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Biocomplexity of deforestation in the Caparo tropical forest reserve in Venezuela: An integrated multi-agent and cellular automata model

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Abstract

A multi-agent model of social and environmental complexity of deforestation was developed for the Caparo Forest Reserve, Venezuela. It includes three types of agents: settlers, government, and lumber concessionaires. Settlers represent people of limited economic resources that deforest and occupy reserve land to grow crops and eventually claim property rights of this land. Their agricultural practices generate unintended environmental problems. The concessionaires extract lumber using management plans approved and monitored by the government. The agent model links to a cellular automata simulation of the natural system. Representational tools include Galatea (multi-agents), Actilog (rule description), and SpaSim (cellular automata). Three scenarios were explored for government policies: hands-off, pro-forestry and agro-forestry. Results agree qualitatively well with history of land-use change in the area. Old-growth forest is replaced by logged and secondary forest but the rate at which this transformation occurs varies by scenario. These results suggest that some of the agent's behaviours and forest management plans should change to promote sustainability of the forest reserve; e.g., broadening government's role to improve management plans and monitoring, and to prevent invasion of reserve land by improving living conditions of potential settlers outside the reserve. These and other alternatives will be modelled in future work.

Keywords: Biocomplexity; Multi-agents; Simulation; Deforestation; Tropical forests; Venezuela

1. Software availability

Name of software: GLIDER (simulation language and environment); it works under Windows and Linux. Developers: CESIMO and IEAC. Universidad de los Andes (ULA).

Contact address: Tel.: +58 274 2401116; fax: +58 274 2401115. E-mail address: sananes@ula.ve.

Availability: free download from http://afrodita.faces.ula.ve/glider.

Name of software: SpaSim; it works under Java Virtual Machine (JVM).

Developers: CESIMO (N. Moreno, M. Ablan), ULA.

Contact address: Tel.: +58 274 2402879; fax: +58 274 2402872. E-mail address: morenos@ula.ve.

Availability: free download from http://cesimo.ing.ula.ve/investigacion/proyectos/spasim/spasim/.

Name of software: GALATEA (it includes ACTILOG); it works on any Java Platform. Tested on Linux and Windows

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ME, NT, 2000 and XP (latest version of ACTILOG requires any PROLOG).

Developers: CESIMO and SUMA (J. Dávila, M. Uzcátegui, K. Tucci), ULA.

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Availability: in-house software for use in research and consultancy; see http://cesimo.ing.ula.ve/investigacion/proyectos/galatea/galweb/.

2. Introduction

The purpose of this study is to develop multi-agent and land cover models to help understand the biocomplexity of tropical forests, using as a case study the Caparo Forest Reserve in western Venezuela. The result is the BIOCAPARO model, which seeks to (1) understand the land cover dynamics that have occurred in the reserve, (2) simulate, through the development of scenarios, different land-use change policies, and (3) evaluate the implications of these policies for the sustainability of the forest reserve. These methods are very important tools that could help the preservation of Venezuelan forest reserves that have been subject to deforestation and degradation processes of considerable magnitude during the past decades (FAO, 2003; Centeno, 1997).

Biocomplexity means here the dynamic and complex web of relationships between human and natural ecosystems. This interaction is crucial in the field of integrated resource management where emphasis is placed on the sustainable use of the resources and resolving conflicting interests of stakeholders (CIFOR, 1999). Multi-agent simulation has been proposed as one of the tools for the study of ecological complexity (Bousquet and Le Page, 2004) and is increasingly used in environmental and ecosystem management (Hare and Deadman, 2004; Bousquet and Le Page, 2004).

In the framework of the taxonomic classification of models proposed by Hare and Deadman (2004), the BIOCAPARO model would be spatially explicit, with no social interaction and with agents that have multiple strategies for intrinsic adaptation. These agents have a belief-desire-intention (actually, belief-goals-preferences) architecture and the environment mediates their interactions. The main ecological process simulated is forest secondary succession, which is implemented as cellular automata model (Hogeweg, 1988).

Several different approaches have been reported in the literature to model deforestation. Most spatial explicit models are empirical, based on extrapolations of the patterns of change observed over the past, with a limited representation of the driving forces of this change (see for example, Mas et al., 2004). The combined multi-agent and cellular automata model presented here allows the representation of the human decisions that drive the land use/cover changes with the advantage of a spatial representation that is able to capture, at least in principle, the location and magnitude of the changes.

