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Articulating land and water dynamics with urbanization: an attempt to model natural resources management at the urban edge

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Abstract

In a rapidly urbanizing world, population densities no longer allow for unlimited access to safe water. Competition for water, often associated with competition for the access to land, tends to be exacerbated in peri-urban areas. The objective of this paper is to propose a multi-agent model prototype to represent the relationships between urbanization dynamics and land and water management in a peri-urban catchment area. A spatially explicit pilot model was developed using the Cormas platform. This prototype deals with a catchment that is the main drinking water reservoir and spring of a metropolitan area, and is subjected to high urban pressure and problems of pollution connected to land use and rain. The combined use of cellular automata, spatialized passive entities and communicating agents allows the articulation of the connections between hydrological processes (water cycle, pollution), land-use changes and urbanization. However, the representation is based on simplified dynamics and further work is needed to develop a simulation model that could be used as a discussion tool for land and water management at the urban edge.

Keywords: Water resource management; Peri-urban interface; Land use changes; Multi-agent modelling

1. Introduction

The Alto-Tietê catchment committee, the body in charge of water management in the metropolitan watershed of Sao Paulo (Brazil) that includes some 18 million inhabitants, identified five main management issues for the next 10 years (FUSP,

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2000). They are: urban land occupation versus degradation of water resources in the spring area of the catchment; intersectorial competition, especially conflicts between urban and hydro-electricity use or agricultural use in the upstream catchment; management of flooding; and inter-basin conflicts. All these issues, except for the last one, are rooted in peri-urban dynamics, characterized by an increased pressure on natural resources, and the evolution of economic activities (new activities, diversification of income), of migration, and of land use—this last process being itself constrained by natural vegetation dynamics (Adell, 1999).

Management of water resources at the urban edge is a common challenge in our rapidly urbanizing world. The expanding urbanization in developing countries dramatically affects water resources in terms of quality (physical, chemical, biological pollution, etc.) and quantity. This leads to competition for water, associated with a competition for access to land, which is exacerbated in peri-urban areas. In this context, management of water resources supposes the ability to articulate the biophysical processes (pollution of soil and water, hydrological processes) with social dynamics (migration flows, urbanization, land and water management rules, and urban, rural and environmental policies), while taking into account the legal and institutional constraints of peri-urban areas.

For several years, agent-based modelling (ABM) has been used in the field of natural resources management to facilitate the understanding of complex systems by allowing the simulation of their functioning on computers. In water resources management, different types of ABM have been developed. Thoyer, Moradet, Rio, Simon, Goodhue, and Rausser (2001) describe simulations about negotiations between diversified water-user groups, at the scale of the catchment basin, from an economist point of view. Moss, Downing, and Rouchier (2001) is focusing on the representation of household responses to water demand policy, with emphasis on social behaviour. Other models are dealing with water allocation in irrigated schemes (Barreteau., 2000; Becu, Perez, Walker, & Barreteau, 2001; Le Bars, 2001). These models are stressing (1) interactions between two types of agents (farmers and water suppliers or managers) and (2) cropping pattern determination at the farm level, linked with water consumption at the plot level. Land-use change models, for their part, are based on specific procedures for land allocation either in agricultural areas (Balmann, 1997) or urban areas (Torrens, 2001).

The objective of this paper is to describe a first prototype of an ABM built to represent the relationships between urbanization dynamics and water management in a peri-urban catchment. The question addressed—in the context of Latin American peri-urban catchment—is how to spatially represent the hydrological process, as a continuous flow, and its dynamic in time and space, with more specific spatial processes such as land-use changes and human settlement expansion while taking into account their social, economic and management aspects.

In the first section, the mean features of water resources management in peri-urban areas of a metropolitan catchment are presented. This review of water management processes at the urban perimeter contributed to the selection of the processes and interaction to be represented in the prototypes. The second section presents the modelling platform used to develop the prototype. The third section gives an overview of the prototype and the way the different processes were represented within an ABM structure. The final section discusses the interest in, and limits of, this prototype.

2. Peri-urban interface and water resources management

Most of the poverty in less-developed countries can be found in the immediate surrounding areas—the peri-urban interface—of their rapidly growing cities where already most of their populations are concentrated. This is the case of many cities in Latin America, where 70% of the population is concentrated. While there is still no consensus on the definition of peri-urban interface, it appears to be characterized by: (1) a ''patchwork structure'' in terms of functions, values, strategies of occupation of the territory, or appropriation and transformation of natural resources; (2) a dynamic pattern with a wide range of transformation and flows (people, goods, income, capital, natural resources such as water, energy, and building materials); (3) the new economic opportunities it provides to peri-urban dwellers such as land speculation, or informal activities linked to mineral extraction, etc. (Allen, Da Silva, & Corubolo, 1999). This ''patchwork'' structure applies to the type of land-use occupation that ranges from urban infrastructure to strictly rural and agricultural uses. Thus, land-use changes combine different processes: conversion from non-urban (rural and/or natural) to urban activities; loss of farmland; and development of special infrastructure, due to appropriation of land and changes in property rights (Maxwell, Larbi, Lamptey, Zakariah, & Armar-Klemescu, 1998). But in the cities of the developing world, the access to land by low-income groups is mainly possible though illegal channels. They tend to occupy low-value land, generally environmentally unsuitable (highly sensitive to risks such as earth slides and pollution impact on hill slopes and marshlands, etc.) and vulnerable to floods and other hazards (Baroos & Van der Linden, 1990; Douglass, 1992). Land-use changes at the urban edge are thus linked to a combination of diverse land market mechanisms that range from speculation to illegal occupation. Illegal settlement in these areas are characterized by a lack of basic infrastructure and public facilities—access to electricity, public transportation, rubbish removal, safe water, and sanitation systems (Brennan, 1994). Illegal settlements are thus associated with major non-point pollution flow sources, either caused by microbiological/nutrient pollution, litter and sediment transportation, or habitat destruction.

