Evaluation Of Preliminary Models Of Swidden Agriculture In The Toledo District Of Belize

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Abstract

Swidden farming in the Toledo district of Belize is a relatively young subsistence agricultural technique in which each farmer enlists help from his friends to clean a patch of land, grow crops, and harvest. The resulting near-reciprocal social network of exchange of agricultural labor constitutes an essential component of the coupled human natural system that operates in this region. This paper describes a preliminary effort to develop an agent-based model of this system, which started as a demonstration model in NetLogo and evolved into 3 candidate models that were evaluated for basic viability criteria to exhibit fundamental features of the Toledo district, such as its characteristic cultivation cycle in which a patch is usually farmed for 2 years at most, then left to fallow for 7 years at least. In our evaluation, we were able to conclude that the 3 proposed models cannot meet the proposed criteria, thus leaving us with the alternative of introducing the cycle as an explicit constraint. We plan to use what we have learned and the tools we have built in the development of future models that produce viable scenarios in order to move on to the study of social properties and emergent phenomena of such models.

Introduction

This paper describes the preliminary stage of an effort to model the coupled human-natural system constituted by swidden agriculture in the Toledo district of Belize (Downey, 2010). The goal of this larger research is to develop theoretical and computational tools to advance our understanding of the management of natural and social resources related to swidden agriculture. This effort will integrate theoretical and methodological resources from a number of disciplines, in order to understand the interactions among swidden agriculture activities, the social structure and resources of the Toledo communities, and the natural resources of the district. Emergent phenomena will be of particular interest to this research.

In the 2016 Complex Systems Summer School we developed preliminary agent-based models of swidden agriculture, where the agents represent households of farmers which develop their agricultural activities as a social network of labor exchange. We evaluated their suitability for modeling the particular variety of swidden agriculture practiced in the Toledo district. Our results are presented in this paper.

The rest of this section is devoted to expand on the background of this work by briefly describing this agricultural technique. Swidden agriculture, also known as shifting cultivation, or slash-and-burn agriculture, encompasses a range of land-use systems, in which fallows — clean but unsown fields that are allowed to restore their fertility for a number of years — are essential components that keep the productivity of the farmlands (Brookfield, Byron & Potter, 1995, p. 114; Padoch & Pinedo-Vasquez, 2010,

p. 551). The swidden cultivation cycle can be summarized in the following general stages (Batabyal & Lee, 2003, p. 821): (1) Farmers chop down a portion of forest to make a field, generating a pulse of soil fertility by burning the vegetal remains in-situ. (2) The field is planted in time for the rainy season to stimulate rapid plant growth. (3) The crops are harvested and the land is left fallow for a number of years, in order to restore the fertility of the cleared land. Farmers repeat this cycle over a number of fields in asynchronous form, such that at any given moment some fields are cleared, some have crops, and some are left to fallow, hence the name "shifting cultivation".

Swidden agriculture is practiced since prehistory, and today it is estimated that more than 250 million people in tropical regions of the world practice some form of swidden (Metzger, 2003, pp. 93, 325). While researchers generally agree that these techniques are important to the food supply of diverse communities in tropical areas, disagreement has been observed about the ecological sustainability of these systems (Batabyal & Lee, 2003, p. 821). Dove (1983) shows calculations suggesting that there is no unequivocal basis to objectively compare how detrimental or desirable can swidden agriculture be in comparison to commercial logging or other systems of land use. Early studies in Southeast Asia demonstrated that swidden farming with short cropping, long fallows, and a reasonably small scale is a sophisticated, productive use of the environment (Condominas, 1977; Conklin, 1954; Freeman, 1955; Spencer, 1966). A more recent study in America regards it as a relatively benign disturbance (Herrera et al., 1981, p. 114) that does not seriously impair ecosystem function (Uhl, 1987, p. 78). But this system can induce ecological destruction if forced to fit a market-oriented economy or to feed larger populations (Herrera et al., 1981, p. 114, Myers, 1988, p. 192). Thus, the viability of slash and burn agriculture in the long run depends critically on the land use decisions made by small farmers (Batabyal & Lee, 2003, p. 821). Other publications blame swidden agriculture for global deforestation, indicating that farmers are destroying the forests, that the soil quickly becomes infertile (Stitger, 2008), and that these systems "should be replaced by continuous cropping and farming systems, supported by soil conservation, leading to a more rational use of land according to its suitability" (FAO, 1986, p. 46).

The studies mentioned above are but a sample of the diversity of approaches and opinions that surround swidden agriculture, but more generally, it highlights the need to develop scientific understanding of swidden agriculture as a coupled human-natural system (Mertz, 2009, p. 156; Padoch & Pinedo-Vasquez, 2010, p. 551) and of the spatial variability in the conditions in the livelihood of farmers at different scales (Tittonell et al., 2010; Masvaya et al., 2011), which has been a limiting factor in the generalizability of agrarian research (Stigter, 2010, p. 3).

