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DEVELOPMENT OF AN AGENT-BASED MODEL TO SIMULATE THE DYNAMICS OF FORESTS WITH LONG-LIVED PIONEER SPECIE

Merret Buurman
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Technical Report of Research Activity - Projeto IVA/FAPESP.

URL of the original document:
<http://urlib.net/8JMKD3MGP7W/3E2SL7L>

INPE
São José dos Campos
2013

PUBLISHED BY:

Instituto Nacional de Pesquisas Espaciais - INPE
Gabinete do Diretor (GB)
Serviço de Informação e Documentação (SID)
Caixa Postal 515 - CEP 12.245-970
São José dos Campos - SP - Brasil
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sid.inpe.br/mtc-m19/2013/04.30.13.24-RPQ

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ACKNOWLEDGEMENTS

We would like to thank Dr. Pedro Ribeiro de Andrade and MsC. Raian Vargas Maretto for their kind assistance with the use of TerraME and Dalton de Morisson Valeriano for providing important help in discussions about aspects of forest dynamics that were relevant for this model.

We would also like to thank all other colleagues who contributed to this project by providing their critics and suggestions during the processes of model development.

Financial support for Diana Damasceno Valeriano was granted by CNPq (Brazilian Research Council) PCI-DA research scholarship.

This research activity was developed in the scope of FAPESP Project "Assessment of Impacts and Vulnerability to Climate Change in Brazil and Strategies for Adaptation Options - IVA".

ABSTRACT

This research project consisted in developing a simple agent-based model to represent the dynamics and behavior of a forest structurally dominated by the long-lived pioneer species *Araucaria angustifolia*. The objective was to represent complex ecosystems in a meaningful simplified way and to exercise the modeling process. Using TerraME as computational plataform, and LUA language, we represented the succesional evolution of Ombrophilous Mixed Forest, considering the colonization dynamic from *A. angustifolia* life cycle. During the modeling process, we acquired a better understanding of the modeled ecosystem and about the formalization of complex ecosystems in general.

UM MODELO BASEADO EM AGENTE PARA SIMULAR A DINÂMICA DE FLORESTAS COM ESPÉCIES PIONEIRAS LONGEVAS - O CASO DA *Araucaria angustifolia*

RESUMO

Neste projeto de pesquisa foi desenvolvido um Modelo Baseado em Agentes simplificado para representar o comportamento e a dinâmica de uma floresta dominada estruturalmente por *Araucaria angustifolia*, uma pioneira longeva. O objetivo foi ganhar experiência na representação de ecossistemas complexos de maneira simples e significativa visando a melhor compreensão do processo de modelagem. A sucessão ecológica de uma floresta Ombrófila Mista foi simulada a partir do ciclo de vida da *A. Angustifolia,* usando o TerraME como plataforma computacional, e a Linguagem LUA para implementação do código. Durante o desenvolvimento do modelo, melhoramos a compreensão sobre o ecossistema e simplificamos os principais fatores de representação de sistemas complexos de forma geral. O modelo computacional foi testado através de simulação para reproduzir os modelos conceituais propostos na literatura, representando a dinâmica de florestas dominadas por pioneiras longevas. Embora o modelo proposto e implementado ainda tenha algumas limitações, os resultados indicaram o potencial da ferramenta para aprendizado e simulação de processos ecológicos.

FIGURES

Page

Figure 3.1.1 - Model of a cohort structure in a forest with long-lived pioneers. Each lozenge-shaped box represents the amount of biomass of a cohort. Source: Ogden & Stewart 1995. 6

Figure 3.1.2 - Biogeographical model of forest expansion: (1) *A. angustifolia* recruitment in open fields; (2) Broad-leaf trees development underneath Araucaria crowns; (3) *A. angustifolia* only present as old trees; (4) *A. angustifolia* excluded from inside the forest. Source: Klein 1960. 7

Figure 3.1.3 - Gap model: 1) gap formation; 2) gap cicatrization; 3) structural regeneration. Source: adapted from Klein (1960) and Ogden & Stewart (1995). 7

Figure 3.2.1 - Dispersion of A. angustifolia: a) Short distance dispersion – *A. angustifolia* expansion in the forest border; b) long distance dispersion – *A. angustifolia* colonizing grassland hills. Photographs by D.D. Valeriano in Campos do Jordão State Park. 9

Figure 3.3.1 - Lifecycle of an *A. angustifolia* tree. 10

Figure 3.4.1 - Possible spatial pattern of *A. angustifolia* 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 per cell........... 15

