Agent-Based Model to simulate *Araucaria angustifolia* Forest Dynamics as a tool for Forest Management

Diana D. Valeriano[1], Merret Buurman[2], Dalton M. Valeriano[3], Silvana Amaral[1]

[1]Image Processing Division – National Institute for Space Research [INPE]
Caixa Postal 515 – 12.227-010 – São José dos Campos – SP – Brazil

[2]Institute for Geoinformatics – University of Munster
Munster, DE

[3]Remote Sensing Division – National Institute for Space Research [INPE]
{diana,silvana}@dpi.inpe.br, merretbu@gmail.com, dalton@dsr.inpe.br

Abstract. *The objective of this project was developing an agent-based model to simulate the successional evolution of* ***Araucaria angustifolia*** *[Bertol.) Kuntze (Brazilian pine) in a natural forest stand providing useful information for forest management purpose. Using TerraME as computational framework, the colonization dynamic of* ***Araucaria*** *was represented as an agent with behavior modeled by its life cycle of recruitment, growth, dispersion and death. The model functioning was testing simulating scenarios with and without fires disturbances. Preliminary results are in accordance with conceptual models proposed for these forests. This work emphasizes the modelling relevance, constructing simulated scenarios that can be further integrated into decision making for natural resources management.*

1. Introduction

The Ombrophilous Mixed Forest of Southern Brazil, also referred to as Araucaria Forest, includes a larger area in the Southern Region, and isolated patches in mountainous areas in the Southeast Region [Hueck 1972]. The need to evaluate the current status of Araucaria Forest remnants and *Araucaria angustifolia* (Bertol.) Kuntze populations arises from the significant reduction of its original cover. Circa 87% of Araucaria Forest cover was replaced by pasture, agriculture and exotic forest plantations [Ribeiro et al. 2009]. Besides the conversion to agricultural use, these forests were heavily exploited for timber during most of the last century [Sanqueta and Mattei 2006].

The structure of the Araucaria Forest is formed by two components with distinct functional characteristics: the forest canopy composed by the conifer *Araucaria angustifolia* (Brazilian pine) associated with different species of Angiospermae and the understory [IBGE 1992]. Araucaria*,* a dioecious specie, is a long-lived pioneer [Longhi 1980, Souza et al. 2007] expressively larger than the other trees, and being heliophytic demands disturbances to ensure its recruitment [Backes 2001]. The conservation of the Araucaria Forest requires a better understanding of its dynamics in face of future scenarios of habitat fragmentation and climate change.

Forest tree models, initially developed as individual-tree based models, known as gap models [Botkin et al. 1972, Shugart and West 1977] received alternative formulations over the following 30 years [Bugmann, 2001]. New models added parameters such as: dispersion mechanisms [Pacala et al. 1993], angle of incidence of solar radiation [Leemans 1992, Weishampel and Urban 1996], recruitment requirements [Acevedo et al. 1996], treefall damage [Köhler and Huth 1998] and competition among tree cohorts [Bugmann 1996, 2001]. These models are known as Individual-Based Models (IBM) and although very useful they are discrete spatial models, which do not consider neighborly relations and interactions.

New approaches to simulate forest dynamics that included spatially explicit interactions expanded as computer power increased [Chave 1999, Lischke *et al*. 2006]. More recently, Agent-Based Models (ABM) became an important research tool in ecological and economics simulations for ecosystem management [Bousquet and Page 2004]. As the use of IBM and ABM became widespread in Ecology and other fields that deal with complex systems, Grimm et al. (2006) proposed a standard protocol to describe these simulations models, the ODD (Overview, Design concepts and Details).

Hence we decided to set up a learning environment, based on the ODD protocol to build a simulation of a natural process using the ABM simulation. This was possible through the cooperation of biologists, ecologists and sciences experts focused on better understanding the complexity of forest dynamics and on achieving adequate simplifications to represent it.

Based on the major role performed by araucaria on the forest dynamics, we proposed to construct a first attempt to model the forest dynamics, based on araucaria life cycle and its population expansion. Simulations of this species life cycle and dispersion pattern and its consequences on the forest dynamics are useful information for environmental policies and management plans to ensure its persistence in its natural ecosystem.

The main goal of this project was to learn how to represent a natural complex system in a meaningful simplified way, through the development of a computational simulation. The specific objective was to implement an Agent-Based Model to simulate the *Araucaria angustifolia* life cycle and population expansion in the TerraME programming environment.

3. Conceptual Models of Araucaria Forest Dynamics Overview

The hypotheses used for the model simulations were based on three current conceptual models to represent the Araucaria Forest dynamics.