Alternatives and variations to swidden agriculture have been described in scholarly literature. For example, a proposal to increase the ecological sustainability of the swidden agriculture practiced in the vicinity of San Carlos de Rio Negro region in the Amazon territory of Venezuela consists in manipulating the nutrient cycles of the fallow by planting specific crops (Uhl, 1983, pp. 78-79). Another variation is a cropping system based on alleys of an Inga trees (Hands, 2003, p. 601). It started with a comparative study of 13 species of Inga in combination with *Erythrina fusca* and *Gliricidia sepium* for the demonstration of the production of maize, beans, vanilla, pepper, passion fruit, and pineapple. It grew up to constitute projects that currently operate or have operated in Honduras, Costa Rica, Congo, Madagascar, and the Maya heartland (http://www.ingafoundation.org/). Key to the Inga alley cropping system is the finding that sustainability can only be achieved by recovering, retaining, and recycling phosphorus, a necessary condition that only the Inga variety of alley cropping systems could attain.

A number of challenges exist as to the development of variations such as the two examples above, not the least of them being the time frame of any project in the field. Swidden cultivation cycles are of the order of magnitude of a decade including fallows. The second challenge is that the variation needs to develop useful combinations of plants that complement each other in desirable properties such as rooting properties, light availability, pollination requirements, and timeframes of crop production (Uhl, 1983, p. 79). A third challenge is the spatial variability in human livelihood, nutrient cycles, and availability of resources, which means that the assessment of whether a particular technique or variation can be adapted in a different region of the world is not straightforward. As an illustration of spatial variability in nutrient availability, while it was found that in the original research areas of Inga Alley Cropping phosphorus must be provided every 5-6 years in the form of phosphoric rock in small quantities (Hands, 2003, p. 601), Buck (2012) demonstrated that available phosphorus and other soil fertility indicators vary little between undisturbed tropical forest and recovering swidden fallows in the Toledo district.

In this particular region of Belize, swidden agriculture is marked by a social network of farmers exchanging agricultural labor. By using analysis techniques from network science, Downey (2010) demonstrates how overexploitation of the natural resources in this district can be prevented by changes in the reciprocity rates of labor exchange, and proposes a graduated-sanction model in the context of this network. He points out that questions remain open regarding the specific constraints that demographic growth and environmental resources impose on swidden agriculture techniques in general.

Gathering the ideas presented so far, we point out that efforts to find alternatives and useful variations to swidden agriculture techniques should be preceded or at least accompanied by the development of the basic scientific understanding of how these techniques work. With this motivation, this paper marks the start of our effort to build on Downey's work to study the swidden agriculture of the Toledo district using agent-based models.

We developed preliminary agent-based models of swidden agriculture that model the Toledo district as a coupled human-natural system. In accordance with the agricultural dynamics in the Toledo district in Belize, the model will use a time step of one year. Each time step implements the dynamics of clearing, sowing and harvesting, as well as ecological and social dynamics. The social component of the model is implemented as a Birmelé (2009) scale-free network among households of farmers, in order to account for the variability in social relations in a human community, while maintaining a larger clustering than the basic Barabàsi-Albert (1999) algorithm. As described above, the social network is used for exchanges of agricultural labor.

The natural component of these models is the one that received the most attention in this preliminary stage of research. It consists of a grid of patches of land, in which each and every patch has three key properties: fertility, biodiversity, and biomass. As a preliminary approximation, these three state variables are mutually coupled within their patch, coupled to the household that currently claims ownership of the patch, and otherwise uncoupled from the other patches and households. When the patch is left to fallow, the state variables follow logistic growth dynamics as described below in the Methods section.

Results

An initial, unconstrained model was built with arbitrary parameters, which was demonstrated in a presentation at the CSSS. A sensitivity analysis was conducted on 3 arbitrarily selected parameters of this model: the harvest rate, the social network shape parameter Alpha, and the biomass logistic growth parameter biomassB.