Figure 3.4.2 - Cell weights for seed dispersal around the mother tree. The red cell is the location of the mother tree and receives no seeds. The light blue rings receives cells, but less than the dark blue ring (which has double the weight). If the user specifies a larger region, all cells in additional rings will have the same weight as the cells in the light blue ring............................ 16

Figure 3.4.3 - Growth curve of the *A. angustifolia* trees: The height of a tree follows this curve. The x axis represents the age of the tree in years and the y axis the height of the tree in meters. 17

Figure 3.4.4 - The shades provided by trees of different ages. Very young trees provide no shade (A). Older trees provide small, light shades (B) and even older provide larger and darker ones (C). The ages of transition between

the states A, B and C can be specified by the user. The light transmission values written in the cells are example values. The user can specify the shade values. 17
Figure 3.4.5 - Overlapping shades. When shades by neighboring trees overlap, their light transmission values are multiplied to establish how much light reaches the ground or the understory in a cell. 18
Figure 3.4.6 - Understory shade. This figure shows how the light that passes through the *A. angustifolia* crown cover is diminished by the understory before reaching the ground. In this example, 70 % of the sunlight reaches the understory, which has a light transmission of 0.8, so 80 % of the 70 %, i.e. 56 % reaches the floor.. 19
Figure 3.4.7 - Understory development. Diagram showing how understory responds to the amount of light that reaches it.. 20
Figure 3.4.8: Gap size and position. The dark blue cell is the falling tree's location, and its root gap. The blue region around it is the region where the center of the gap may be, given a maximum distance of 2 cells. Every cell inside this region has the same probability of becoming the gap's center. The light blue square overlaid is a possible gap, given a gap size of 2 cells. 21
Figure 4.2.1 - State of the *A. angustifolia* population after 170 years (no disturbance). The map of the simulation space (left) shows locations of the *A. angustifolia* individuals color-coded from green (young) to dark violet (old). The age distribution plot shows the distribution of the individuals' ages. The area is being invaded starting from the several initial (female) trees, forming a kind of front. In the age distribution, a strong presence of young plants is visible. 25
Figure 4.2.2 - State of the *A. angustifolia* population after 240 years (no disturbance). Recruitment has been visibly reduced, as less open space is available. 26
Figure 4.2.3 - State of the *A. angustifolia* population after 340 years (no disturbance). The area is covered by A. angustifolia-dominated forest..... 26

Figure 4.2.4 - State of the *A. angustifolia* population after 470 years (no disturbance). Large parts of the population have died. In the age distribution diagram, it is visible that regeneration is not taking place. 27
Figure 4.2.5 - State of the *A. angustifolia* population after 600 years (no disturbance). Large parts of the population have died............................... 27
Figure 4.3.1 - State of the *A. angustifolia* population after 340 years (with disturbance). The population's state of development is very similar to the one in run A, without disturbances. 28
Figure 4.3.2 - State of the *A. angustifolia* population after 470 years (with disturbance). The population is slightly larger than in the simulation without disturbances and has more young individuals... 28
Figure 4.3.3 - State of the *A. angustifolia* population after 600 years (with disturbance). The population is at its lowest number, but still much larger than in the simulation without disturbances.. 29
Figure 4.3.4 - State of the *A. angustifolia* population after 900 years (end of the simulation) (with disturbance). Compared to fig. 20, the population has slightly recovered. 29

TABLES

Page

Table 3.1.1 - The submodels proposed and their functions 14

Table 3.5.1 - Maps provided as model output during the simulation process ... 23

TABLE OF CONTENTS

Page

1 INTRODUCTION……………………………………………………………1

2 OBJECTIVE...4

3 METHODOLOGY…………………………………………………………5

3.1 Conceptual models to describe forest dynamics............................ 5

3.2 Model formulation process... 8

3.3 The conceptual model 9

3.4 Realization of the conceptual model 13

3.5 Technical details of the implementation 22

3.5.1 The development environment TerraME 22

3.5.2 Outputs of the model 22

4 RESULTS 24

4.1 Simulation without disturbance (A) 25

4.2 Simulation with disturbances (B).. 27

5 FUTURE WORK 29

5.1 Model evolution.. 30

5.2 Parametrization... 32

6 CONCLUSIONS... 32

7 REFERENCES 34

Appendix A. R Script to create age distribution graphics............... 37

Appendix B. Parameters used in the simulations........................... 38

1 INTRODUCTION

The Ombrophilous Mixed Forest of Southern Brazil, also referred to as Araucaria Forest, includes a larger area in the Southern States of Brazil, and isolated patches in mountainous areas in the Southeast region (HUECK 1972). Two components with distinct functional characteristics formed the Araucaria Forest: the conifer *Araucaria angustifolia* (Bertol.) Kuntze, the Brazilian pine, an emergent tree that dominates the forest physiognomy; and different species of Angiospermae, associated to Araucaria, that compose the forest canopy and understory (IBGE, 1992).