Examples of multi-agent models of tropical deforestation include: LUCITA (Lim et al., 2002), SYPR (Manson, 2002) and MameLuke (Huigen, 2002). Despite the fact that these models represent the same processes, they differ in their conceptual underpinnings. In the same manner as these other models, the primary agents of BIOCAPARO model are the colonists or settlers: people of limited economic resources that practice slash and burn agriculture and that arrive at the reserve aiming to improve their economic status and to obtain the property of the land that they have occupied. However, in the Caparo case study the settlers are illegal occupants of the forest reserve. This, together with the difficulties of accessing the site makes it difficult to conduct direct surveys of the settlers. For this reason, the agents are modelled using information from results of previous research (Sánchez, 1989; Rojas López, 1993; CESIMO, 1998).

This study is part of the larger project ‘‘Biocomplexity: Integrating Models of Natural and Human Dynamic in Forest Landscapes across Scales and Cultures’’ that includes another forest reserve in eastern Venezuela and two sites in Texas, USA (Acevedo, 2003). The explicit modelling of human actions and their interaction with ecosystems will provide policymakers information about the impact of their decisions on the future composition, structure, and functionality of local ecosystems. It will also facilitate a more informed analysis of the long-term consequences of private choices and public policies on the natural systems in which human systems are embedded and with which they interact (Monticino et al., 2004). It is also hoped that these models will provide the foundations for a unified process theory for agent-based simulations of biocomplexity.

In the following four sections, we provide a brief description of the Caparo Forest Reserve (CFR), the model agents, the interactions between agents and the environment and the model implementation. The last two sections present the results, conclusions and comments on future work.

3. Study area and conceptual model

According to the Holdridge classification, the forests of the Caparo Forest Reserve (CFR) are in the transition between dry tropical forest and humid tropical forest. The CFR was created in 1961 and its original purpose was to support the development of the logging industry in the zone, while preserving one of the more productive forests of Venezuela (CESIMO, 1998). It is located southeast of the Barinas State, in the Venezuelan western plains region. Its extension is 176,434 hectares (ha), and it has been divided into three units to facilitate its management (Fig. 1).

The study takes place in Unit I, an area of 53,358 ha, which itself includes a special area called the experimental unit, which is used for research and educational activities. Currently, only 7000 ha of forest remain in the reserve and it is all located in the experimental unit. Nevertheless, this area is still not exempted from deforestation due to the agrarian settlement process.

Many factors have contributed to deforestation in the CFR: forest management practices that did not attempt to preserve the ecological integrity of the forest of some lumber concessionaires; contradictions between different governmental

