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Exploring the Choice of Decision Making Method in an Agent Based Model of Land Use Change

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Abstract: In agent-based models of land use/cover change (ABM/LUCC), small changes in micro-level decision-making methods used by agents may significantly affect macro-level outcomes. Yet, the implications of choosing a specific decision making model are seldom explored in ABM/LUCC studies. This paper discusses an ABM/LUCC modelling study of smallholder farming households in the Amazonian varzea in Marajó Island, Brazil. These agents represent the 21 households within the community of Paricatuba. Farmers in this community cultivate acai as a primary source of income, in addition to other farming and economic activities such as off-site employment. In the model, agents make annual decisions to allocate scarce land, capital and labour resources to best provide revenue for the household. Household agents have the same overall goals, resources, information, and feasible actions available to them within the simulation environment. Alternative simulations are developed in which the household agents employ one of two primary decision-making methods, either based on linear programming or decision trees. A comparison of these methods in a Monte Carlo simulation indicates that in certain scenarios, alternative decision-making methods with otherwise common objectives and environments may lead to widely divergent outcomes. The evaluation of multiple decision making methods within a common model can be used to highlight the advantages and limitations of these methods and challenge assumptions.

Keywords: decision-making; agent-based model; land use/cover change; Amazon

1 DECISION-MAKING METHODS IN ABM

Agent-based models of land use/cover change often employ land manager agents manipulating land uses in a dynamic and spatially explicit environment. Typically, land manager agents are goal-directed or aim to maximize utility. Depending on scope, study area and research intent, land manager agents may represent actor entities such as individuals or theoretical decision-makers. However, ABM/LUCC have been analyzed with alternative decision-making methods in only a small number of cases. Schreinemachers and Berger [2006] performed a comparison of heuristics and optimization, stating a smaller-than-apparent difference between the methods, but lacked a concrete implementation. FEARLUS, a theoretical model, has been used to compare imitative and non-imitative strategies, finding that optimizing algorithms consistently perform better than all imitative strategies, although intelligent imitation tied with stochastic optimization in one case [Polhill et al., 2001]. Jager et al. [2000] compared the behaviours of rational actors to psychological actors in a landscape called Lakeland, recommending an implementation of multiple cognitive processes including social comparison, repetition and imitation, to supplement deliberation. This

paper, focusing on alternative implementations of the deliberation process, highlights an effort to perform a comparative study of decision-making methods in a model simulating a real-world environment of land use/cover change.

2 SMALLHOLDER FARMING IN THE AMAZONIAN VÁRZEA

Over the last several years, a team at Indiana University, Bloomington has researched the farming practices of smallholder, sharecropping and co-operative households near Ponta de Pedras, Pará, Brazil [Siqueira, 1997; Brondízio, 2008]. Three communities, in particular, were selected to characterize these farming arrangements. The study in this paper focuses on the smallholder farming arrangement, since decision-making is performed by a single stakeholder, a household which tends to its own land for subsistence and income. Other farming arrangements depend on a proprietor-sharecropper arrangement or community-wide co-operative agreements—multiple decision-makers. (For the purposes of this study, the household is treated as a single decision-making unit.) The community which characterizes smallholder farming is Paricatuba, with 21 households and a total of 144 individuals as of 1994 [Brondízio, 2008]. Paricatuba is located at approximately 1.42°S, 48.87°W. Farming practices in this area consist primarily of housegarden cultivation and açai management. Açai production is often considered an extractivist practice, though such production may instead be a practice of traditional, intensive management performed over the last century [Brondízio and Siqueira, 1997]. This production practice has the potential to sustainably satisfy growing demand [Weinstein and Moegenburg, 2004].