Functional and structural differences between these two forest components play a crucial role in forest dynamics. *A. angustifolia* is a long-lived pioneer (LONGHI 1980; SOUZA et al. 2007), expressively larger than the other components of the forest, and, being heliophytic, requires disturbances to ensure its recruitment (BACKES, 2001). Its presence in the forests of the Southern Plateau of Brazil is indicative of instability of the tree synusiae[1] (HUECK, 1953; KLEIN; 1960). Based on the major role performed by this species on the forest dynamics, we decided to construct the first attempt to model the forest dynamics based on *A. angustifolia* life cycle and its population expansion.

The need to evaluate the current status of Araucaria Forest remnants and *A. angustifolia* populations arises from the significant reduction of its original area. In Southern Brazil it is estimated that 87% of Araucaria Forests were 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 (SANQUETA; MATTEI, 2006). Studies that assessed the population structure of *A. angustifolia* in the remaining forested areas, with different disturbance histories, recorded the presence of large trees and very few juveniles in preserved forests and high recruitment in disturbed areas (SOUZA

[1] Synusiae is a structural unit of a plant community characterized by uniformity of life-form or of height.

et al., 2008; VALERIANO, 2010). This observation raised the question about the persistence of this species in preserved areas without disturbance.

The Araucaria Forest ecosystem was represented using the agent-based modeling paradigm. Agent-based models are models based on the behavior of individual entities, in this case the *A. angustifolia* trees, which together form a complex system. 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; CROOKS, 2006).

In general, this kind of model is used when something is known about the individuals' behavior and one is looking for an emergent behavior: "Generally, one is looking for emergent phenomena, that is some patterns arising at the level of the system as a whole that are not self-evident from consideration of the capabilities of the individual agents." (GILBERT; TERNA, 1999).

This kind of modeling is frequently used in the social sciences, as it allows to model the behavior of societies or other groups of human beings based on individual human decision-making (CROOKS et al., 2008). As nature also has complex systems agent-based modeling is also useful for the geographical domain (CASTLE; CROOKS, 2006).

This modeling paradigm was chosen because we were interested in how the behavior of the individual *A. angustifolia* trees reflects the behavior of the entire population. An agent-based model allows the identification of which properties of the trees affect the population's behavior, and to what degree.

This report describes the process of building an Agent-Based Model (ABM) to simulate Araucaria Forests dynamics. Forest dynamics concerns the changes in forest structure and composition over time and can be analyzed at different spatial and temporal scales. As the life span of a tree, and by consequence the development of a forest, ranges from many decades to centuries, simulations through modeling are important tools to help understand forest dynamics and predict possible future scenarios.

The purpose of this project was to set up a learning environment to build a simulation of a natural process. This was possible through a profitable interlocution between biologists, ecologists and computer sciences experts focused on better understanding the complexity of forest dynamics and on achieving possible simplifications to represent it.

2 OBJECTIVE

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 METHODOLOGY

In this section we will describe the model development process. First, we will describe the existent conceptual models that aim to explain the behavior of *A. angustifolia* forest dynamics (section 3.1). Then, we will explain the sequence of steps we performed (section 3.2), the resulting conceptual model (section 3.3), its implementation as a computer model and some technical details (sections 3.4 and 3.5).

3.1 Conceptual models to describe forest dynamics

Conceptual models, briefly described on this section, have been historically used to investigate the dynamics of forests with long-lived pioneers. These theoretical references were considered as starting points for the computational modeling proposed.

3.1.a)Temporal Stand Replacement

The Temporal Stand Replacement model (Ogden 1985; Ogden & Stewart 1995) hypothesizes that intermittent recruitment pattern influences the dynamics of long-lived pioneers, and that the recruitment pattern is dependent on severe disturbances (Figure 3.1.1). In our case, the recruitment of *A. angustifolia*, that structurally dominate the forest, depends on disturbances regime.