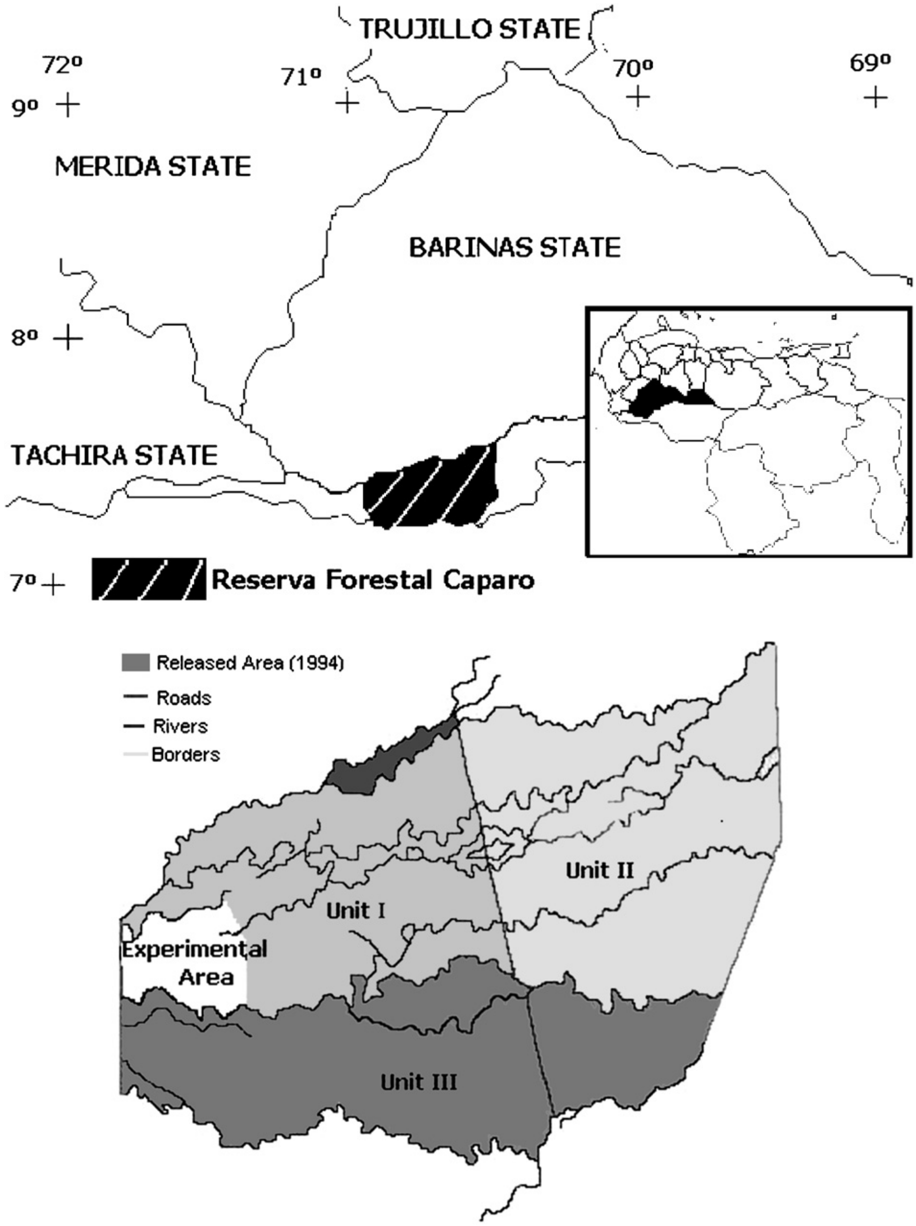

Fig. 1. Relative location and management units of the Caparo forest reserve. Adapted from Jurgenson (1994).

organisms; poverty; demand of lands for agricultural activities; and the existence of political interests in favour of settlements (Ablan et al., 2003). The BIOCAPARO model captures the ''First Stage'' or ''Primary Cycle'' of the agrarian settlement process of forest reserves in the Venezuelan western plains described by Rojas López (1993). In future research we will include the two other stages described by Rojas López (1993).

During the first stage or primary cycle, a settler takes possession of a parcel of land in the reserve and practices subsistence (i.e. slash and burn) agriculture. This surface can be uncultivated land (previously deforested and unoccupied) or can be forested land (deforested by the settler). Typically, within five years the soils are exhausted, and the harvests are no longer sufficient to sustain the settler and his family. Some settlers try to expand their farms at the expense of new deforestation. However, sooner or later, they will end facing the same situation.

The ''Second Stage'' or ''Land Market Cycle'' consists of seeding pasture to avoid soils exhaustion, and later to sell these improvements to landlords or other settlers. After selling these improved lands, settlers can buy new land from other more recent settlers, or just return to initiate a new primary cycle of invasions and work for the landowner that has bought the land. This second stage continues with three processes: (1) the pasture retailers and landowners acquire the improvements of primary settlers; (2) cattle ranching dominates the land use; (3) the property of the parcels is transferred to the settlers, by application of the Agrarian Reform, and then they are sold at very low prices, to the landowners, politicians, military officers and cattle dealers who urged and supported the original settlements (Centeno, 1997).

The third stage, ‘‘Cattle Ranch Consolidation’’, leads to cattle ranching as the main activities in previously forested land. Ranchers buy deforested land rights from the settlers and expand pasture land-cover for cattle grazing to a greater extent, typically under a holding corporation. This process, characterized by the concentration of the property, forces the initial group to move towards primary cycle settlements or to wage-earning work (Sánchez, 1989).

4. The agents

Because the current version of the model emphasizes the primary cycle, it includes one hundred settler agents, but only one concessionaire agent and one government agent. The following is a description of the most important characteristics of the agents implemented in the models.

4.1. Settler agent

The settler agent behaviour corresponds to the one described in the first stage of the conceptual model. Furthermore, there is a settlement function that considers those sites that are more attractive for the settler agent: land-uses without monitoring, such as plantations, secondary shrubs and fallow. At the same time, this function models the movement of the settlers using buffers weighted by distance around rivers, borders and roads since they represent the entry points in the reserve. In the model, 100 settler agents were introduced in different initial locations. During the simulation they differ in extent and duration of occupation as well as their effects on the forest environment.