First one [Klein 1960] hypothesizes that the presence of a population of araucaria inside a forest indicates ongoing succession that follows the forest expansion over grasslands, and that the fate of this species is to be substituted by broad-leaved trees in very mature stages of the forest.

The second, the Temporal Stand Replacement model [Ogden 1985; Ogden and Stewart 1995] hypothesizes that the dynamics of long-lived pioneers (in this case *A. angustifolia*), which structurally dominate the forest, is influenced by intermittent recruitment episodes, dependent on severe disturbances.

The third one, a gap model, states that an araucaria treefall gap establishes conditions for its own recruitment inside the forest, resulting in an autogenic succession process [Jarenkow and Batista 1987].

4. Methodology

The model was implemented using the open source TerraME [www.terrame.org] - a programming environment for spatial dynamical modeling, developed by INPE and Federal University of Ouro Preto [Carneiro et al. 2012]. It is an extension of the programming language Lua and provides data types and functions useful for (spatial) modeling, such as cells, cellular spaces, neighborhoods, automatons and agents [Carneiro et al. 2012]

Regular meetings were held to present the theoretical assumptions about the ecosystem under investigation, and the possibilities and limitations of a computer simulation, following the ODD protocol [Grimm et al. 2006].

4.1. General conceptual model description

The Araucaria Forest ecosystem was represented using the agent-based modeling paradigm. In contrast to top-down models, which explicitly model the behavior of a system as a whole, agent-based models are bottom-up, i.e. the behavior of the system is derived from and defined by the behavior and interaction of the individuals making up the system [Crooks et al. 2008, Castle and Crooks 2006].

This modeling paradigm enables observing how the behavior of individual araucaria trees reflects on the behavior of the entire population, or specifically, which properties of the trees affect the population's behavior, and at what degree. Other species present in the forest are considered as "Understory" and their behavior is modeled as cellular automata with environment controlled by the araucaria spatial and life cycle dynamics.

In our model, after a random dispersion of seeds in a finite space representing the stand initialization a araucaria tree has a well-defined life cycle from seed to death and the Understory is controlled the environment created by the trees. Time scale for any transition operation is one year. During its life cycle, an araucaria tree lies in one of four possible stages: seed, juvenile, reproductive adult and senile adult. Each tree changes from one stage (or state in the model) to another according to a defined age threshold with density dependent death of juvenile.

The life cycle is modeled considering the processes of reproduction, growth, shade competition, interaction with the understory, and tree-fall gaps. Furthermore, disturbances are modeled to evaluate their effect over the forest.

4.2. Conceptual model Implementation

The lifecycle of the araucaria trees structured the main part of the model implementation, and the processes of growth, shade, reproduction, gaps and understory are submodels. The main part creates a simulation space and the initial trees. It is also responsible for controlling the sequence of events. At each time step, it increments the age of all trees and changes their states if applicable.

The simulation space is a gridded flat horizontal square with side of 250 m and grid cells with side of 5 m. As araucaria trees are our main interest, only this species is represented as agents locating on the simulation space. All other species together form the understory and, at this stage of model development, are not modeled as separate species nor as individual plants.

For the life cycle of the araucaria trees, the age thresholds at which the transitions between the life stages happen and death by old age are modeled as parameters that can be adjusted according to the knowledge about the species characteristics.

The spatial distribution of araucaria trees considers limits for minimum distances between trees and maximum tree densities, by establishing the rules: a) it is allowed only one adult tree per cell and adult trees cannot live in neighboring cells, (Figure 1a); b) seeds and juvenile araucaria trees can be in in the same cell and in neighboring cells, with the limit of two individuals per cell (Figures 1b and 1c).

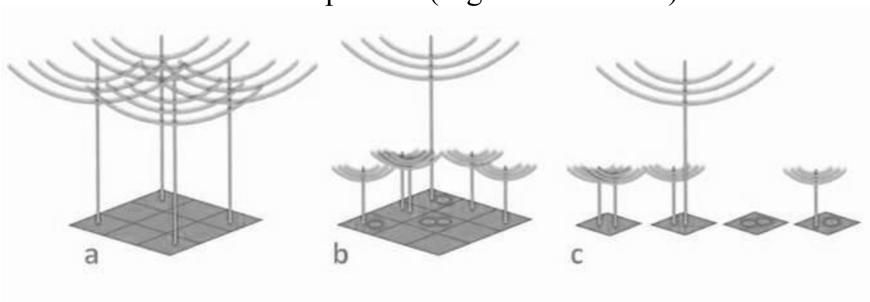

Figure 1. Possible spatial configuration of araucaria trees: (a) Adult trees cannot live in directly neighboring cells. (b) Seeds and juveniles can be in the same cells as other seeds and juveniles and as adults, and in neighboring cells. (c) Possible combinations of individuals in one cell.