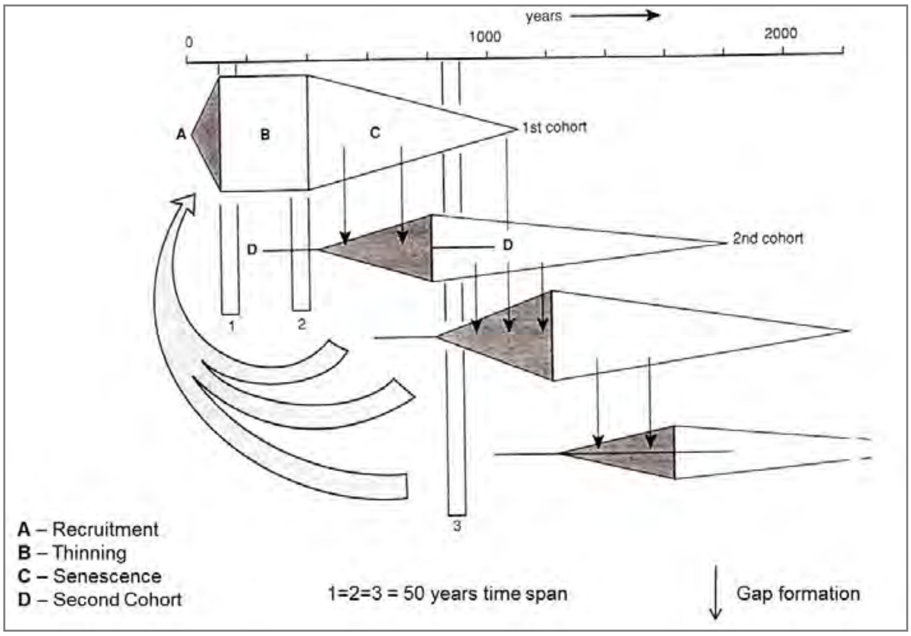


Figure 3.1.1 - Model of a cohort structure in a forest with long-lived pioneers. Each lozenge-shaped box represents the amount of biomass of a cohort. Source: Ogden e Stewart (1995).

3.1.b) Biogeographical Model of Forest Expansion

The Biogeographical Model of Forest Expansion (KLEIN, 1960) hypothesizes that the presence of a population of *A. angustifolia* inside a forest indicates ongoing succession, and that the fate of this species is to be substituted by broad-leaved trees (Figure 3.1.2).

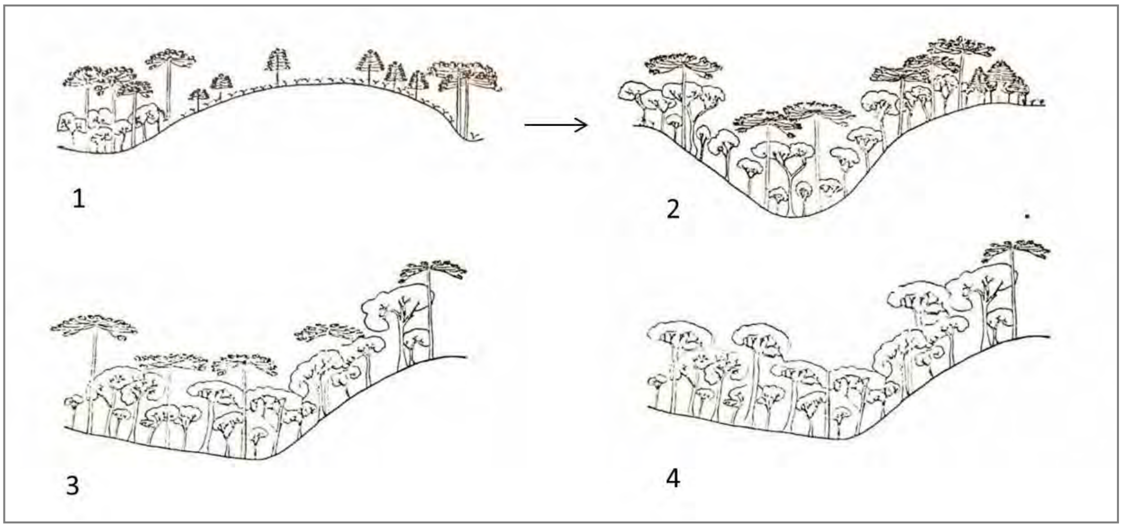


Figure 3.1.2 - Biogeographical model of forest expansion: (1) *A. angustifolia* recruitment in open fields; (2) Broad-leaf trees development underneath Araucaria crowns; (3) *A. angustifolia* only present as old trees; (4) *A. angustifolia* excluded from inside the forest. Source: Klein (1960).

3.1.c) Gap Model – Autogenic Succession

This hypothesis by Jarenkow & Batista (1987) states that a gap formed by a falling *A. angustifolia* establishes conditions that allows its own recruitment inside the forest (Figure 3.1.3).