On the other hand, the peri-urban interface provides specific hydrological functions to a city—a catchment area and space for drinking water reservoirs—and supports groundwater recharge zones and absorbs rainwater. Its dynamics thus affect the hydrological processes of large areas through the alteration of the natural hydrological network, the expansion of the impermeable surface, and the pollution of surface and subterranean aquifers through industrial activities and inadequate sanitation/wastewater management (Dourojeanni & Jouralev, 1999). In this interface, urban water competes with other needs such as irrigation or environmental/recreational use. In the developing world's rapidly growing cities, competition for access to land and water in peri-urban areas tends to be exacerbated, because of the wide range of users, the rapid growth of shantytowns with inadequate sanitation arrangements, the difficulty of access to running water, and increased polluted run-off. These processes directly affect the water quality in drinking water reservoirs and aquifers (Baykal, Tanik, & Gonenc, 2000). In many metropolitan centres, these tensions are already leading to water use restrictions and open conflicts, as in Sao Paulo (Brazil) (Braga, 2000).

Conflict resolution tends to be difficult in the institutional landscape of water management in peri-urban areas, characterized by the traditional dual (urban/rural) focus of the institutions, the disconnection between land and water management policy, institutions, and intervention levels, and the implementation of specific protective legislation and rules, in a context of uncoordinated metropolitan planning. These policies are currently being revised to take into account changes in international paradigms in water management as well the development of decentralized municipal management. The changes emphasize the need for more participative and integrated management processes that will take into account the needs of all stakeholders and water users. A decentralized municipal policy aims at better integration of the local specificities of the edge districts of mega-cities. The policies propose to take into better account the water management and municipal management needs of the marginalized communities at the edge such as surrounding municipalities and peri-urban communities. In Brazilian mega-cities, these include shantytown communities and peri-urban small farmers that traditionally have rarely been included in city or catchment planning.

Management of such complex and dynamic systems must be able to build a joint representation of the hydro-social functioning of the catchment. Agent-based models were tested in this kind of approach in other types of ecosystems and proved to be interesting tools in the initial stages of the approach (Bousquet et al., 2003). The modelling work is viewed as a way to structure representations and exchanges, and to facilitate discussion and learning processes. In this feasibility test, we chose thus to focus the agent-based prototype on the relationship and interaction between urban and agriculture land and water users in the peri-urban interface. These interactions were supposed to be mainly determined by market processes (legal or illegal) for land-use changes, and by competition for water availability by urban demand, agriculture irrigation and pollution.

3. Agent based modelling, natural resources management and urban phenomena

In computer sciences, an agent is an autonomous decision-making entity that senses, deliberates internally, communicates and acts (Ferber, 1999). One of the main reasons why ABM is becoming more popular in the developing field of research dealing with modelling artificial societies is its ability to conceptualise entities in natural resources management (Epstein & Axtell, 1996). This explains the need for simulation tools to facilitate the modelling of social dynamics in a spatially explicit context (Grimm, 1999).

Cormas[1] is a multi-agent simulation platform specifically designed for natural renewable resource management. It is a framework, based on the object-oriented language Smalltalk, aimed at facilitating the design of ABM to focus on interactions between groups of agents (stakeholders) using a common resource in specific ways. A recent example of such ABMs built with Cormas describes the hunting activity performed by social networks of villagers to catch small antelopes in the forests of Eastern Cameroon (Bousquet, LePage, Bakam, & Takforyan, 2001). In the most basic case, the resource commonly used by the agents is simply the land (i.e. the spatial support), but this common resource may also have its own natural dynamics.

Designed as a tool for exploring, through simulation, the interplay between social and natural dynamics, the entities used in Cormas are: (1) situated agents that interact and communicate, their interactions being mediated either through a spatial support or via messages sent to other agents and delivered in their mailboxes; (2) cells defining the topological support of the situated agents, a cell representing the smallest homogeneous portion of the environment (Bousquet, Bakam, Proton, & Le Page, 1998).

As the standard spatial support provided by Cormas is a regular spatial grid, there exists a strong similarity between a cellular automata (CA) model and the way natural resources dynamics are implemented with Cormas. The originality of the platform arises from a hierarchical organization of compound spatial entities defined as aggregation of cells (Le Page, Bousquet, & Etienne, in press). These entities, as well as a set of methods to manipulate them, exist as generic functions in the platform, and are used to specialize by inheritance spatial entities specific to particular applications. The utility of defining dynamic spatial entities at several levels appears when: (1) some natural dynamics are more easy to describe at a specific spatial level; (2) the information available to describe the processes has been gathered at a particular spatial scale; (3) the way an agent of the model (representing a stakeholder of the real system), performing its specific actions, is strongly related to a specific "management unit".

In urban simulation, CA have been more commonly used than ABMs, which are classically restricted to situations where the mobility of the entities has to be explicitly taken into account. Yet the critical element in urban phenomena is the human agent. Individuals, households, firms, public institutions, etc. act according to their own decision rules They are all engaged in a very complex system, with different organizational levels, in which they evaluate economic and non-economic alternatives (Torrens, 2001). Thus it seems promising to develop an ABM where the basic spatial dynamics would be managed by an incorporated CA layer, while the behaviours of the stakeholders and their decision-making processes would be written as internal methods of agents. This general organization is precisely the standard architecture of a Cormas model.

[1] Common-pool Resources and Multi-Agent Systems (Website: http://cormas.cirad.fr).

4. The case study

The context of this study concerns a catchment submitted to high urbanization pressure and hosting one of the main drinking water reservoirs plus the natural spring area of a metropolitan city. This theoretical case study was inspired from the spring areas of Sao Paulo city (Brazil). Urbanization in this catchment consists mainly of the expansion of shantytowns with inadequate sanitation arrangement that contributes to high pollution rate in surface waters. For example, in the Guarapiranga catchment of Sao Paulo, the pollution rates due to domestic sewage represent 96% of the total charges in dry weather and 40% in rainy times (42% resulting from diffuse urban polluting source and 11% from agricultural sources; FUSP, 2000). In the rural part of the catchment, agricultural use of land represents only one third of the area, because of an important demand for recreational use of land, and an agricultural crisis. Agriculture relies on small farming systems with a nucleus of intensive agriculture, irrigated through individual pumping. Some polluting industrial sites are directly responsible for pollution of surface waters. The spring area is part of the remains of a tropical forest and its protection is being promoted by means of a national park. The catchment is responsible for 20% of the drinking water of the metropolitan area. The prototype model has the following features:

- Water resource systems in the catchment include river flows, in terms of quantity and quality with a specific attention given to the reservoir. Domestic water use was restricted to the reservoir; agricultural and industrial water use is possible from the surface water network.
- The origin of the pollution is linked to land-use habits in the catchment, while its transfer in the catchment (surface run-off, river flow) are linked to the hydrological processes described earlier.
- Land market dynamics in the rural part of catchment have been modelled in order to demonstrate their consequences on the urbanization progress.
- The management of water resources and land was represented by three mechanisms: land market procedures, land use/cover choice, and reservoir management.