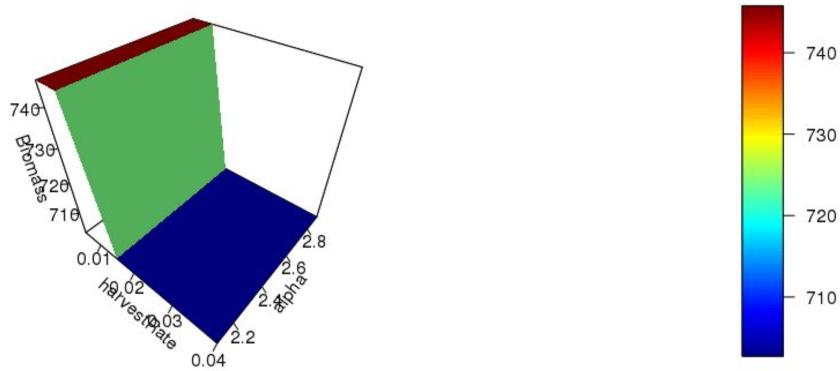

Figure 1. Biomass for biomassB = 0.00020

The preliminary version of the model highlights the harvest rate parameter as determining a phase transition in the long-term stable value of biomass. We hope to be able to better characterize this phase transition and to assess its dependence on other social parameters. For the time being, this figure shows that the harvest rate is a far larger predictor of the behavior of the biomass than the exponent of the scale-free network alpha. When the harvest rate is low, the biomass recovers more than in regimes with larger harvest rates.

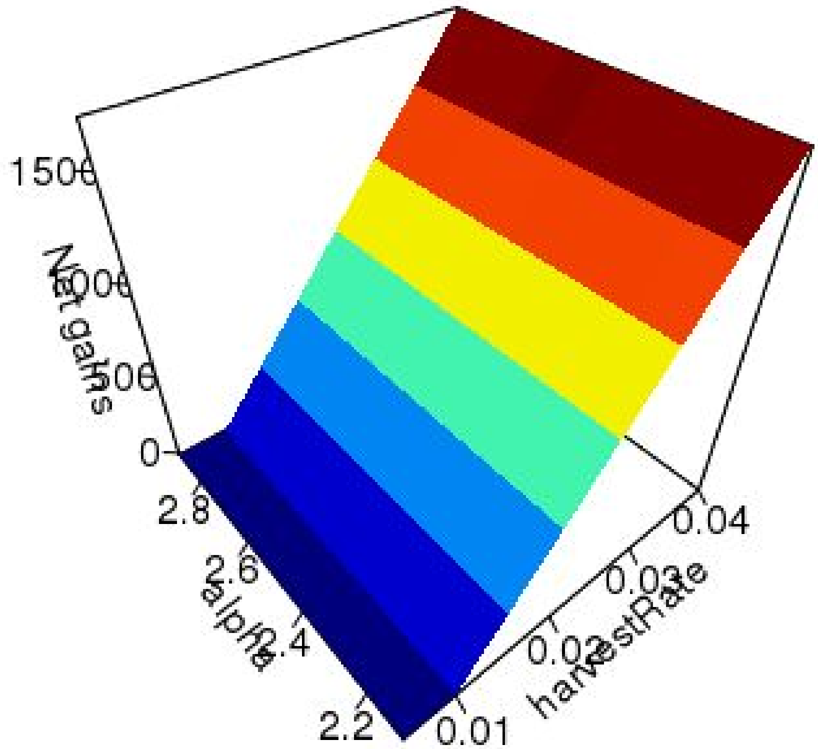

Figure 2. Yearly energy balance per farmer for biomassB = 0.00020

There is a transition from a regime with flat energy balance to a regime with positive energy variation as the harvest rate rises.

Work with this first model involved the implementation of basic constraints such as maintaining nonnegative fertility, biomass, and biodiversity. Initial parameterization work consisted in a sensitivity analysis of state variables in a space of social and ecological parameters of the model. Evaluation of the model consisted in finding viable parameter scenarios, for which all criteria for the model could be met.

The first criterion for a viable scenario is that the resulting time series of fertility, biomass and biodiversity are all sigmoid in shape for fallows.

The second criterion for a viable scenario is the suitability of this basic model for reproducing the crop and fallow cycles of the swidden agriculture that is practiced in Belize, in which a patch of land is not farmed more than two consecutive years, then left to fallow for at least seven years (Downey, personal communication; see a related example in Linnard, 1970, p. 195). If a patch of land was cropped for a third year, the yield would be unacceptably low. The evaluated models follow Barton (2014) in proposing the existence of a fertility threshold, below which a patch is not eligible to grow crops, and above which the patch is considered for farming. Moreover, the threshold is expected to guarantee that the land is eligible for farming for one or two years, after which the fertility is expected to fall below the threshold, naturally maintaining the fallow for at least seven years. Then the fertility is expected to reach the threshold to make the patch farmable again.

A thorough exploration of the parameter space was carried on in order to find viable scenarios. Scenarios generated sequentially were employed first, in the order of 10^7. No viable scenarios were found. Sequential exploration was supplemented by an analysis on scenarios with parameter values generated by Monte Carlo methods. Scenarios were evaluated in the order of 10^8 using this method, but no viable scenarios were found.