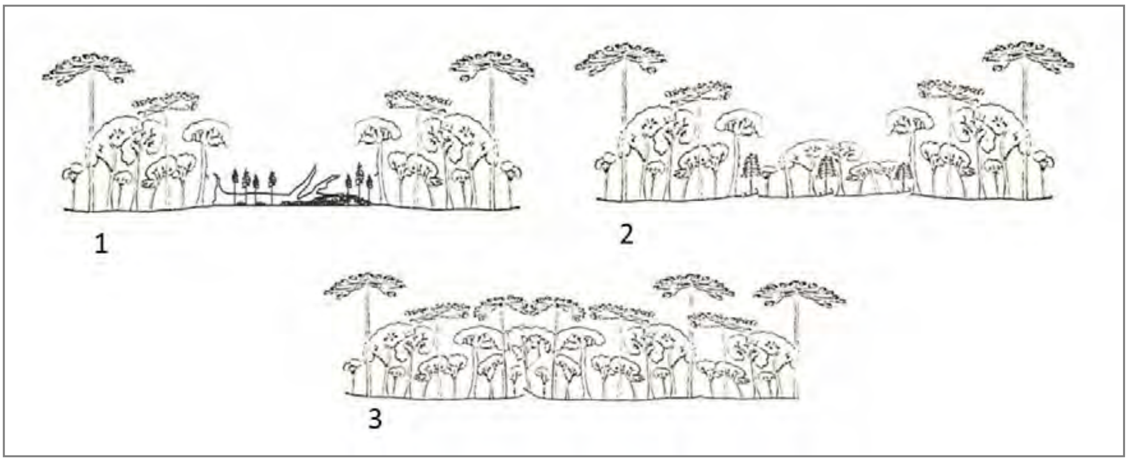


Figure 3.1.3 - Gap model: 1) gap formation; 2) gap cicatrization; 3) structural regeneration. Source: adapted from Klein (1960) and Ogden & Stewart (1995).

3.2 Model formulation process

Before deciding which model to use, we discuss at regular meetings the theoretical assumptions about the ecosystem under investigation, and the possibilities and limitations of a computer simulation. The methodological approach can be simplified in two phases. At Phase 1 we discuss the general theory, ideas, concepts, parameters and purposes for the modeling, and at Phase 2 the conceptual model was implemented. The main steps for each phase are summarized below.

<u>Phase 1:</u>

a) Discussions and literature review about Araucaria Forests in Brazil.

b) Discussions and literature review about forest dynamics.

c) Discussions and literature review about the role of long-lived pioneers on forest dynamics.

d) Definition of the model purpose.

e) Discussion about how to represent a complex ecosystem with few parameters.

f) Decision about which parameters would represent the process under investigation in the simulation.

g) As a first attempted to build a model the group decided to simulate the life cycle of A. angustifolia, considering it as the driving force in the establishment and evolution of the Araucaria Forest.

h) The questions to be answered were: Is *A. angustifolia* able to recruit inside the forest? Is the species recruitment dependent on disturbances?

g) The final stage of phase one was a fieldwork in a State Park (Campos do Jordão State Park, São Paulo State) to observe the ecosystem to be represented by the model simulation. During the fieldwork we identified sites where *A. angustifolia* recruits to characterize the species dispersion distances (Figures 3.2.1a and 3.2.1b).

a)  b) 

Figure 3.2.1 - Dispersion of A. angustifolia: a) Short distance dispersion – *A. angustifolia* expansion in the forest border; b) long distance dispersion – *A. angustifolia* colonizing grassland hills. Photographs by D.D. Valeriano in Campos do Jordão State Park.

Phase 2:

In phase 2, the model was implemented and refined by iteratively running it, evaluating the results and adapting the model. The resulting model is described in the following sections. All the input values to run the model were arbitrary numbers, as our objective was to set up a learning environment to build a simulation of a natural process.

3.3 The conceptual model

To simulate the forest's dynamics using a computer model, we first had to formalize its behavior and to define which aspects of it we consider crucial to represent. In this section, we will describe the outcome of this simplification and formalization.

We focus on the representation of A. angustifolia, modeling, considering the behavior of individual trees. A well-defined life cycle describes *A. angustifolia* life from seed stage to death. The important aspects selected to be modeled were: reproduction, growth, shade, understory (the *A. angustifolia* trees' interaction with the understory) and tree-fall gaps. Furthermore, disturbances were modeled to evaluate their effect over the forest.

All other species present in the forest were unified as "understory" and we modeled their behavior as a whole.