5. Overview of the prototype

The model presented later is a prototype that has been designed to test the validity of the approach and provide insights into the potential contributions of this agent-based modelling approach to understanding the urbanization process in a peri-urban catchment. This section intends to give a general overview of the structure of the model, but not all the implementation details. A copy of the Cormas model with the Smalltalk code is available on request.

5.1. The virtual landscape

A 90 km^2 catchment was represented in a 60×50 regular spatial grid. The unit cell corresponds then to a 3-ha land plot. To create an archetypal landscape, each cell initially received a unique value of land cover among the eight following possibilities: reservoir, river, favelas, residential building, industry, tourism infrastructure, irrigated crop (horticulture), and non-irrigated crop (cereals). Cormas provides the possibility to "paint" areas to assign values directly by mouse-clicking, as well as possibilities to export a spatial grid, including topological properties together with values of selected attributes of the cells. Once the user has achieved the design of a particular spatial grid, he/she should then export it so that all the simulation experiments could start from the very same initial spatial configuration. The archetypal landscape that is used by the prototype is displayed in Fig. 5a.

Taking advantage of the spatial facilities provided by Cormas, three different kinds of spatial entities have been defined. Fig. 1 shows a class diagram for the spatial package of the model. The formula used is named UML for "Unified Modelling Language". Simple arrows represent "inheritance" relationships: the arrow goes from the specialized class up to the generic class (also called superclass). Arrows with diamonds represent "aggregation" relationships. The different entities used are more specifically described in Tables 1 to 4.

The "Cell" entity is simply a square piece of land representing 3 ha and holding an initial value of land cover to be used to initiate the other spatial entities. "Plot" and "HydroSegment", categorized as "passive" entities as per the superclass from which

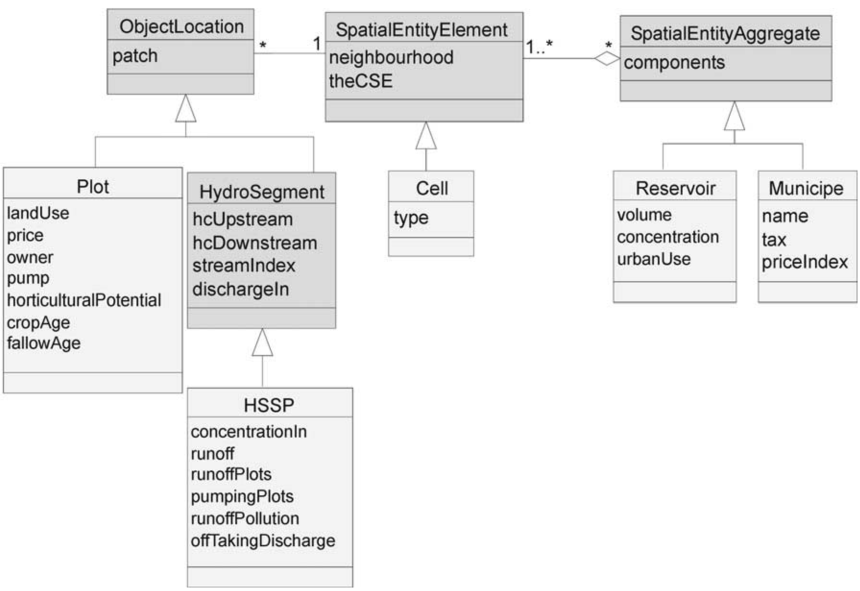


Fig. 1. UML class diagram (spatial package). Boxes in light grey correspond to Cormas generic entities according to which the specific entities of the Sao Paulo model have been defined.

they derive, are used to contain specific dynamic processes. “HydroSegment” is not context-dependent but rather a generic Cormas entity available to design standard flow processes. What is specific to the Sao Paulo prototype (which is dealing with pollution and runoff) is that it has been isolated in the HSSP.

Table 1
Description of the different entities of the prototype

Entity Attribute	Type	Meaning	Additional comments
*ObjectLocation** patch	Spatial Entity Element	Cell on which the object is located	Any cell from the spatial grid
Plot			
landUse	Symbol		#Cereal #Fallow #Horticulture #Industry #Residential #Tourism
price	Float number		4000 * Municipe priceIndex + (20 400/distW)- (18 600/distF) where distW is the minimum distance to water (#River or #Reservoir cells) and distF the minimum distance to a favela (#Favela cells)
owner	LandUser		A producer or a speculator
pump	Boolean	Presence of a pump	
horticultural Potential	Boolean	Is it a good place or not for horticulture	True for #RuralLand cells along each side of the river (range 2); false anywhere else
cropAge	Integer	Number of time-steps since the establishment of the crop	Used for plots with landuse = #Cereal or #Horticulture. Crops are harvested when cropAge = 5, then landuse = #Fallow
fallowAge	Integer	Number of time-steps since the crop has become a fallow	Used for plots with landuse = #Fallow
*HydroSegment**			
hsUpstream	Collection of HydroSegments	Neighbour upstream hydroSegments	
hsDownstream	Collection of HydroSegments	Neighbour downstream hydroSegments	
streamIndex	Integer	Rank between the outlet and the source	1 at the outlet, then successively +1 for the neighbour upstream hydroSegments. For the source in the middle of the lower border (see Fig. 5), streamIndex = 50; for the source in the middle of the right border, streamIndex = 54.