3 MARIA: A COMMON MODEL FOR APPLYING ALTERNATIVE METHODS

3.1 Model Design

In an effort to further understand the farming practices in this area of the Amazonian estuary in the context of economic opportunity and land use change, an agent-based model was developed. Termed MARIA (Multi-Agent Reasoning in Amazonia), the model was designed to allow alternative decision-making methods to be substituted. The agent-based model was built using Repast Symphony 1.2 [North et al., 2007], a Java-based ABM framework. The model is separated into two sub-models (contexts), Human and Environmental. The combination of these models is intended to simulate a system in which feedbacks between anthropogenic and environmental factors influence a changing landscape. The landscape itself, a spatial grid with a resolution of 15 m, is the interface between the sub-models. A grid size of 612x600 is used, with watered cells masked out based on interpreted satellite imagery. The cell resolution has been chosen to balance memory requirements with the ability to model spatial details, such as small housegardens. The Environmental Context contains the land cover model, which includes spatial variables of elevation, land cover, and cell productivity. For each cell, rules govern transitions between land uses and impacts on productivity. This creates an environment where appropriate actions, such as maintenance, increase productivity while abandonment reduces productivity and, in turn, the yield. Two primary managed land uses are available in the model, housegardens and intensively-managed açai. Housegardens must be fallowed after 2 years, whereas açai may be managed for a long period of time. Abandoned açai cells become forest cells.

The Human Context encapsulates human decision makers and their decision-making variables, such as resources and opportunities. Similar to a prior ABM/LUCC of another study site within the Amazon, LUCITA (Land Use Change in the Amazon) [Deadman et al., 2004], households are endowed with capital and labour upon arrival. The amount of labour is based on household demographics: Households and their members are placed in the model according to a population distribution [Brondízio, 2008]. Formal cadastral data is unavailable, so households first select a number of random cells from the grid, then settle on the cell closest to the water while satisfying a minimum distance from other households. The household then takes possession of 0.5-10 ha of land surrounding the initial cell placement.

Each simulation year is arranged into stages: The initial stage sets the conditions for the year, pertaining to any exogenous variables. This Exogenous stage includes economic opportunities, such as market prices and availability of off-site employment. This is followed by Planning, Action, Biophysical and Harvest stages. The Action stage includes all of the pre-harvesting stages of cultivation, while the Harvest stage involves the collection of yield and the resulting revenue.

In the Planning stage, household agents deliberate over which actions are to be taken. Cells may be allocated for either housegardens or for intensive açai management. Agents may elect to send members off-site, if employment is available, or may recall members back to the farm. The annual allocation of labour and capital toward land use change, maintenance and other employment is the key decision-making process in this study. Household agents intend to maximize revenue, given the prices of goods for the year. It is assumed that households are price takers and any harvested yield can be sold for the given price. Using a weighted linear cost function, households select cells to convert to gardens or intensive açai, minimizing the distance to household, with a secondary objective to cluster similar land uses.

3.2 Application of Decision-Making Methods

The primary decision-making process taken by household each year is related to the allocation of labour and capital toward land use change, maintenance and off-farm employment to maximize revenue. Two decision-making methods are developed for comparison. The first, linear programming [Dantzig, 2002], is used as an analog for rational, optimizing decision-making. Optimizing agents first take an inventory of their resources in order to prepare the linear program (LP) formulation. This takes into account labour availability, cell productivity and crop rotations. The LP is defined with revenue-maximization as the objective function. Variables are selected to maximize this expression, subject to constraints defined as linear inequalities. Optimization is performed by `lp.solve`, an open-source Java native interface to a C++ LP solver. The formulation can be expressed as follows (omitting simple bounds as well as integer and non-negativity constraints):

$$\begin{aligned}
 \max \quad & p_{\text{acai}}n_{\text{acai}} + p_{\text{garden}}n_{\text{garden}} + p_{\text{acai}}m_{\text{acai}} + p_{\text{garden}}m_{\text{garden}} + \sum_i s_i w_i + \sum_j \bar{r}_j w_j \\
 \text{subject to} \quad & l_{\text{n_acai}}n_{\text{acai}} + l_{\text{n_garden}}n_{\text{garden}} + l_{\text{m_acai}}m_{\text{acai}} + l_{\text{m_garden}}m_{\text{garden}} \\
 & + \sum_i s_i l_i + \sum_j \bar{r}_j l_j \leq \text{Labour} \\
 & c_{\text{n_acai}}n_{\text{acai}} + c_{\text{n_garden}}n_{\text{garden}} + c_{\text{m_acai}}m_{\text{acai}} + c_{\text{m_garden}}m_{\text{garden}} \leq \text{Capital} \\
 & n_{\text{acai}} + n_{\text{garden}} \leq \text{Land}
 \end{aligned}$$