3.3.a) Lifecycle

During its life, an *A. angustifolia* tree traverses four stages: seed, juvenile plant, reproductive adult plant and post-reproductive adult plant (Figure 3.3.1). An age threshold defines the trees step from one stage to the other, or if some particular conditions is reached.

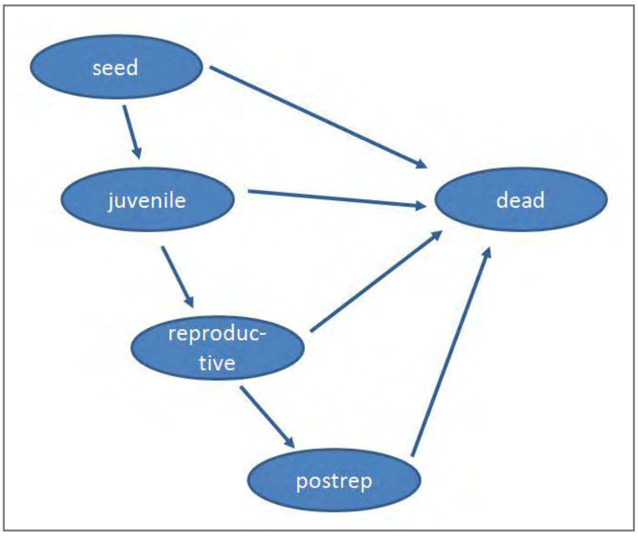


Figure 3.3.1 - Lifecycle of an *A. angustifolia* tree.

A seed turns into a juvenile plant in one year after its creation: if the parent tree releases seeds in one year, the seed will turn into a juvenile plant in the following year if enough light reaches the forest floor to enable germination. When a certain age threshold is attained a juvenile plant either turns into a reproductive tree or, if there are adult trees too close to it, it dies from competition for light and other resources. A juvenile tree dies before reaching this age threshold if a nearby juvenile tree turns adult. When reaching another age threshold, the reproductive tree turns into a post-reproductive one. The age at which a post-reproductive tree dies of old age (natural death age) is expressed as an age range. This avoids all trees of a generation dying exactly at the same time.

Every year, a fraction of the trees die by chance, to represent deaths happening before the tree could reach the natural death age, caused by events such as diseases or competition between trees. Modeling explicitly competition was beyond the scope of this work, at this initial version.

Trees of any age and stage can die in consequence of disturbances such as fire or the falling of other trees that generate tree-fall gaps.

3.3.b) Reproduction

As *A. angustifolia* trees are dioecious, only a part of the population's individuals is females. Every female individual reproduces yearly while in the reproductive stage. The female produces a certain number of seeds that fall to the ground around the mother tree, most of them at approximately 10 m distance from the trunk. Locations that are closer or farther away from the trunk are possible, but less likely. A large fraction of the seeds dies by predation or similar phenomena.

3.3.c) Distances between trees

The forest develops in a flat two-dimensional space. The effects of relief were not taken into account at this model version.

Adult *A. angustifolia* trees cannot grow very close to each other. We assume a minimum distance of 10 m between them. Younger trees can be closer to each other and closer to adults, but the spatial density of trees should not exceed 800 trees/ha.

3.3.d) Growth

As a measure of tree size this model used tree height. During their first years of life, trees grow relatively fast. We assume that at the age of 45 years, the tree reaches 25 m of height. Afterwards, the tree has a lower, constant growth. At the age of 400 years it reaches 30 m of height, unless it has died before reaching this age.

3.3.e) Shade

Every *A. angustifolia* tree that exceeds a certain age threshold provides a shade. Size and opacity of this shade depend on its age. Shade is modeled as the fraction of the sunlight that the *A. angustifolia* tree allows to pass through its crown, for example, 70 % of the light passes through the crown and the remaining 30 % are intercepted.

If trees are standing close to each other, their shades overlap. In this case, the light transmission values of the various individual shades are multiplied to establish how much light passes through the *A. angustifolia* crown cover.

3.3.f) Understory

The only aspect of understory that was important in the context of this model is its shade, as it keeps the *A. angustifolia* seeds and young plants from establishing themselves. Thus, the shade is the only aspect of understory that is modeled. Species, height and individuals are not considered. The understory is represented by a value of light transmission between 100 % (i.e. no understory is present, so all the light is transmitted) and a lower percentage (representing strong understory).

As soon as the *A. angustifolia* trees provide a certain level of shading, the understory begins to develop. As long as the *A. angustifolia* continues to provide shade, the understory continues to increase until it reaches its maximum. If the shade provided by the *A. angustifolia* 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 *A. angustifolia* shade is removed or weakened, and can only be removed by tree-fall gaps (see next paragraph) or other disturbances.