4.2. Concessionaire agent

The lumber concessionaire agent represents private companies that extract lumber following management plans in the reserve areas under the monitoring of the government. The concessionaire agent implementation assumes a simplified and hypothetical forest management within the reserve: it extracts trees and plants commercially valuable species; furthermore, the concessionaire is in charge of forest plantations monitoring during the first two years after plantation (Ablan et al., 2003).

When the concessionaire finds a settler on its concession, it continues to work at another site that is not occupied by settlers, but there are two alternative behaviours implemented: one, used under the hands-off policy, is to ignore the settler. The other, used under the pro-forestry and agro-forestry scenarios, is to inform the government about the settlements. The three policy scenarios will be described in the following section.

The implemented concessionaire agent operates under a 30-year logging cycle and it is allowed to harvest 1200 ha annually from a set of ‘‘compartments’’ that rotate sequentially on an annual basis. After the concessionaire acts on a site, the use of land is changed to ‘‘logged forest’’. Once the 30-year cycle is over, the concessionaire could harvest the first compartment again.

4.3. Government agent

Three different behaviours or scenarios were implemented for the government agent. These behaviours represent possible roles of the government at the CFR, which in fact have been in place during the past years. Their specification is as follows.

The government neither interacts nor interferes with the activities of the other agents. It does not have any monitoring activity. This is called the ‘‘hands-off’’ government scenario or model.

The government has a ‘‘strong’’ policy to keep settlers away from protected forest areas (the ‘‘pro-forestry government’’). This agent has a monitoring process where any settler founded at the CFR area is evacuated. Furthermore, if the concessionaire agent, on its extraction process, finds a settler in the zone, the government agent receives the settlement’s information from the concessionaire and the indicated settlers will be removed from the CFR area in the next government’s monitoring process.

The government has an ‘‘agroforestry’’ policy, which means that it monitors the forest area trying to protect it; when he finds a settler, the settler will be relocated to a special area for agricultural activities. At the same time, the government agent receives settlements’ information from the concessionaire agent and the indicated settlers are relocated.

The ‘‘pro-forestry’’ and the ‘‘agroforestry’’ governments evaluate the concessionaire’s exploitation and plantation quotas. The concessionaire permit is revoked for three years in case of failure to comply with the agreed quotas.

Monitoring is based on a function that considers the places that are more attractive for settlements (buffers around rivers, CFR borders, and roads).

5. Agents’ interactions with the environment

Land use change is modelled as cellular automata (Hogeweg, 1988) based on a Moore neighbourhood, i.e., eight adjacent cells for every target cell (Zeigler et al., 2000). State transition rules are simplifications of the ecological dynamic of forest succession at the CFR using six layers:

1. Land-use layer: each cell can be in any of the fifteen states (the ten states described in Fig. 2 plus five permanent states such as roads, rivers, wetlands, etc.).
2. Time in use layer: used as a time count layer that indicates the time that a cell has spent remaining at a determined state.
3. Population layer: each cell can be in some of the following states: 0, an unoccupied cell; 1, there is a settler occupying the cell; 2, there is a landowner occupying the cell.
4. Supervision or monitoring layer: each cell can be in one of the following states: 0, represents an unwatched cell; 1, indicates a watched cell.

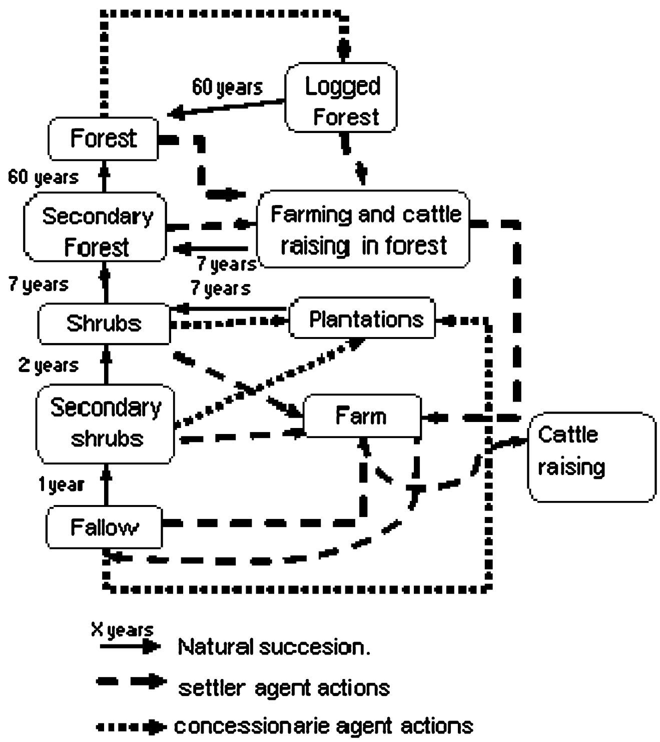

Fig. 2. Land use transition graph showing agents' interactions with the environment.

