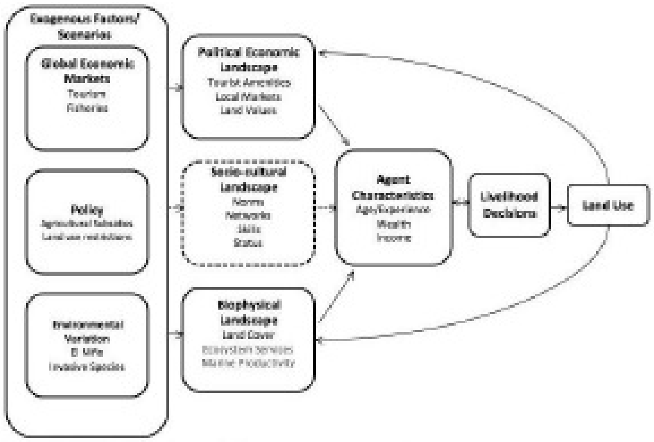

Figure 1. Conceptual framework for modeling livelihood decisions and land use/land cover processes. Dashed lines and gray text indicate variables not explicitly featured in the current version of the ILLUM model.

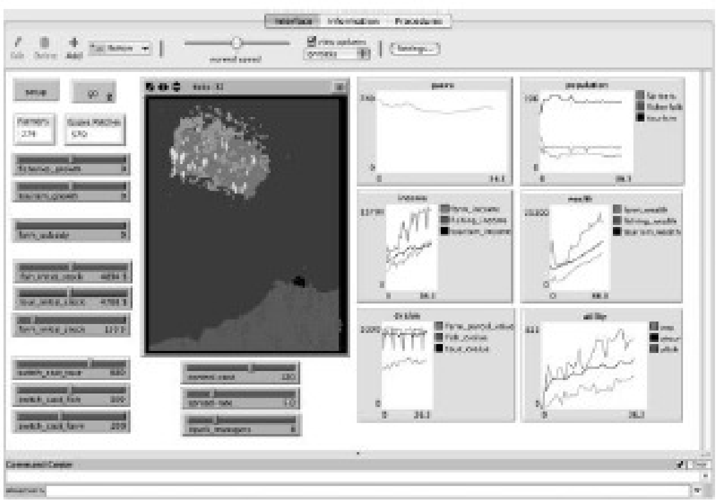

Figure 2. NetLogo 4.0.4 Interface of the *Isabela Livelihoods and Land Use Model*.