3.3.g) Tree-fall gaps

When large *A. angustifolia* trees (above a height threshold) fall, they cause gaps in the vegetation that facilitate the development of new vegetation. The crown of a large tree can fall on other trees, causing their respective death.

Furthermore, their roots cause an opening in the soil. In this model, we call these two types of gaps crown gaps and root gaps, respectively.

The crown gap is located at a distance of some meters from the trunk's location and it is usually larger than the root gap. When a tree falls, it kills all *A. angustifolia* trees that are growing in the gap and the understory is partly removed.

3.3.h) Disturbance

So far, only fire disturbance is considered in the model. It is modeled as patches in which a part of the vegetation is removed, freeing space for its renewal. There are two intensities of disturbances: weak and strong ones. The understory and young trees (below an age threshold) are completely removed in both disturbance intensities. Adult trees survive weak disturbances, while strong disturbances kill some of them.

Disturbance regimes are defined by the time interval between disturbance events, the number of disturbed patches in a disturbance event and by the percentage of strongly and weakly disturbed patches.

3.4 Realization of the conceptual model

The different requirements of the conceptual model were translated into computer concepts. The source code of the model will be made available as TerraMe examples[2]. For further information, please refer to the authors of this report.

The implementation is structured into a main part, representing the lifecycle of the *A. angustifolia* trees, and the submodels, representing growth, shade, reproduction, gaps and understory.

The main part is responsible for the creation of the simulation area and the trees and for controlling the sequence of events. At every time step, it

[2] http://www.terrame.org/doku.php?id=examples

increments the age of all trees and changes their states (juvenile to reproductive, etc.) if applicable. Then, the various submodels are called. Some submodels are executed for every single tree, while others are executed once for the whole simulation space (Table 3.1.1).

Table 3.1.1 - The submodels proposed and their functions

Submodel *	Execution	Procedure
Growth	For every single tree	Computes and adds the growth of every single tree
Shade	For every single tree	Computes the light transmission by a single tree
	For the whole simulation space	Computes the light that reaches the forest floor at each cell
Reproduction	For every single tree	Produces and places seeds
Tree-fall gap	For every single tree	Creates gaps and removes the vegetation in it, if applicable
Understorey	For the whole simulation space	Determines the understory development and computes the light transmission by the understory in each cell

* The modules are not listed in the sequence of execution.

3.4.a) Cell space

The simulation space is a two-dimensional flat space consisting of square cells that represent patches of 5 m by 5 m in the real world.

3.4.b) Agents

Only *A. angustifolia* trees are represented as agents. All other species together form the understory and are not modeled as separate species nor as individual plants.

3.4.c) Life cycle

The life cycle of the *A. angustifolia* trees is modeled according to the previous description (section 3.3). The age thresholds at which the transitions between the life stages happen are modeled as parameters, so the user can adapt them according to his/her needs. In case of death by old age, the user can specify the average death age and a range of years. Each tree's individual death age will then be drawn from a uniform distribution centered at the average death age and encompassing twice this range.

3.4.d) Spatial pattern of trees

The desired minimum distances between trees and the maximum tree densities is define for each 5 m by 5 m cells: there is at most one adult tree per cell. Adult trees cannot live in neighboring cells, so a distance of at least 10 m between adult trees is maintained (Figure 3.4.1a).

Seeds and juvenile *A. angustifolia* trees can be close to other seeds and juvenile trees and to adults: They can be in neighboring cells and in the same cell, while not exceeding a maximum of two individuals per cell (Figure 3.4.1b and 3.4.1c).