Table 2
Description of the different entities of the prototype

Entity Attribute	Type	Meaning	Additional comments
HSSP			
dischargeIn	Float number	Discharge (m^3/s)	For the two sources (see above), it is randomly set at each time-step between 4 and 8
concentrationIn	Float number	The concentration of pollution	
runoff	Float number	Volume of water that will run off	Depends on the runoff Plots size and a rainfall which is randomly set at each time-step (same value everywhere)
runoffPlots	Collection of Plots		Rural land or Favela cells in the neighbourhood (range 2)
runoffPollution	Float number	Volume of pollution that will run-off	Depends on the runoff absolute value, weighted by the distribution of land-use among the runoffPlots, each land-use having a specific pollution index (tourism being the reference index, cereal is 2.5 times more, horticulture five times more and favela 40 times more polluting)
offTaking Discharge	Float number	Volume of water that will be pumped	A fixed quantity of water for each plot among the run-off plots being either used for industry or horticulture
*SpatialEntityElement**			
neighbourhood	Collection of Spatial Entity Elements	Neighbour cells	The topology from the Cormas spatial grid menu allows to choose the shape (hexagonal or squared) of the cells and the boundaries (either periodic or closed) of the grid. When these properties change, the neighbourhood of the cells is reset
theCSE	Collection of Spatial EntityAggregates	Register of aggregates to which the cell belongs	A same cell may belong at the same time to different aggregates

Table 3
Description of the different entities of the prototype

Entity Attribute	Type	Meaning	Additional comments
Cell			
type	Symbol		#RuralLand #Favela #River #Reservoir #Park. Plots (with particular land-use) may only be built on #RuralLand cells. #River, #Reservoir and #Park cells remain unchanged. #Favela may expand over #RuralLand under specific conditions
*Spatial Entity Aggregate**			
components	Collection of Spatial Entity Elements	Cells being the components of the aggregate	An aggregate is made of contiguous components
Reservoir			
volume	Float number	Volume of water (m^3)	Initially set to 24 millions of m^3, it is balanced every month by an input ("dischargeIn" * 30 * 24 * 3600) of the outlet hydro Segment and by an output ("urbanUse")
concentration	Float number	Concentration of pollution	
urbanUse	Float number	Water demand (m^3)	Initially equal to 13 * 30 * 24 * 3600, it is increased by 1% every two years
Municipe			
name	Symbol		The 60×50 spatial grid is dissected in three rectangular "municipes". The left part (colums 1–16) represents #Embu. Then the remaining part (colums 17–50) is divided at line #25, the upper part represents #SaoPaulo and the lower part #Guara
tax	Integer		100 for #Embu, 120 for #SaoPaulo and 90 for #Guara. This is an annual tax the land-user owning the plot has to pay
priceIndex	Float number	Basis for the price of a plot of land	1.1 for #Embu, 1 for #SaoPaulo and 0.9 for #Guara. It will balance the price of the plots being located in (components of) the corres. Municipe

Two classes of aggregates made of contiguous cells have been designated: "Reservoir" and "Municipe". The virtual landscape has been split up into three municipes, each one with a specific tax level. The reservoir contains information about available water level and pollution rates, which will influence the agents' decision-making process.

5.2. The land-users agents

The prototype is combining two different kinds of social agents, "Producer" and "Speculator", both being land-users (hence the intermediate abstract class "LandUser" as shown in the class diagram, Fig. 2).

Initially, each plot of land was randomly attributed to a "farmer" (producer) or an "urban" (speculator) owner. There were 3000 initial owners in the model, two-thirds being farmer types and one-third urban types, forming two different

Table 4
Description of the different entities of the prototype

Entity Attribute	Type	Meaning	Additional comments
*AgentComm**			
mailBox	Collection of messages		The messages used in the model are signed with a sender, a receiver, an object (a plot) and a price
channel	Channel		With Cormas, the channel takes care of all messages deliveries, either synchronously or asynchronously (immediate delivery)
LandUser			
cashbox	Float number	Amount of money	Initially randomly set between 3000 and 12 000 for a speculator, and between 150 and 9000 for a producer
plots	Collection of Plots		Initially a plot is set on each #RuralLand cells of the spatial grid and simultaneously attributed to a newly created land-user which has 20% of chance to be a speculator and 80% to be a producer. Plots is then initially a collection made of a single plot
Speculator			
costs	Float number		Initially randomly set between 20 and 300. There are specific costs for the different land-uses
wages	Float number		Initially randomly set between 20 and 300. There are specific wages for the different land-uses

populations. While all farmers follow the same strategy in this prototype, which consists in growing crops on their plots, three different types of strategies were randomly attributed to urban owners. They could use their plot for recreational purposes (week-end house), for speculation purposes, waiting for higher plot prices, or as an investment allowing the development of profitable activity such as tourism or industry: the choice of investment depended on the location of the plot, its distance from water and parks as well as the owner's investment capacity. All owners were characterized by a cashbox and family needs, randomly attributed. Their decision-making processes, about the changes of land use for all the plots they own, are based on the current values of these parameters and on the local configuration around each plot.

Two processes account for migration. To represent immigration, every 12 months new potential owners (land-users) are added into the farmers or speculators population (for speculators, the strategy is randomly assigned). Any land-user whose set of plots becomes empty is removed from the model, representing emigration. The calibration of the concerned parameters has been made so that these two balancing migration processes result in a regular increase of both populations of land-users.

5.3. Decision-making processes

Plot owners act as land managers who decide every 6 months what kind of use they will make of their plots. Land-use modes reflect owner's strategies. For farmer's plots, three crops (modes of land use) were possible: horticultural crops that need to be irrigated, cereal crops (not irrigated), and fallow. Irrigation was only possible in

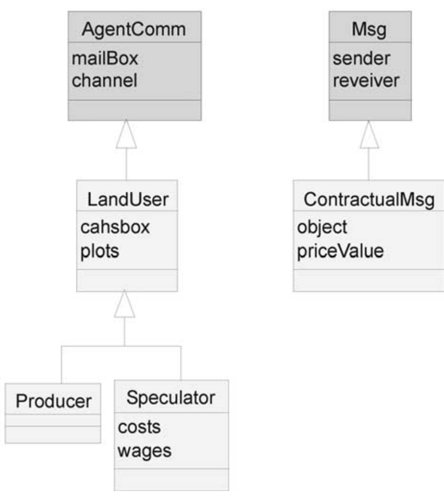


Fig. 2. UML class diagram (social package). Boxes in light grey correspond to Cormas generic entities according to which the specific entities of the Sao Paulo model have been defined.

the proximity of the rivers (at maximum distance of two cells from “water”) and supposes an initial investment that represents the installation and development of irrigation equipment in the plot. While two irrigated crops per year are possible, a non-irrigated plot can only be farmed during one season. Horticultural crops require higher cropping investments at the beginning of the season than “cereal” crops, but when harvested they provide a better income. Fallow that provided no income was chosen when the cashbox was so low that it did not allow any other farming. Thus, rural land-use mode could change every 6 months (six time steps) depending on the owner’s cashbox at the beginning of the season.