The decision variables of this problem are the number of cells of new açai and housegarden cells, n , the number of açai and housegarden cells to be maintained, m , and whether household members should be sent away or recalled from non-farming employment. Each candidate member to be sent or recalled is characterized by a binary variable s or r , respectively. Since total revenue is to be maximized, the sum of new and maintained cells of each land type are multiplied by the expected revenues per cell, p . Similarly, the wages of each sent and non-recalled member are multiplied by the wages received by the member. The constraints of this problem are limitations of labour, capital and land available for new cells of açai or housegardens. Each resource requirement are calculated by multiplying the per-cell requirements, l and c , by the number of applicable cells or members for each activity. These per-cell requirements are indicative of conversion or maintenance requirements of labour and capital. Further constraints limit land available for each type of land use, if applicable. The above linear program characterizes the land use allocation process. A secondary linear program, not shown for brevity, is used to solve optimize harvesting and other revenue-generating resources, including extraction from fallowed cells.

The second decision-making method is a decision tree, similar to those used in LUCITA. A decision tree is an example of fast and frugal heuristics [Gigerenzer et al., 1999]. Choices are modelled as the outcome of a series of if-then conditions arranged in a hierarchy, allowing agents to quickly make decisions based on easily calculable variables. The decision tree process first considers sending members to take employment, if available, or recalling members, if farming is

more profitable. Then, cells which need to be maintained are attended to, due to the assumption that agents are loss averse. Finally, new cells are allocated for new crops until either labour or capital are extinguished. In some cases, where an ambiguous choice among multiple outcomes must be made, one is chosen using a selection weighted by expected revenue.

Unlike the linear programming decision-making method, which can calculate the shadow price of labour, the heuristic method can only estimate opportunity cost. If an employment offer is received, the agent multiplies the previous year's net income (or loss) by the proportion of the candidate agent's contributing labour to total labour. After the labour valuation is compared to the employment offer, if the offer is deemed more valuable, the member is sent to take up non-farming employment. A similar process occurs when considering recalling members to farming.

Each decision-making method is implemented into the model exclusively. That is, for a given simulation run, all agents adopt the same method. Methods are then evaluated between multiple runs for comparison. Unlike the decision-making comparison in FEARLUS [Polhill et al., 2001], where agents imitated other successful agents through imitation, agents in this model cannot change methods. A tournament involving imitation may be performed in the future, but this study intends to measure the relative performance of optimizing and heuristic agents.

3.3 Scenarios

Three scenarios are presented in order of increasing complexity, each selected to illustrate particular outcomes resulting from the use of the alternative decision-making methods. Each scenario differs by market prices as well as off-site employment availability and compensation. Household decision-making methods, knowledge and constraints do not differ between each scenario. The first scenario is that of constant market prices with no external employment opportunity. In this scenario, the market prices of açai and housegarden goods are fixed and do not vary over time.

In the latter two scenarios, the prices of açai and housegarden goods vary according to historical price indices. The price of açai is recorded and corrected for inflation by Brondízio [2008], while the aggregate price of goods produced in housegardens is assumed to vary in proportion to the IPA-PARA (Agroforestry and Husbandry Price Index for the state of Pará) published by the Fundação Getúlio Vargas (FGV).

The third scenario introduces the availability of alternative employment to the variable price scenario. Off-site employment is used as an analog of urbanization. It is modelled by a process which generates a random number of offers in each simulated year. These offers are distributed among households, who may then send a member to accept employment. With an assumption of inefficiencies in the labour market, related to imperfect information or individual differences in job skills, offers are not redistributed if they are rejected. Thus, the number of accepting members may be less than the number of offers made. The member, and thus the household, will receive an annual wage, but the member may not contribute to farming activities during employment. This models the opportunity cost associated with outside employment. It is up to the household to decide whether or not a member's employment constitutes a better value than agricultural activities.

4 RESULTS AND ANALYSIS

To illustrate the difference in outcomes between the decision-making methods performed, a comparison of land use trajectories of individual households is presented, where households are selected to match in terms of household demographics and initial endowment. This is followed by more detailed analyses of land use allocation, migration and a measure of household success (capital).

