Agent-based and boolean network modeling of socio-ecological interactions in a protected area in the Yucatan Peninsula, Mexico

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Abstract

A challenge for understanding the use of natural resources by human populations is the complex dynamics of social-ecological systems (SES). Crucial to these dynamics, in areas that still have high biodiversiy and resilience to external perturbations, are the multiple use strategies (MUS) used by people that traditionally have inhabited these areas. We study the MUS as practiced by the Yucatec Maya communities that inhabit a protected area in the Yucatan Peninsula, Mexico. Due to several internal and external factors, some of these communities have started to abandon the MUS and specialize on tourism-related activities. To study the consequences of these changes on the resilience of this SES, we built an evidence-based dynamical computational model that allows us to explore different virtual scenarios. The model, through the incorporation of agent-based and boolean network modeling, explores the interaction between the forest, the monkey population and some productive activities done by the households (milpa agriculture, ecotourism, charcoal production). We calibrated the model, explored its sensibility, compared it with empirical data and simulated different management scenarios. Our results suggest that the MUS enhances the resilience of this SES in terms of income and food availability, as it increases the system's response diversity and functional redundancy, thus reducing income variability and increasing the resistance to natural and anthropogenic disturbances. Our study integrates diverse mathematical formalisms into a model that can be used for participatory decision-making processes in this and other important SES.

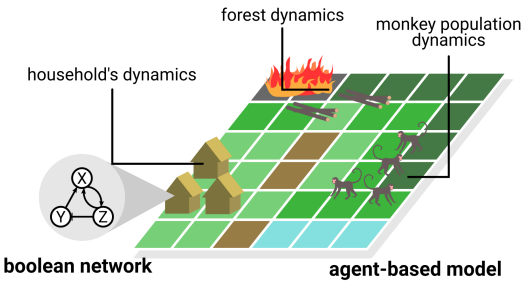
Introduction

A crucially important research challenge is to understand the mechanisms underlying the resilience of SES, i.e. their capacity to maintain their structure and function in the face of disturbance and ongoing change. In the exploration of these mechanisms, some traditional practices, largely overlooked and considered unproductive and environmentally damaging, have been re-evaluated (Berkes et al., 2000). An example of these practices is the multiple-use strategy (MUS) on which indigenous communities inhabiting tropical forests in Mexico often base their resource management and family household (Toledo et al., 2003). In this work we study the MUS practiced by a Maya community inhabiting the Otoch Ma'ax Yetel Kooh protected area, in the noertheastern Yucatan peninsula, in Mexico. Traditionally, the local Maya inhabitants have managed their resources following a MUS based on swidden *milpa* agriculture (García-Frapolli et al. 2008). But after the declaration of the protected area in 2002 in response to their own initiative, and particularly as a result of the growth of the tourism industry in the region, local households have abandoned their MUS, specializing instead in providing ecotourism services. We explore the consequences of these changes on the resilience of the SES, in the face of typical disturbances in the region. We integrate, formallly and explicitly, the information generated in previous studies in the area into a model combining an agent-based approach and boolean networks.

Methods

Detailed methods are in García-Jácome et al. (2020). Briefly, the purpose of the model is to explore how different productive and management strategies affect the resilience of the household's economy, the spider monkey population and the forest of this SES to some frequent disturbances in the region: hurricanes, forest fires and temporality of tourism. The model has been designed for scientists and managers, mainly those interested in conservation and forest management in the region. The model consists of four agents: landscape patch, household, monkey, and fuel biomass (Figure 1). The rules for their behavior are based on ecological and social studies carried out in the area during the past 20 years (rev. in García-Jácome et al. 2020). Landscape patches can change in succesional stage of vegetation, burn or turn into agricultural land. Households have different productive activities, each one with different monetary value depending on the disturbances. The monkey population follows normal population dynamics and fuel biomass accumulates in patches depending on storms and hurricanes.