Each submodel interacts with the main part simulating interactions between araucaria and other forest processes. Some submodels are executed for every single tree, while others are executed once for the whole simulation space, as depicted at Figure 2 and described at Table 1.

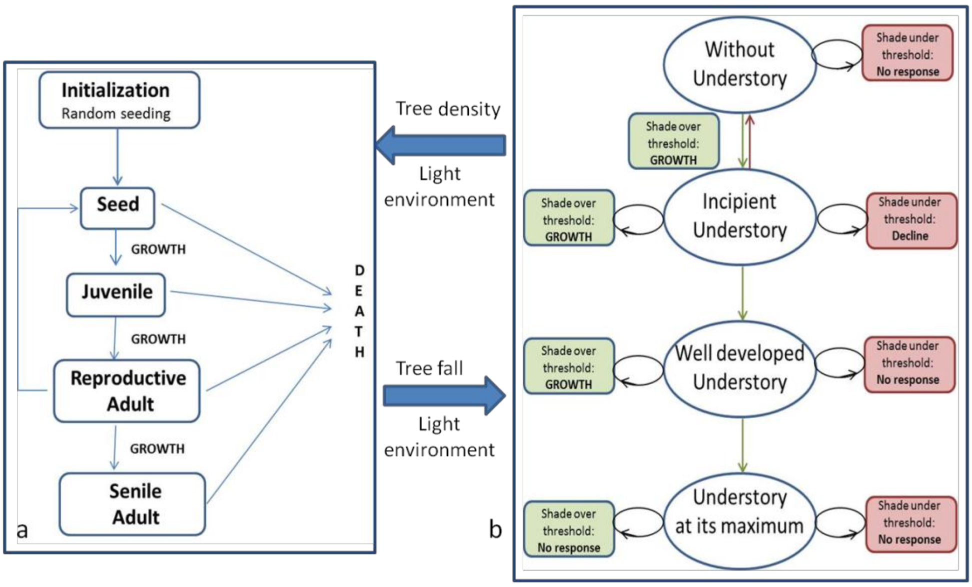

Figure 2. Conceptual model representation and submodels interactions. a) agent module; b) cellular automata module

Table 1. The submodels and their functions

SUBMODEL	APPLIED TO	PROCESS
Reproduction	Every single tree	Produces and places seeds
Growth	Every single tree	Computes and adds the growth of every single tree
Shade	Every single tree	Computes the light transmission by a single tree
	Simulation space	Computes the light that reaches the forest floor at each cell
Tree-fall gap	Every single tree	Creates gaps and removes the vegetation in it
Understory	Simulation space	Determines the understory development and computes the light transmission by the understory

4.2.1. Submodel Reproduction

We established that Araucaria seeds are produced with a sex ratio of 1, a realistic simplification [Bandel and Gurgel 1967]. Female individuals start producing seeds when they are in the reproductive state. As Araucaria seed has a high mortality rate [Iob and Vieira 2008] we set a fixed amount of 15 seeds per year for each female tree.

The seeds are dispersed in cells around the mother tree but not allowed in the same cell. Seeds can fall into a square region around the mother tree whose extent and probability density are specified by the user. We set two reaches for weighting probability of seed dispersion, a first and a second order neighborhood. Weight for probability density of the inner one is twice the weight of the outer one.

4.2.2. Submodel Growth

In this model, growth is represented by steady change in tree height according to tree age. During the first years trees grow relatively fast, reaching 25 m of height at the age of 45. Afterwards, the tree has a lower growth rate. It reaches 30 m at the longest age possible of 400 years.

4.2.3. Submodel Shade

After an age threshold, araucaria trees start casting vertical shades modeled as the fraction of the sunlight that the tree allows to pass through its crown. If trees are standing close to each other, their shades overlap. In this case, the light transmission coefficients of the various individual shades are multiplied to establish light transmissivity.

Initially shade casting trees provide a small shade. Above another age threshold they provide a larger, darker shade. The light transmissivity coefficient cannot vary inside a cell. In this model, the shade of a young tree has the size of one cell (5m x 5m), while a larger tree shades an area of 9 cells (15m by 15m) with a darker core shade and a lighter shade at the edges. The user can specify the ages of transition between each state and the light transmission in these shades.