Omitted from this paper for brevity are the analyses used to verify and validate the model. Independently for each decision-making method, Monte Carlo simulation and sensitivity analyses were used to identify model artifacts. The analyses indicated an overall difference in performance

between each decision-making method and varying responses to the parameter sweeps. The results presented here illustrate differences in behaviour particular to selected households in individual scenarios, but the marked difference between decision-making methods is present across each parameter sweep. The sensitivity analyses are intended to be discussed in a future paper.

4.1 Constant Price Scenario

In this scenario, both methods would be expected to settle at a common steady state. The constant prices are set such that housegarden cultivation is slightly more profitable than açai agroforestry, so at the very least, the heuristic household may settle at a steady state landscape of a mixture of housegardens and açai agroforestry. However, while the optimizing household favours the former outcome, a homogeneous landscape of housegardens (among managed cells), the heuristic household settles at a homogeneous landscape of managed açai (Figure 1). Comparing the relative success of optimizing households to heuristic households, optimizing households are predictably more successful. Both types of household are typically labour-constrained, with a very small minority of households constrained by land.

The contrast in landscape composition between decision-making methods is the result of the difference in management requirements between the alternative land uses. Since housegardens must be fallowed for a period of time after intensive cultivation, new housegardens must be cultivated to maintain yield. Açai agroforestry, however, can be performed for a longer duration. Once the initial preparation has been performed, açai yield can remain relatively steady [Brondízio, 2008]. Thus, there is a lesser incentive to abandon açai for other land uses. As households abandon swidden plots through the natural fallow cycle, they consider new land uses. Using the random selection algorithm, weighted by market price alone, new cells of both açai and housegardens are allocated. Açai plots are not abandoned, eventually leading to a steady state landscape of açai. This behaviour could be corrected by considering the current state of the landscape as revenue-weighted selections are made. As a result, the landscape would be evenly split between housegardens and açai, with housegarden cells at a slight majority. As the landscape produced by the linear programming plot would be a homogenous one of housegardens, the difference in landscapes between methods would still be significant. Of note, such a correction was not performed in LUCITA, where the diversity of land uses mitigated the behaviour present in this model.

4.2 Variable Price Scenario

Introducing variable prices of goods according to the Açai Price Index derived by Brondízio [2008] and the IPA-PARA, both decision-making methods now produce similar steady-state outcomes (Figure 2). However, land use change within intermediate years highlight the differences between households. Optimizing households continue to exhibit extreme behaviour, choosing homogeneous landscapes of housegardens, when more profitable, then abandoning entirely for açai. Heuristic households show a similar trend to the constant price scenario. Since açai is more profitable in later years, households continue to intensively manage those plots.

Investigating this scenario further using sensitivity analysis, household demographics are shown to influence economic performance. Although açai and agroforestry price indices have been provided by Brondízio [2008], it is difficult to relate these to conversion and maintenance costs. A sensitivity analysis has been performed in order to characterize the relationship between variable selling prices and the costs of maintenance and conversion, which are assumed to be relatively constant. This is done by applying a “price-scaling factor” which multiplies the price indices relative to constant costs. With a low price scaling factor, households operate at a loss throughout the simulation (lower revenue than costs). With a higher scaling factor, profits are gained. The scaling factor is not varied within a simulation run. By varying the scaling factor in a parameter sweep while keeping costs constant, the sensitivity analysis indicated that demographics were a key factor in economic performance. While selling prices were shown to significantly affect profitability, the heterogeneity in household composition produced a wide spread in terms of profitability within each simulation run since labour was typically the binding constraint.