One time step of the model represents a bimester and weather conditions are modeled using a boolean network (López-Martínez 2017), with three nodes: temperature, pressure and precipitation. The dynamics of this network



generates a periodic attractor of length 6, where the precipitation node spends 3 consecutive bimesters in the rainy state and 3 in the dry state, approximating the natural seasonal weather in the region.

Natural disturbances in the model are storms and hurricanes, which occur with probabilities and strength taken from natural occurrences. When an event occurs, a proportional amount of fuel biomass is accumulated in landscape patches, which may result in a forest fire depending on the fuel biomass and the speed of wind during the next dry season. The fluctuations in number of visitors are also modeled using a boolean network, which has two nodes, high and low visiting numbers, that vary depending on hurricanes and other stochastic factors (for example, a travel ban due to a pandemic, as in the real world). The activities of households are also modeled using boolean networks particular to each household, with seven different nodes corresponding to different activities (Figure 1).

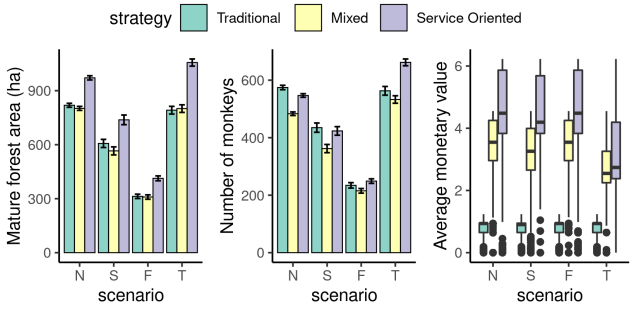
The model was calibrated using values of the burning probability of patches, the function relating the speed of wind and the proportion of affected patches by fires and the duration of fuel biomass such that the occurrence of fires resembled natural observations. We explored the sensitivity of the model using variations of all the relevant parameters, one at a time, running 30 simulations for each combination for a span of 200 years. Model results were compared with empirical data for land use change, monkey population size and household activities. We tested the effect on these variables of four different scenarios: normal, an increase in storms, an increase in forest fires and a decrease in tourism.

Results

We obtained a periodic attractor in the boolean networks corresponding to single households. This attractor contains states that correspond closely to the situation observed in the SES: a dry season with the precipitation node turned off, with a high flow of tourists. This is when a household prepares the plot for the milpa, harvest apiculture and produce charcoal (all these activity nodes on). On the contrary, a state with precipitation on, a low flow of tourists and the milpa ready to be harvested corresponds to the last bimester of the rainy season.

The sensitivity analysis revealed that most output variables respond to a change in the explored parameters. Mature forest area and the total number of monkeys were sensible to the burning probability of patches, duration of fuel biomass, relationship between wind and proportion of affected patches in the event of a fire, and patch size. Average monetary value was sensible to the burning probability of patches, patch size, the flow of tourists and the minimum number of monkeys for tourism. The model reproduced relatively well the area of forest of each successional stage, although overestimating the area of mature forest and the population size of monkeys, compared to empirical data.

Households in the model practiced three different strategies: traditional, mixed and service-oriented. These have increasing monetary value, although also with a higher fluctuation in the case of the service-oriented. When there is an increase in storms and hurricanes, all strategies generate a reduction in mature forest and monkey populations, with no noticeable change in monetary value (Figure 2). When there is an increase in forest fires, under all strategies there is a strong reduction in the mature forest area and monkey population, with no noticeable change in monetary value. Finally, when there is a decrease in tourism, traditional strategies do not change but the mixed and especially the service-oriented strategies decrease their monetary value and suffer the greatest fluctuation along the 200 years of simulation (a more detailed account can be found in García-Jácome et al. 2020).



N: normal; S: increase stroms; F: increase forest fires; T: decrease tourism

Concluding remarks

We have explicitly integrated an agent-based approach with boolean networks, allowing us to reproduce some of the SES dynamics with fewer parameters than in a traditional agent-based model. Our results support the idea that MUS are important mechanisms underlying the resilience of socioecological systems on which biodiversity and long-term sustainance depends. Future work will test the usefulness of such models for participatory decision-making by a diversity of stakeholders.

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