A second model was designed with simpler fertility dynamics than the first model. Rather than having its own sigmoid shape, fertility is modeled as a fixed proportion of the biomass.

The second model was subject to the same treatment than the first one, implementing the same constraints and criteria, and similar parameter explorations in sequential and random fashions. It was determined that this model does not produce viable scenarios.

A third model was designed in which fertility, biomass, and biodiversity all fall in a fixed proportion when the land is farmed, instead of falling to zero as was initially proposed for the previous two models. Under the same treatment, including the variation of this proportion, it was determined that this model does not produce viable scenarios. As a matter of comparison, we determined that by eliminating the second criterion we were able to consistently produce a ratio of 5.8% of viable scenarios out of all examined scenarios.

Discussion

In this initial stage we were able to evaluate three preliminary models of swidden agriculture. We learned that a threshold fertility, which is the basic approach to the decision on whether farming a patch (Barton, 2014) is insufficient or outright unsuitable to describe the cultivation cycles that emerge in these agricultural techniques. In our evaluation we also developed a tool, the Monte Carlo generation of scenarios, that helps us supplement our exploration of the parameter space.

We hope to be able to design and evaluate a model that can help explain the cycle of swidden agriculture from land state variables such as biomass, biodiversity, fertility, or specific nutrient levels such as phosphorus.

We also hope to be able to continue to explore social aspects and emergent phenomena in this model once we are able to work out the cycle. Of particular interest will be the study of graduated sanctioning as a tool to prevent the overexploitation of the land, and its relationship to yield and ecological sustainability.

Methods

Our models were created in NetLogo and C++. Source code for all models is available on request.

The evaluated models have the same social structure, Basically farmer A enlists the help of his farmer friends for clearing, sowing, and harvesting, and farmer A keeps the produce for his family. All farmers in the district take part in this labor exchange.

The degree (number of friends) of each farmer constitutes a limit on the total number of patches that can be farmed, and thus the amount of energy that will be gained by the farmer.

All patches are initially available for farming. A farmer takes ownership of the patch and farms it for 1 or 2 consecutive years. It is expected that the farmer leaves the patch to fallow for 7 years at least, and in the mean time the farmer takes ownership and farms other patches. If a patch remains a fallow for 15 years, it is freed to be taken by other farmer (Downey, personal communication).

In the first and second models, when a patch is farmed, its fertility, biomass, and biodiversity are set to zero. In the third model, when a patch is farmed, these 3 state variables are reduced by a fixed farming factor. The re-establishment of biodiversity when the cleared area is left fallow, and at the end of each farming year, is simulated using a logistic growth curve. This represents the non-linearity in the re-establishment of the forest and the associated diversity:

$$\Delta\theta_i = \beta_\theta \times (\theta_{max} + \theta_c) \times (\theta_{i-1} + \theta_c) - \beta_\theta \times (\theta_{i-1} + \theta_c)^2$$

Where θ_i is the biodiversity at time step i, θ_{max} is the maximum possible biodiversity, θ_c is a small value that affects how quickly biodiversity becomes established (working as an offset so that after clearing when the biodiversity is zero, $\Delta\theta_i$ is still positive), and β is a growth parameter.

The simulated biomass regrowth is also based on a logistic growth curve, but with a maximum possible biomass that is related to the biodiversity. This allows an initial period of growth to be simulated based on a logistic growth curve, but a slower increase to continue if the forest is left for longer. Hence

$$\kappa_{max} = \kappa_{max0} \times (1 + \gamma \times \theta_i / \theta_{max})$$

$$\Delta\kappa_i = \beta_\kappa \times (\kappa_{max} + \kappa_c) \times (\kappa_{i-1} + \kappa_c) - \beta_\kappa \times (\kappa_{i-1} + \kappa_c)^2$$

Where κ_{max0} is the maximum biomass if the forest is re-established with little biodiversity, γ is a factor that accounts for the extent to which biodiversity can increase potential biomass, κ_{max} is the maximum biomass at any time step, κ_c is an offset factor similar to θ_c that affects the rate of re-establishment and β_κ is a growth factor.

In the first model, when the forest is established, the soil fertility builds up in proportion to the forest biomass (representing an input of organic matter from this source). The soil fertility decays continuously, thus when the forest is burnt and inputs cease soil fertility is quickly lost:

$$\omega_i = \lambda\, \omega_{i-1} + \alpha\, \kappa_{i-1}$$

Where ω is the soil fertility, λ is the rate at which fertility decays in the absence of inputs and α is the fraction of the biomass that contributes to the fertility. High soil fertility then contributes to producing a higher yield.

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