In the case of “urban” owners, land use depended on the strategy of each owner, as well as the cashbox level. “Investment” strategies, and “recreational” strategies were linked to a prior investment. If this investment was impossible because of the cashbox level, the plot was left in a “fallow” state, which was also the case with “speculative” plots. Landowners thus accumulated wealth from the results of their investment (whether agricultural, or industrial) as well as from external income, randomly given. Another charge was a land tax to be paid by plot that was linked to the municipality the lands belonged to.

Farmers with negative results had to sell their plots of land, and a land market was organized every year (12 time steps). In this prototype model, “urban” owners did not sell their plots. When a farmer had sold his plot, it was removed from the agent population. An initial set of prices was attributed to all plots, taking into account the distance from water and from the “favelas” nucleus. A plot to be sold was first offered to the farmer’s neighbours; if no neighbouring farmers could afford to pay the price proposed, the plot was offered to all land owners (farmers and urban owners) including those newly arrived. In the first step of the process (plot offer to neighbouring farmers), the plots were attributed to the highest bidder using a simple algorithm based on a random increase of the initial price. In the second step (general offer of the plot), the plot’s buyer was randomly chosen between those agents that could afford the plot. If no one could afford it, the price of the plot was lowered for the next land market.

5.4. Overall land use dynamics process

Land-use dynamics in this model relied on two different driving forces: transition rules between cells, and agents’ decision-making. If a land cell in the immediate surrounding of a favela nucleus was not occupied (that is either cultivated or built) during 10 consecutive months, it became urbanized and was aggregated in “favelas” at spatial grid level. But, the choice of crops or investment[2] resulted from the decisions made every six-time steps, corresponding to the agricultural calendar. Indeed, it is at the beginning of the season that the farmer decides whether or not to cultivate. Land use could change from farming activities to investment if the plot was bought by an owner of the corresponding type. Fig. 3, which is a UML state diagram,

[2] Either in a “week-end” house, in an “industrial” activity, or in an eco-tourism activity.

allows the representation of all the possible land-use values of a plot, and provides all the transitions from one state to another.

Some of the transitions between the two plot states may be triggered due to one activity of the farmers or to one activity of the speculators, while some others are only triggered by a specific activity of a given land-user. Behind each activity name there is a method that has been written in Smalltalk in the corresponding class.

To have an idea of what is happening during one time-step of a simulation run, see the UML sequence diagram (Fig. 4). The control flow is scheduled by the class representing the model itself (Sao Paulo class). The activity of each entity of the model is followed along an activity lane: when an activity has to be performed the activity lane appears wider. As Cormas models are all scheduled on a discrete-time basis, this kind of diagram allows observation of the sequential ordering of the elementary activities of all entities involved.

At this stage, a complete description of the model should include as many detailed algorithms as there are elementary activities names on the sequence diagram of the model shown in Fig. 4. To give all the elements in a formalized way (at least in a way independent from the implementation, i.e. no source code) represents a quite long and difficult process, which is challenging the community of ABMs' builders (Edmonds, 2002).

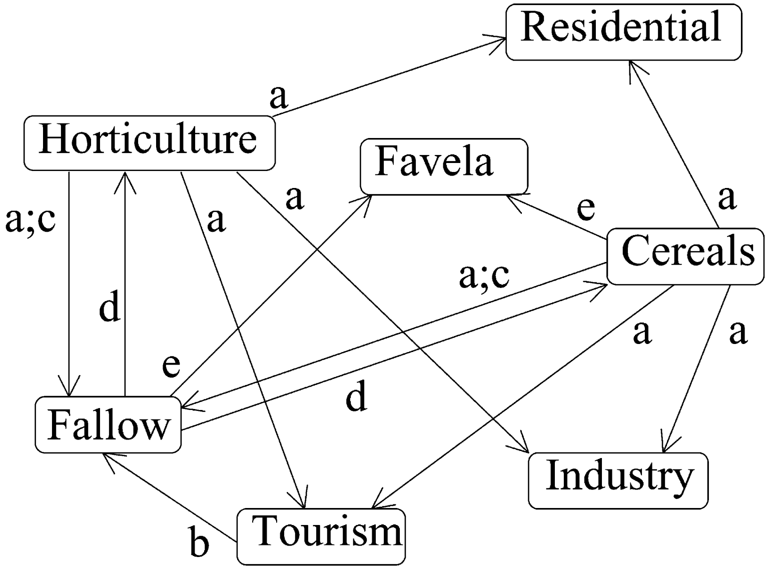


Fig. 3. UML state diagram for the attributed land use of a plot. The transitions are triggered by the execution of specific methods of the two classes of agent, "Speculator" (*a* stands for "affectLandUse", *b* for updateTourismActivity) and "Producer" (*c* stands for "harvest", *d* for "updateFarmActivity". The creation of the favelas (*e*) is incorporated as a global process written at the level of the model class itself.