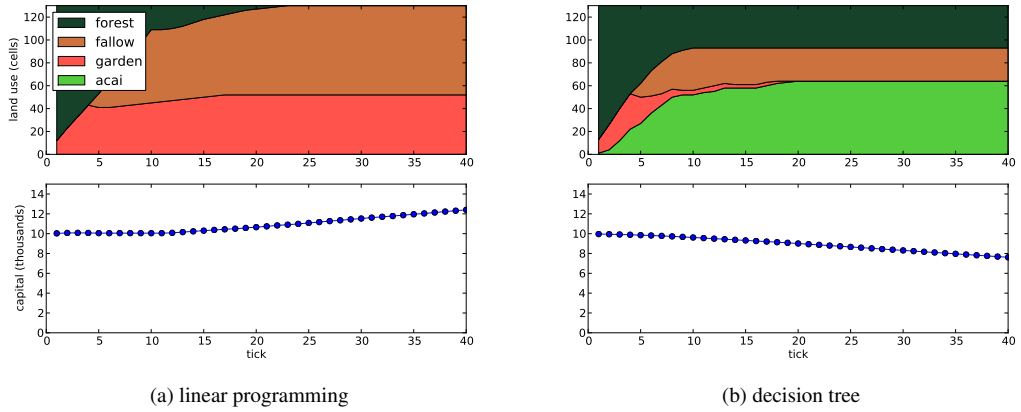


Figure 1: Constant price scenario time series for individual households

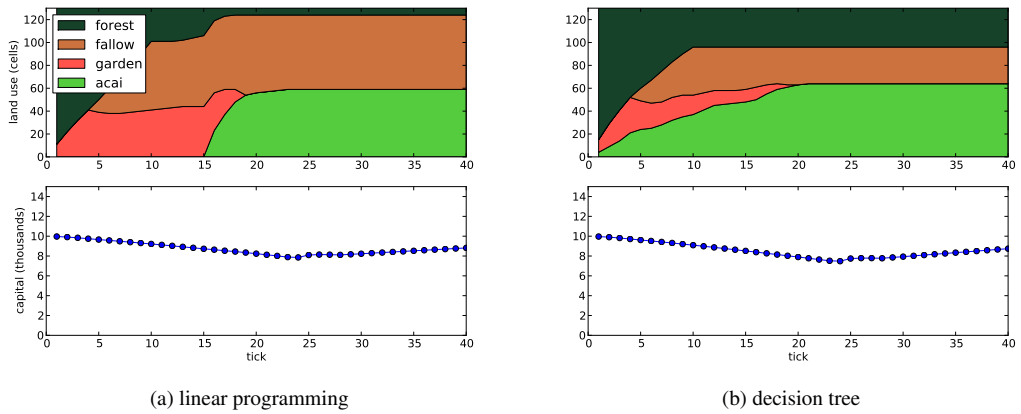


Figure 2: Variable price scenario time series for individual households

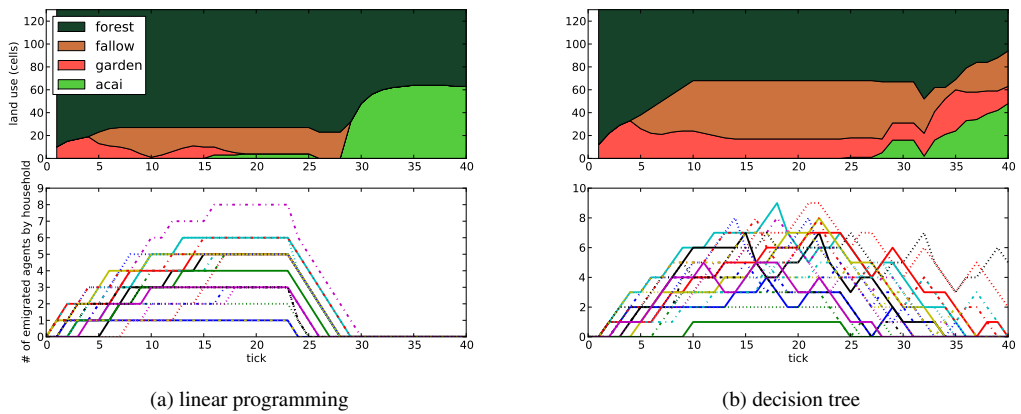


Figure 3: Employment scenario land use trajectories (selected households) and migration patterns (simulation-wide; one line per household)

4.3 Alternative Employment Scenario

With external employment available, the land use trajectories of households become complex as members emigrate. Figure 3 (bottom) graphs the numbers of emigrated members by household, with one trendline per household. Figure 3 (top) shows land use trajectories for selected individual households. Like the previous scenario, household capital is relatively equal between methods, so it is omitted. Recalling the respective land use trajectories in the variable price scenario, the general trend was that of housegardens replaced by açai as the expected revenue of açai rose above that of aggregate housegarden goods. This trend continues to be shown in this scenario, though there are differences as a result of more limited and dynamic labour availability. Compared to the variable price scenario, land use trajectories are dampened. Labour continues to be the binding constraint, as less labour may be allocated for farming in the presence of other opportunities.