5. Settler identification layer: the cell in this layer will have the identification number of the settler if a settler occupies the cell.
6. Compartment layer: it indicates the compartment's sequence to be followed by the agent concessionaire in his exploitation process.

The natural succession dynamics is simulated so that a given cell remains in the same state until the required transition time, as indicated in Fig. 2 by the straight lines arrows, is achieved. In absence of agents' actions, the system path will be that indicated by natural succession. Permanent states are: flood riverbank, seasonal wetland used for cattle grazing, rivers, roads, livestock, and farming.

The interaction between the settler agent and the environment is described as follows:

- A settler agent can settle a farm on a cell that is unoccupied and without monitoring. Certain land-uses are preferred for the initial settlements, and once the settler is established, it will change the land use to adapt it to its agricultural activities.
- A settler agent can expand its occupation at neighbouring cells that are unoccupied or without surveillance.
- After a mean time of five years, the soils are exhausted, and then the settler agent moves to another place inside the CFR.
- Once the settler leaves the place, the land use is changed to fallow.

The concessionaire agent interacts with the environment in the following ways:

- To exploit the forest, the concessionaire agent needs an unoccupied cell with a land use equals to forest. Then, the land use is changed to logged forest.
- To reforest, the concessionaire agent needs an unoccupied cell with a land use equals to fallow or secondary shrubs. Then the land use is changed to plantations.

6. Implementation

6.1. Computational tools

The agents are codified using Galatea's agent library and languages (Uzcátegui, 2002), while land use change is modelled as cellular automata representing a simplified account of the dynamic of the environmental system. The cellular automata model is implemented using the SpaSim library (Moreno et al., 2002). Both, the libraries and the model are encoded in Java.

SpaSim allows the specification, simulation, visualization and analysis of spatial models in the same environment, using a user-friendly interface while providing at the same time considerable flexibility. Square cells are used to keep compatibility with raster geographic information systems (GIS). It also includes simulation techniques such as cellular automata, spatial analysis, spatial-temporal analysis, and maps visualization (Ablan et al., 2003). The method employed to combine the simulator (SpaSim) with the tool that implements the agents (Galatea) is presented in Moreno et al. (2002).

The spatial extent of the model corresponds to unit 1 of CFR (53,358 ha.). The spatial resolution corresponds to cells of 4 ha. A six months time step is used. The agents changed the rules of evolution of the cellular automata, as explained in Fig. 2.

Galatea (Uzcátegui, 2002) is a multi-agent simulation platform that nicely fits with SpaSim (Moreno, 2001) for the sake of an integrated spatial, agent-based simulation model. Galatea provides a collection of classes to model reactive and rational agents, with a scalable, logic-based, inference engine which will eventually allow the agents to perform meta-reasoning, of the kind required to reason about other agents' reasoning. For the time being, however, the agents are more of a reactive kind, with behaviours that can be modelled by means of generalized condition-action rules (Dávila, 2003; Dávila and Uzcátegui, 2004).

The simulation method employed here combines the simulator Galatea with SpaSim, using the class NodeCellularHistory of the SpaSim-lib to define the environment and its natural evolution in terms of cellular automata. It uses the class Ag of Galatea to define the social agents of the model. The simulation results were stored in the database of the SpaSim and analyzed directly with this tool.

To detail settler agent's rules the approach of this paper uses Actilog: a language for writing generalized, (condition → action), activation rules. The semantics of the language are based on the assumption that implications (conditional goals) can be used to state integrity constraints for an agent. These integrity constraints describe conditions under which the agent's goals must be reduced to plans that can be executed (Dávila, 2003).

6.2. Agent modelling approach

The methodological path tries to embed as much behaviour as possible with simpler agent models in such a way that extensions, such as those required for meta-reasoning, remain computationally feasible. This is why this research has first developed simplified agent models, testing for their expressiveness and evaluating their validity progressively. In this respect, it coincides with the work done by Monticino et al. (2004) for the Texas study areas of the same biocomplexity study.

However, the BIOCAPARO model is not formulated using decision theory, but attempts to be of a more general nature. One of the reasons for this is that, even though decision-theoretical approaches have the advantage of their straightforward psychological interpretation, the same advantage can be achieved with logic based models, without using numerical estimates of the utilities of the potential consequences to compare alternative courses of actions and select the preferred ones.