6. Discussion

The prototype model proposed is mainly meant as a feasibility test to try to establish how to jointly represent the different processes involved in land and water management in peri-urban catchment. While the main features of the model were inspired from the spring area of Sao Paulo city, it was not possible at this stage to include in the model precise data sets (rainfall, hydrological processes, pollution, land and water management). Thus, running the model at this stage was simply a

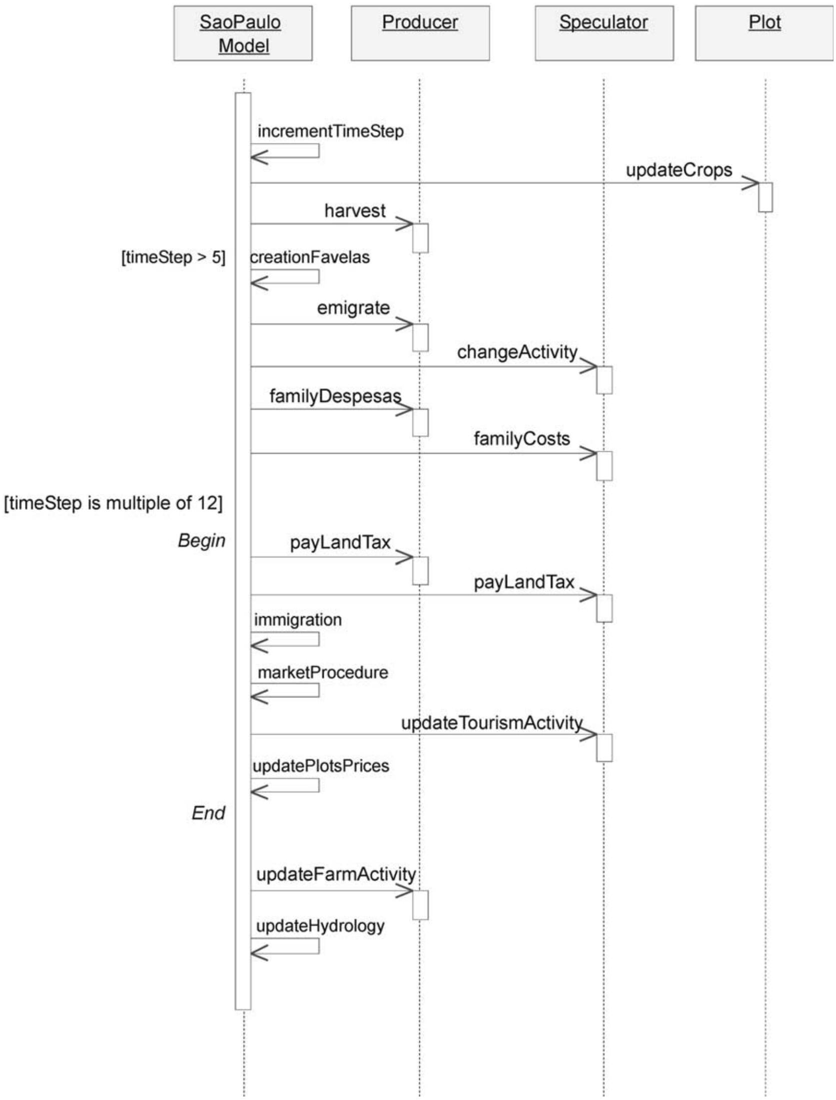
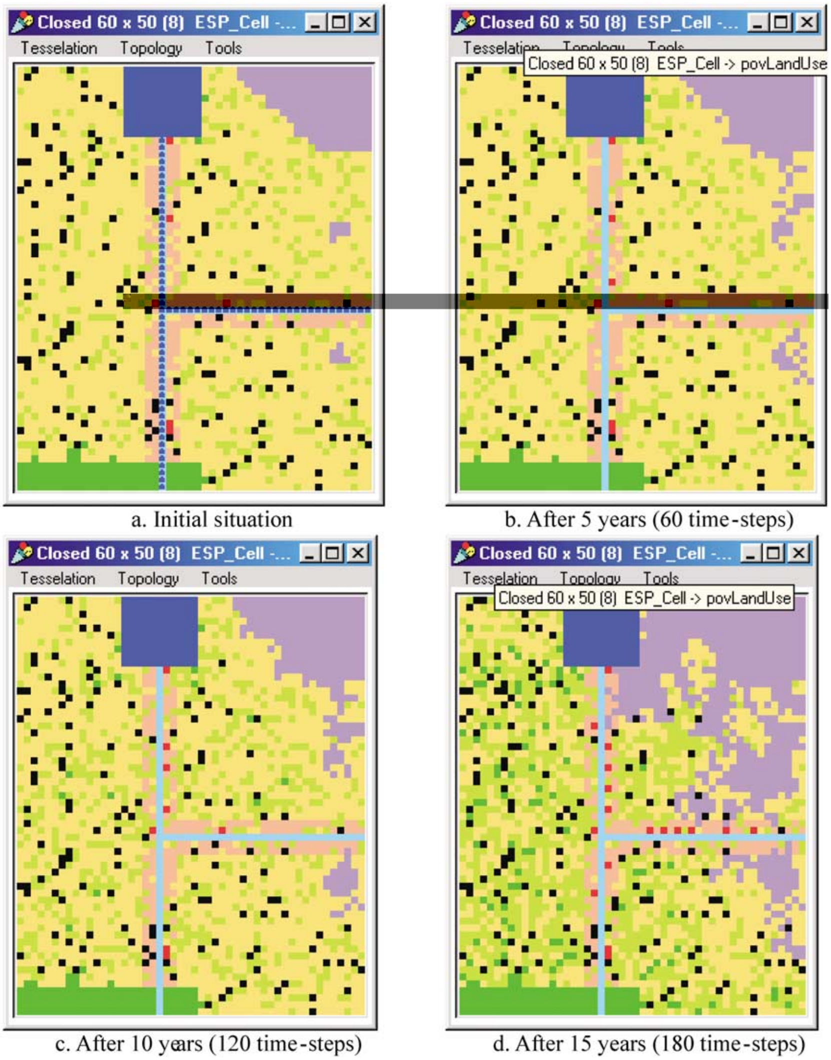


Fig. 4. UML sequence diagram for a simulation time-step.

way of testing it, with a random initialization of the model. The type of landowner, as well as the initial cashbox of each landowner, was thus randomly allocated for each plot.