4.2.4. Submodel Understory

The only environmental variable of understory is the light environment represented by shade cast by the trees and by the understory itself. Light controls araucaria seed viability, and young plants survival rate. As soon as the araucaria trees provide a certain level of shading, the understory begins to develop. As long as the araucaria continues to provide shade, the understory continues to increase until it reaches its maximum. If the shade provided by the araucaria trees is removed (or weakened until below the required level) before the understory has reached a predefined maturity level, it slowly diminishes again. A mature understory does not diminish when the araucaria shade is removed or weakened, and can only be removed by tree-fall gaps. There is no interaction between the understories in neighboring cells; the understory only depends on the light that reaches its very cell.

4.2.5. Submodel Tree fall gaps

We adopted the "chablis" model of canopy gaps caused by a tree fall with a crown and a root gap [Oldeman 1978]. The crown gap is represented by a square region close to the location of tree fall. The root gap is limited to the cell occupied by the felled tree. The understory in both gaps can be fully or partly removed or remain untouched, according to user specifications.

To cause a gap, a tree has to be an adult and above a certain minimum height (which is defined by the user). Also, an araucaria that died by a gap itself is not allowed to create a gap to avoid a domino effect. The size of the gaps is the same for all the trees and can be defined by the user. The crown gap's distance and direction from the falling tree is determined randomly. The user defines the maximum distance.

4.2.6. Submodel Fire disturbance

Fire disturbances are square patches of user-defined size, occurring at random locations in the simulation area. The understory and young trees (under a specified fire resistance age,) are completely removed. The percentage of older trees that are killed by the fire can be defined separately for weak and strong disturbances. Overlapping patches are possible and result in stronger disturbance effects. The user can also define the time interval between disturbance years, how many patches should be burned in such a year and how large a burned patch should be. Furthermore, the percentage of patches that undergo a strong disturbance can be specified.

5. Results

As the main objective of this research was the process of formulating the model and the model as a whole, in this section we present two simulation scenarios and their outcomes only to observe the model functioning, disregarding the model parameterization that has to be done in a further work. These simulations should reproduce the Araucaria Forest dynamics behavior proposed by the theories explained in section 3, considering two scenarios: with and without disturbance.

For the simulation without disturbance, it is expected that araucaria population would disappear after the first generation, as proposed by Klein (1960) (see section 3). In a scenario with disturbance araucaria trees should regenerate after removal of the understory biomass that inhibits seedlings' establishment. The Temporal Stand Replacement model (see section 3) claims that after a first strong generation, a second weaker generation would develop.

For these scenarios, the model run simulations for 900 years, in an area of 250 m by 250 m, initiating with 20 seeds randomly located. The first simulation (A) did not contain any disturbance. The second simulation (B) includes 20 fire disturbances every 50 years (square patches of 10 m by 10 m), removing the entire understory, all young araucaria trees (< 15 years) and, in strong disturbances, 3 % of the adult ones.

A) Simulation without disturbance

In the simulation without disturbances, araucaria trees reproduce and spread over the area. After about 340 years, the area is mostly covered by araucaria trees and at the same time, the trees start to die out, there is no more regeneration happening after 410 years. From this moment on, the population only gets older and smaller, and after about 750 years, the last individual dies (Figure 2).

B) Simulation with disturbance (B)

In the beginning, the development of the forest is similar to the one without disturbances: araucaria colonizes the area and the trees start to die out around the year 370. After disturbance events, some regeneration takes place, but the number of trees that establish is not very high the population still decreases, until it only covers about a third of the area after 600 years (Figure 3). Helped by the disturbances, the population can regenerate and even slowly increase in number. This second cohort develops slowly, as it depends on disturbance to open space for regeneration. After 900 years, by the end of simulation, about two thirds of the area is covered by araucaria trees again. The population is at its lowest number, but still much larger than in the simulation without disturbances (Figure 4).