Logic-based agents bring to this problem an important resource. The combination of object and meta-logical languages allows access to domain-specific, context dependent information and, within the same language, to the inference rules that characterize the reasoning mechanism of the agent. Thus, the logical language allows for description of a more complex reasoning mechanism where the control on the inference rule is tailored to the requirements of the application, e.g. planning and explanations (Pino and Uzcátegui, 2003).

Logical languages can be as effective as decision theory for the purposes of preference representation. To see this, consider that a preference is a relationship between two courses of action: one is preferred before the other. In decision theory the modeller establishes a total order of preferences by computing a preference value for each action. However, using a logic-based approach, preferences can also be represented by partial order sets, which allow for pair of actions that are not related (Pino and Uzcátegui, 2003). A partial order set, a mathematical structure with a set of elements and a ordering relation among "some" of them, can represent a total relation when the application so requires (i.e. taking "all" and not only "some" of the possible combinations of the elements).

As Actilog rules can trigger actions leading to different goals, the agent must have some way of choosing the most urgent and useful ones. The agent can perform some kind of ordering or priority setting, based on the urgency of each task and according to some quantitative or qualitative measurement of the usefulness, utility or likelihood of that plan to achieve the goals. In this first version of the BIOCAPARO model and for the sake of simplicity, all tasks are urgent and a usefulness measurement was not implemented. The model will be expanded to allow for means to represent other preferences between actions in a plan (the urgency criteria) and between actions (the usefulness criteria).

6.3. Towards a qualitative formalization of preferences

Simon's bounded rationality was an attempt to go beyond the limitations of previous models of rationality in traditional economic theory. Simon (1955) thought that rationality assumption made severe demands upon the choosing agent because of the need to attach definite "pay-offs" to each possible outcome of its actions. This implies that the outcome should be precisely defined and that pay-offs must be completely ordered, i.e. the agent is assumed to be omniscient with respect to its preferences.

One of the main concerns inspiring the methodology used in the BIOCAPARO model is the desire to overcome the "omniscient agent" problem, albeit in a different sense. The idea is to capture the notion of an agent that cannot reason about all the consequences of its beliefs because of its limited resources to compute them. It is encouraging to find out that the BIOCAPARO model can incorporate all the notions in Simon's rationality and allow for qualitative criteria and subjective preferences.

Although the BIOCAPARO model is simple, future expansions will be able to incorporate much more of the complexity of decision making in this domain and presenting the agents as fully qualified economic agents, at least in Simon's sense.

7. Results

For each one of the three government scenarios implemented, the model was run for 65 years, because this was the estimated time required to observe a transformation from a logged forest into a regenerated mature forest. The initial state of the CFR corresponds to the land-use reported in Pozzobón (1996) for the year 1987. Rather than predicting the land use for the year 2052, the time horizon of the model was chosen to fully observe the implications of the different scenarios on the land use at the CFR.

Simulation results are portrayed as maps that show the spatial distribution of land-use types obtained in each of the scenarios at each time step. An illustration in Fig. 3 shows the resulting maps at the end of the simulation for each one of the policy scenarios. The spatial pattern is more homogeneous and less fragmented in the pro-forestry scenario and more heterogeneous and fragmented in the hands-off and agroforestry scenarios. The agricultural intrusion in forest areas is more noticeable under the agroforestry scenario, due to widespread agricultural activities.

In all the scenarios the original forest is replaced by logged and secondary forest. The results by scenarios differ in the rate at which this transformation occur and in the relative influence of the concessionaire and the settlers in the land use change. In the hands-off scenario, the concessionaire rapidly exploits the forest making the dominant land-use logged forest. In the