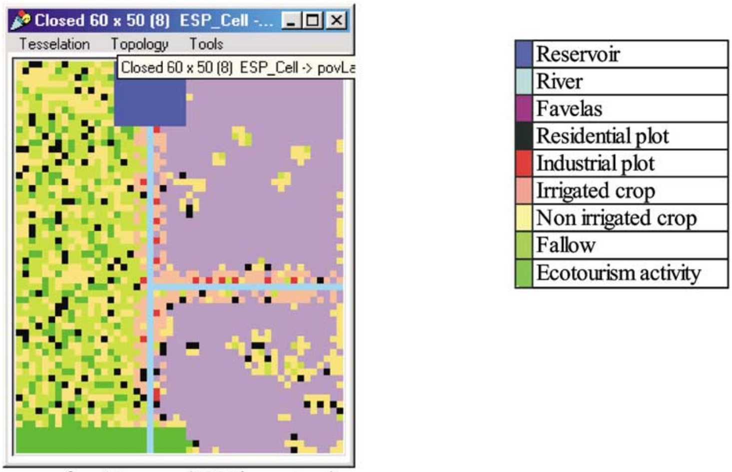
At the initialization stage, three spatial aggregates of #Favela cells were created, in the right part of the grid (see Fig. 5) To simulate the expansion of the favela areas, two processes have been written in a specific method (which is implementing the arrows labelled "e" in the state transition diagram, Fig. 3). They are both based on



a. Initial situation b. After 5 years (60 time-steps)

c. After 10 years (120 time-steps) d. After 15 years (180 time-steps)

Fig. 5. Example of spatial grid with land use overview for a given simulation at (a) initial stage, after (b) 5 years, (c) 10 years, (d) 15 years and (e) 20 years.



e after 20 years (180 time-steps)

Fig. 5 *(continued)*.

the principle that only cells in contact with a favela aggregate and being typed as rural land may be incorporated to the favela aggregate. The first process selects cells that have not been cultivated or built for 10 time steps, and that have at least one neighbouring cell being part of a favela aggregate. The second process corresponds to a situation where a rural land cell is "surrounded" by a favela (more than five neighbouring cells are parts of a favela). Such a cell is incorporated to the favela, even if it was still cultivated or built. Due to the definition of these rules, the river is stopping the expansion of the favelas (see Fig. 5c and d). The expansion of the favelas is occurring faster after a while, when less and less non-irrigated cells are cultivated (see Fig. 5).

We are just discussing here the results from a single run of the model. As in the initialization step there are already some probability choices, the final configuration is different for each simulation experiment. But the same trends are always observed. Two land-uses are clearly increasing: #Favela and #Tourism; #Residential, #Fallow and #Industry are more or less remaining at the same level (after an early rise for the last one); #Cereals (non-irrigated crops) is the only land use which is strongly and continuously decreasing.

The expansion of the favelas has been explained earlier. To understand how ecotourism penetrates non-irrigated crops, the method labelled "a" in Fig. 3 which states how a speculator is setting-up and updating the land-use of its plots—will be detailed here. It is described in a formal way in Fig. 6. When it is created, a speculator is typed (random choice among three types). As shown in Fig. 7, type 1 systematically leaves its plots in fallow. Type 3 may build a residence under a specific condition based on its amount of money and the relative isolation from a favela area. Type 2 is a bit more complex; its decision may result in the creation of an industrial or tourist activity.

The decrease of #Cereal cells in time, which turn into #Fallow cells are linked to the ''economical'' amounts chosen for this type of crop: non irrigated cells may only be turned into #Cereal once every 12 times step (one cycle per year), if its owner cashbox is above a certain level (200), representing planting investment. The #Cereal state provides only 300 every 12 months (crop selling price), while farmer's cashbox is randomly reduced every time step from a certain amount chosen between 10 and 25 to account for family monthly expenses. Because of the values chosen, the ability of a non-irrigated cell to turn into #Cereal or #Fallow state depends mostly on the initial cashbox level of its owner, that is randomly set at initialization stage. To compare with, #Hort is associated with a planting investment of 400, a crop selling price of 800, with two cycle a year if allowed by farmer's cashbox. These values have been chosen to favour irrigated agriculture by comparison with non-irrigated traditional agriculture. While consistent with the first indications of agriculture in the area, the different values need to be better calibrated in order to better account for the economic dynamics in the area.

With time, as their owners cashbox tend to diminish, more and more non irrigated cells thus turned into #Fallow state. It leads the cell to be integrated into the market

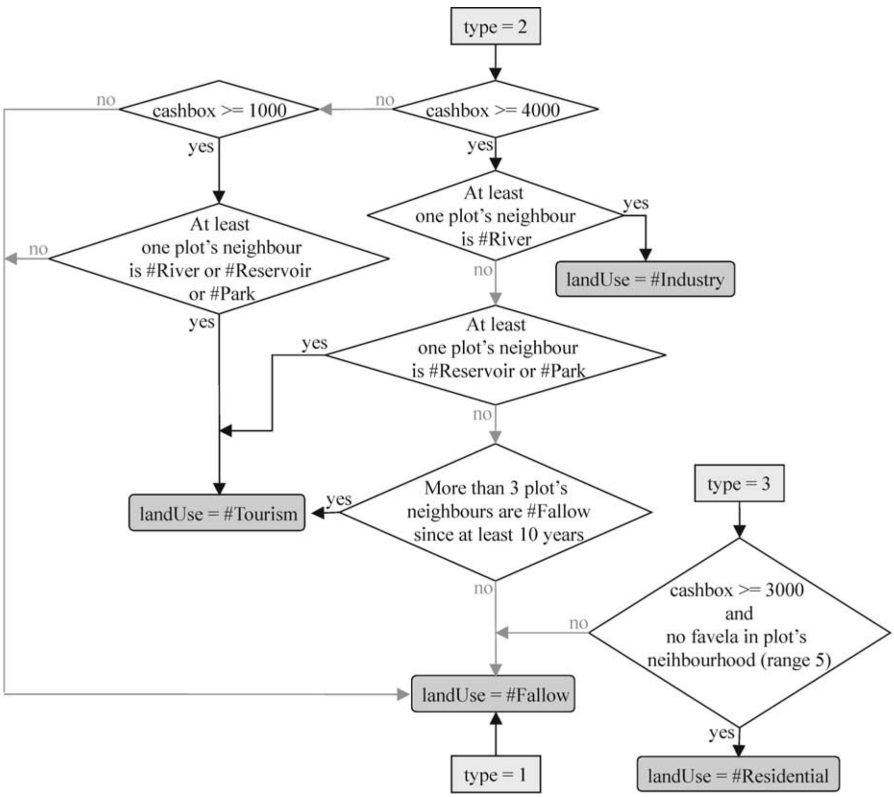


Fig. 6. Description of the process of land-use change for the transition to ''eco-tourism''.

process or into a Favela aggregate, if its localization allows it. The process is further more accelerated because the market process favours farmers: The plot to sell is first offered to neighbouring producers before being offered to all plot's owners, including urban owners; The transaction process also contributes to deplete the new owner cash box of the plot price. Thus, the number of farmers in the model tends first to increase and then to decrease up to one third of total plots owner.