The linear programming agent continues to act in extremes, now in terms of both land use and migration decisions. There is, however, a lag in migration due to the limited availability of off-site employment. For these agents, the general trend is one of emigration in the early years, then one of immigration in later years, as the market price of açai increases. For the particular household in the land use trajectories, non-farming employment replaced farming activities completely for a brief period, as housegardens were abandoned with no replacement. The price of housegardens soon increased, so farming of housegardens resumed, only to be replaced by açai soon after. Continued variability in the revenue gained from açai relative to the employment wage led this particular household to abandon açai cultivation briefly as well. Finally, as the market prices of açai rise, members are recalled and açai cultivation grows significantly.

The land use allocation of heuristic households appears more balanced. Various households differ in their particular land use choices, due to weighted random selection, but the typical household presents a balance between açai and housegardens. In contrast to the trajectories seen in the variable price scenario, heuristic households presented with non-farming labour do not necessarily tend toward açai despite its relative permanence. With dynamic and limited labour, both açai and housegarden cells become candidates for abandonment. Like LP agents, heuristic agents recognize the increasing value of açai cultivation and recall their agents. Unlike LP agents, however, they maintain a diverse landscape of both housegardens and açai. As the estimated shadow price of labour becomes close to the available wage, households begin to practice circular migration, as shown by the complex patterns in Figure 3 emerging toward the end of the simulation run. Due to the extreme behaviour and the exactitude of the linear programming method, this behaviour is much more difficult to model with optimizing households.

5 CONCLUSION

The decision-making method was shown to significantly affect the land use trajectories of household agents in this model. In separate simulation runs, two alternative methods have been implemented with the same objectives, environment, household demographics, wealth and information regarding prices and opportunities. The models differ only by the decision-making method. Rational optimizing agents have tended to act in extremes in this model, cultivating homogeneous landscapes of the more profitable good. In response to small changes in prices resulting in a newly optimum good, the linear programming agent chooses to shift an entire landscape of crops, irrespective of the small difference in profitability. Additional non-economic constraints such as risk aversion may be implemented to curb this behaviour. The heuristic method, on the other hand, adopts heterogeneity by design, since it uses weighted random selection. While the optimizing agent performs sudden shift in crops in response to changing prices more readily than the heuristic agent, the optimizing agent actions are far too extreme. The moderation practiced by the heuristic agent appears to be more a realistic response to small changes in price.

Although this paper presents a comparison between methods within a single model, the potential for stark differences in outcome call for a wider investigation into the choice of decision-making methods used in agent-based models of land use/cover change. The method chosen depends on

its application: Optimizing agents best describe economic agents, while heuristic methods may better reflect human decision-making. The heuristic method, unlike the optimizing solution, is not a black box. Rational optimizers have been argued to be black box reasoners, not necessarily due to their abstraction of underlying rules—the outcomes of which can be investigated through sensitivity analyses—but rather their inability to model cognitive processes [Gigerenzer, 2008]. The decision trees and stochastic choice used by agents in this model can be customized to best describe the true households in the applicable study area. Neither method is a one-size-fits-all solution, but the appropriate method is prescribed to be as descriptive as possible, especially if only one method is tested. Particular details of the method chosen may have undesired effects: In this case, the permanence of açai resulted in a long-term trend trajectory toward açai cultivation with heuristic households, due to the decision-making method used for land use selection. The evaluation of alternative methods allows researchers to better understand decision-making processes and potentially highlight deficiencies in underlying assumptions or implementation. Broadly speaking, without careful investigation, the chosen decision-making method has effects on model outcomes which may not be apparent during design or testing.

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