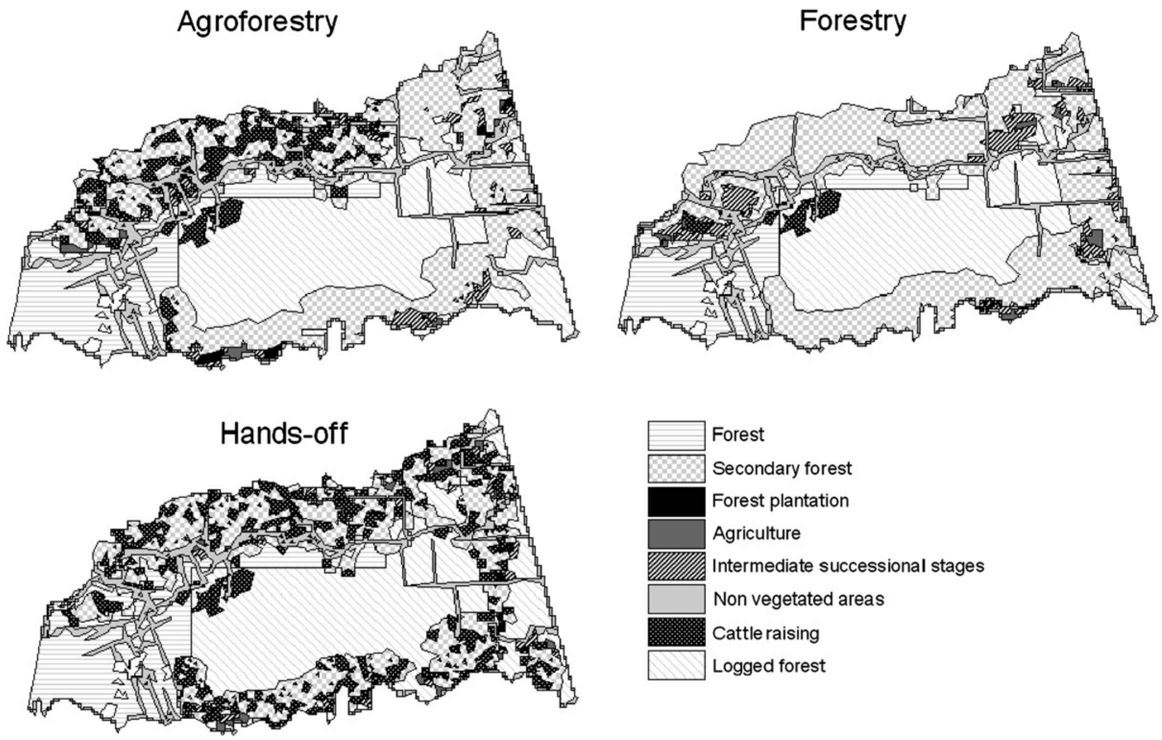

Fig. 3. Simulation results at the end of the 65 years run for each type of government.

pro-forestry government scenario, the rate of lumber extraction by the concessionaire is reduced by the intervention of the government and after 40 years of simulation the secondary forest, product of the settlers actions start to dominate.

In the agroforestry government scenario there is a mix of both of the previous behaviours: at the end of the simulation in the protected areas, the forest has been converted to logged forest, but in the area reserved for agricultural activities, the settlers have left and the landowners have occupied those areas for cattle and ranching activities.

In order to verify the output of the model, the scenarios were compared using several spatial-temporal metrics such as: average time of an area under a given land use, number of times that a cell is visited by a settler and dynamics of the percentage of the total area in a given land use.

For the purpose of illustration, some examples of these metrics are presented here. The average time that a cell remains in agricultural use (farm state in the cellular automata) varies by scenario. This time is a minimum (1.9 years) in the pro-forestry policy scenario because the settlers are evicted from the CFR even before the fertility of the land has been exhausted and it is a maximum (3.2 years) in the hands-off policy scenario where the agents have not other restriction that the one provided by the fertility of the land. The time is intermediate (2.3 years) for the agro-forestry policy scenario.

Fig. 4 shows the percentage of the forest area in each of the scenarios. It is interesting to note that regardless of the scenario, sooner or later the percentage of the forest that remains reaches a minimum non-zero value. This is explained by the fact that only the experimental unit remains untouched at the end of the simulation run. Although this may seem drastic, it is hardly unrealistic since currently the only remains of the original forest are found there. In fact, it is expected that this minimum value would be achieved even earlier with the implementation of the landowner agent and a dynamic number of settler agents.

The maximum number of times that a settler holds a cell is two for all scenarios. In average, this number is greater in the pro-forestry scenario since a greater pressure is exerted on the non-protected areas by systematically evicting the settlers from the reserve.

At the end of the simulation, the percentage of the total area in agricultural use in all the scenarios is less than 2%. In both the hands-off and agro-forestry scenarios, areas under agriculture are replaced by pasture for cattle grazing.