Others results of the prototype, with the chosen assumptions and data includes the following trends: the farm size tends first to augment, and then to decrease after 15 years. The reservoir tends to reach the critical value of 1 million m^3 in a few years. The pollution level in the reservoir is strongly linked to discharge in the reservoir, and thus to the amount of rainfall. After 20 years, and conforming to cellular automata properties, "favelas" cells tends to spread rapidly in the spatial grid (see fig. 5). These preliminary results, whose meaning is limited by the random choice of landowner and of some economical value, were not related to the initialization data sets of the model.

Though based on simplified dynamics, the pilot model architecture allowed land management processes and hydrologic flows to be articulated at cell levels. Spatial distribution was thus made explicit in this model at least for the hydrological processes, even if the choice of space scale does not allow for detailed distribution. The hydrologic processes were represented on a cellular basis, which allowed the monitoring of pollution processes along the rivers and the representation of a great variability of use on a spatially diffuse basis which is adapted to deal with the peri-urban patchwork spatial structure. In a perspective of further development, this representation will also allow for a temporal representation of rainfall, water flows, uses and reservoir storage. Other kinds of representations are possible: some models represent hydrological processes by focusing on a reference point connected by "channels" or "segments" on which hydrological mathematical functions are applied (Kuper, 2001; Thoyer et al., 2001).

Land-use market processes were close to the Fearlus model: as in this prototype, "the agents are land managers who accumulate wealth by the yield generated by their land parcel, and must sell their plots when they reach a negative accumulated wealth. Plots are transferred to other land managers by choosing at random from the set of land managers with sufficient wealth who own land parcels next to the one that is for sale" (Polhill, 2001). In the case studied, priority sale to neighbouring farmers was chosen to account for social links between farmers as well as for a preference to avoid land dispersal. However, this representation of decision-making processes in land marketing is rather simple and does not account for diversified farmers land strategies. It should take into account not only economic criteria but also social, technical and geographical factors. While rural land markets were represented, the urban market processes have not been developed, and more information is required on the mechanisms that cause shantytowns sprawling. Decision-making processes in land management should also include municipal policies for land-use planning.

We intend to use the agent model as a basis for intervention in order to enhance stakeholders co-operation as it has been tested in other contexts, for example in

Senegal (d'Aquino, 2001). In Senegal, the emphasis was placed on stakeholder participation in the design of the tools and on formalizing as accurately as possible the knowledge and points of view expressed by stakeholders. Different studies indicate that models may only be used as mediating tools if they are perfectly understood and legitimate in decision-makers' eyes (Simonovic, 1996). They suppose that they should neither give an oversimplified representation of reality nor be too complex to be difficult to understand (Le Gal, De Nys, Passouant, Raes, & Rieu, 2000). They should not necessarily rely on very complex agent architecture, even if it appears necessary to provide an accurate and validated representation of the biophysical dynamics and of the management rules included.

The first step of this mediation approach is supposed to recurrently test the cognitive framework on which is based the artificial world build with the representation of the stakeholders. Thus, the prototype was presented to some thematic scientists and decision makers in water management on the Alto-Tietê water committee as a way to demonstrate the framework retained for describing the functioning of urban/agricultural interaction in resources management at the urban edge. The assumption that the competition over land should be represented only by land market processes (whether legal or illegal mechanisms) was questioned, as it appears to oversimplify the urban pressure on farming systems. The discussion underlined the role of insecurity and violence due to the expansion of urbanization, as well as the increasing competition between agriculture and mining activities with developing urbanization. Both sectors tend to explore the same type of soil, in the sedimentary areas of the valleys. Mining activities that provide construction materials are directly linked to the urbanization processes, being sometimes directly involved in illegal housing development. But development of mining activities is submitted to an administrative authorization, which depends on a sphere of decision making other than catchment management bodies, and municipality or market processes. This competition could thus take place relatively far from the urbanized nucleus and be responsible for the specific spatial process of housing development affecting large areas. In an ABM representation, taking into account the rate of increasing insecurity and violence is clearly a question of modelling the representation of the agent over its environment, which was not included in this prototype. Other discussions questioned the distinction between urban land owner and agricultural land owner as some types of farmers are moving more to leisure activities or part-time farming, as well as specific, speculative land strategies. On the other hand, leisure plots could be transformed into productive farming plots. Thus, goals and strategies of agents may evolve in time, and the agents in this model are rather simplistic and more reactive than cognitive. Their specification does not include for example any belief representative of the environment, or flexibility, in their goal focus. Actually, few agent-based social simulations do rely on agent architecture with developed cognitive abilities or based on theories of social sciences (Jansen, 2001). Agent architecture should also depend on the future use of the model.

At this stage, the model is focusing on our own point of view of the rural processes, and the urban processes have been integrated in an "aggregated" way. However, the different points of view of the diverse stakeholders e.g. shantytown communities, water managers, farmers will also need to be discussed and integrated, in order to design a simulation model that could be used as a discussion tool for land and water management at the urban edge.

The work should include not only the reconstruction of land and water management rules from empirical data in order to provide a more realistic representation of decision-making processes should also take into account the representations of all groups concerning their articulations with other stakeholder groups It also appears necessary at this stage to complete the information on the environment by a field survey on the water-use practices of different users that would include other resources such as ground water or waste water, both of which are widely used in the catchment studied. The impact of urbanization on hydrological processes should also be taken into account. The hydro-functioning of the model should be validated taking into account the difficulties of validation of agent-based social simulation models, which remains a research issue in itself (Barreteau, Bousquet, & Attonaty, 2001; Le Bars, 2001), especially if the model aims to be used by decision makers.

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