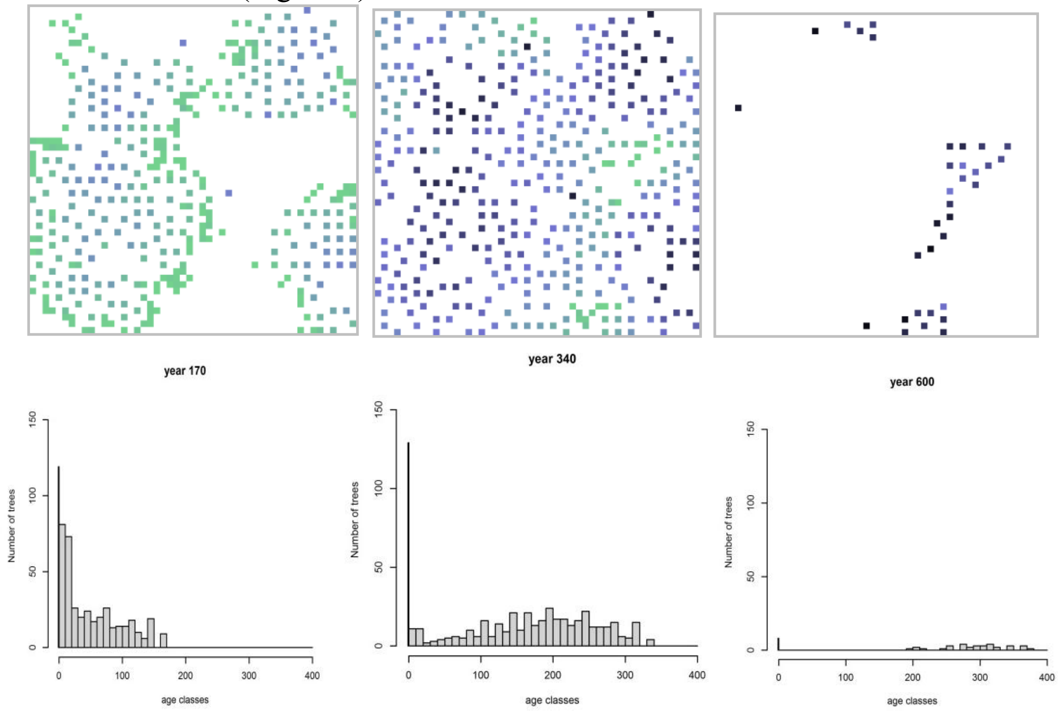

Figure 2. Simulation without disturbance: araucaria population after 170, 340 and 600 years; individual trees color-coded from green (young) to dark violet (old); histograms showing respective age classes.

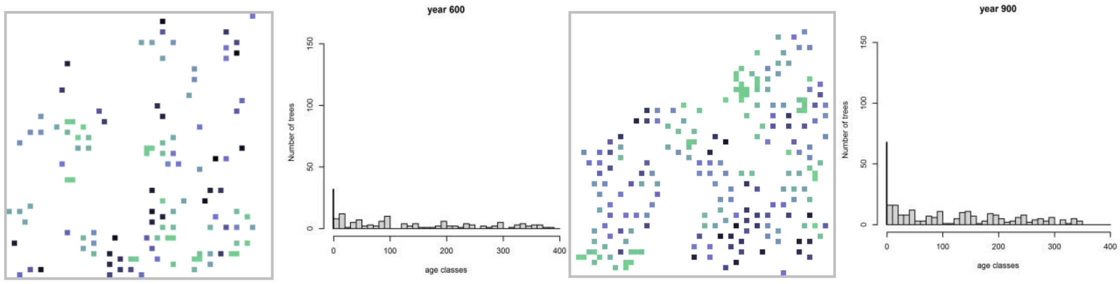

Figure 3. Simulation with fire disturbance: Araucaria population after 600 and 900 years; histograms showing respective age classes.

6. Conclusions

At this work, the agent-based model reproduced the forest dynamics proposed by theories, and in accordance with research results from a permanent plot in an Araucaria Forest remnant in Southeast Brazil [Valeriano 2010]. Rather than providing a new forest dynamics computer model, this research contributes to the process of modeling a forest ecosystem. During the iterative process the influence of the modeled properties on the forest was clear, improving our understanding about the ecosystem functioning.

When formulating, implementing and testing the model, we could see from the results what was missing or not well represented in our simulation. When the results diverged from expected, we studied the reason for this unrealistic behavior, which aspects were not well represented or where important properties were missing, adapting the model until it presents reasonable results. This way, we could find out which aspects of the forest had influenced the araucaria population development and how.

The simulation outcome shows that, despite its shortcomings, the model in its current status is able to depict the theories. Of course, the outcomes do not realistically represent existing Araucaria Forests. For example, the density of araucaria is too high and the time needed for colonizing an empty area is faster than expected.

Two aspects of the model need to be improved: the parameterization and the model itself. To make the results more evidence-based and thus more realistic, it is necessary to use data collected in different study sites to summarize information about recruitment, dispersion mechanisms, growth rates, mortality, light environment, seed dispersal and fire events. Submodels of ecosystem processes have been simplified, mainly understory and disturbance dynamics, and therefore they need to be refined in order to better reproduce real processes.

Taking into account all caveats, this work is considered a useful exercise in formalizing the knowledge about a complex system. Forest managing projects can benefit from computer models: once the model is fed with realistic and calibrated parameters, it can provide information about the behavior of the ecosystem in unknown situations, e.g. about the future or about different disturbance / climate change / harvesting scenarios.

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