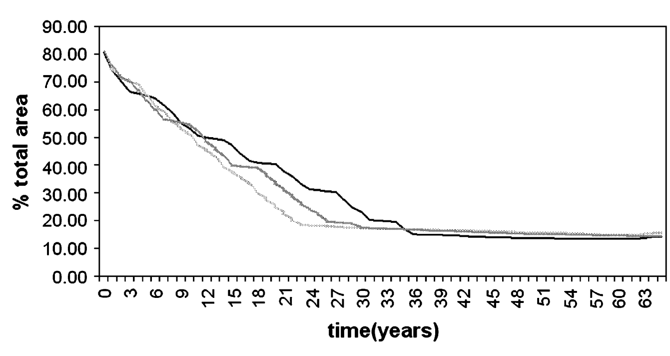

Fig. 4. Percentage of total forest area of mature forest for the three scenarios of government policy.

8. Conclusions

The BIOCAPARO model is a good representation of this natural-human system since it includes many of the important characteristics described in the conceptual model of colonization:

- Heterogeneity: the model incorporates different agents with diverse goals, resources and behaviours. Also the environment where these agents interact is heterogeneous.
- Spatial interdependency: the behaviour of the agents is influenced by their relationship to neighbour agents, competition over space and information flows.
- Temporal interdependency: the agents' decision making process is influenced by their past actions and by decisions of other agents.

The model was evaluated by qualitative comparison of the results to the known history of land use change in the area. Once all the cycles of the conceptual model of colonization are implemented, more quantitative validation will be undertaken using landscape indices (e.g. Turner et al., 1990) to compare simulated with actual land use maps. Nevertheless, as stated by many authors such as Parker et al. (2003) and Bousquet and Le Page (2004), validation of agent based models poses important open challenges that are subject to further discussions and research.

Simulation results agree qualitatively with what is now known about land-use change, tropical forest succession and forest management in the area. Contrary to what was believed a few decades ago, it takes vegetal succession in tropical forests relatively long periods to fully recuperate its original state, both in volumes of wood and in floristic diversity. For example, Guariguata and Ostertag (2002) and Gómez-Pompa and Vázquez-Yáñez (1985) state that the process leading to the reappearance of the initial forest species could take around a hundred years. Our results corroborate that a 30 year cycle is too short and would compromise the availability of the forest's resources in the future, just as Martínez-Angulo (1955), Lamprecht (1956: cited by Kammescheidt et al., 2001) and Veillon (1971) had warned. In this first version of the model, with only the primary cycle of the colonization implemented, the forest concessionaire has the greatest influence in changing the original forest. As explained above, the cattle-raising state replaces the farming state in the hands-off and agro-forestry scenarios, despite of the fact that the landowner agent has not been implemented yet in the model. In its place there is a coarse approximation that assigns to a cell the cattle raising state thirty percent of the times that a settler abandons an area. This remains to be validated in future developments of the model.

Although many important processes are not implemented yet, it is clear that none of the scenarios result in a sustainable use of the forest. One of the challenges to undertake in the future is to design realistic scenarios that do lead to sustainability. Another related challenge, which is also being contemplated, is the use of the Agent models in "reverse" to infer (automatically or semi-automatically) the rules of behaviour that could lead to sustainability.

Simulation results suggest that agent behaviour need to change in order to promote the sustainability of the forest. For example, the regulatory role of the government could be strengthened and broaden. In the current implementation, the government oversight of the concessionaire is limited to the verification of exploitation and plantations quotas. Even a "perfect" concessionaire, one that always meets the required quotas, will cause forest degradation because of short cycle management plans. It seems necessary for the government to evaluate characteristics of the condition of the forest such as forest fragmentation and recovery times to decide upon continuation of permits and lengthening of cycles.

As another example, agent behaviour would have to change to prevent the never ending cycle of new invasions. Alternatives could include providing technical and financial agricultural incentives to potential settlers in land outside the reserve and incentives to participate in forest conservation and thus prevent deforestation. These challenges and the following items will be included in future research:

- Population growth of settlers will be represented in the future version of the model, in order to incorporate the influence of government policies.
- The landlords will be implemented explicitly as agents. This will increase model realism by including key agents' interactions, such as expanding ranch land and acquire settler improvements. Alternatives for this agent behaviour change will also be studied to search for forest sustainability.
- The government agent will implement a more detailed evaluation of the concessionaire performance; measuring beyond exploitation and reforestation quotas.
- The ecological realism of the cellular automata will be improved by estimating its parameters from detailed gap-model simulations, as in Acevedo et al. (2001a,b), and Monticino et al. (2002).
- Implementing a concurrent version of the model on top of a parallel Galatea, to cope with an expected increase in computational complexity.

Details of the work and future developments can be found at the project webpage: http://cesimo.ing.ula.ve/investigacion/proyectos/biocomplexity/.

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