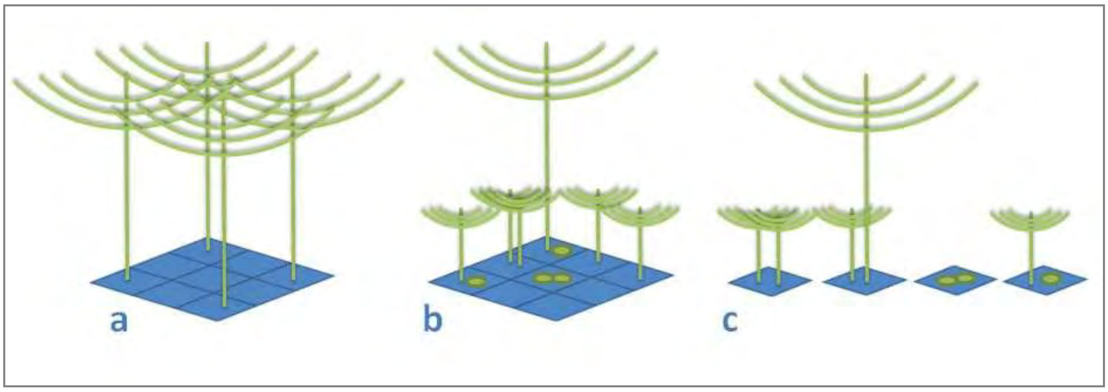


Figure 3.4.1 - Possible spatial pattern of *A. angustifolia* trees. (a) Adult trees cannot live in directly neighboring cells. (b) Seeds and juveniles can be in the same cells as other seeds and juveniles and as adults, and in neighboring cells. (c) Possible combinations of individuals per cell.

3.4.e) Reproduction

All female individuals start reproducing when they enter the reproductive state. The sex of a tree is determined by chance when the tree is created. The fraction of female/male trees can be specified by the user as a probability of each single individual to become a female.

As a large number of seeds will never germinate and establish, only a relatively small number of seeds is actually created. These seeds are positioned in cells around the mother tree based on weight, not in the cell of the mother tree itself. Seeds can fall into a square region around the mother tree whose extent can be specified by the user (Figure 3.4.2). The cells of that region have different probabilities of receiving seeds. Most seeds will fall on the second "ring", i.e.

between 7.5 m and 12.5 m away from the mother tree. The other rings receive less seed, as their cells have half the weight.

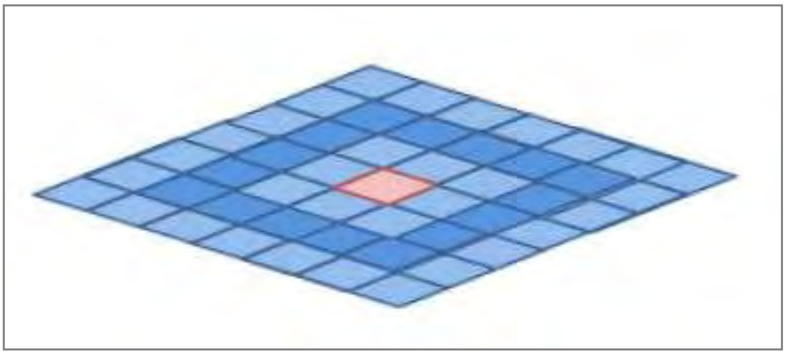


Figure 3.4.2 - Cell weights for seed dispersal around the mother tree. The red cell is the location of the mother tree and receives no seeds. The light blue rings receives cells, but less than the dark blue ring (which has double the weight). If the user specifies a larger region, all cells in additional rings will have the same weight as the cells in the light blue ring.

As the close proximity of a large adult *A. angustifolia* tree is not an appropriate location for establishment, a seed dies if it lands in a cell where an adult tree is present. If it lands in a cell where several *A. angustifolia* individuals are already present (regardless of the state, as two seeds, two juveniles, ...), it dies as well, as the maximum number of agents per cell is two (see section 3.4.d).

3.4.f) Growth

The *A. angustifolia* growth pattern outlined in section 3.3 is modelled by two growth functions. In the first 45 years, a tree's yearly growth in meters is computed by the function y = 3.279 * age -0.7 and added to the tree's current height. Afterwards, the growth per year is constantly 0.0143 m. Figure 3.4.3 presents the resulting growth curve.

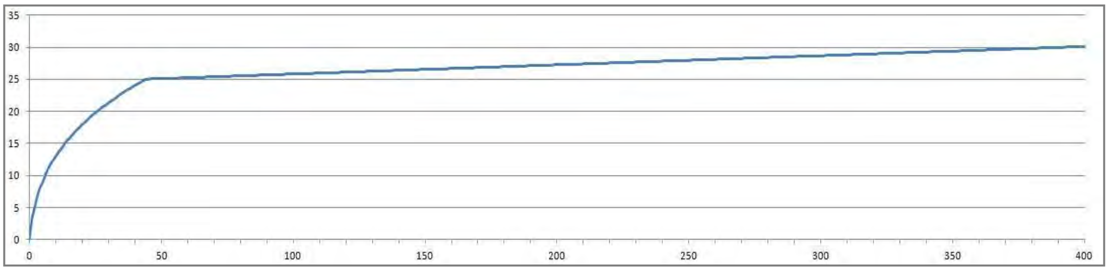


Figure 3.4.3 - Growth curve of the *A. angustifolia* trees: The height of a tree follows this curve. The x axis represents the age of the tree in years and the y axis the height of the tree in meters.

3.4.g) Shade

With a spatial resolution of 5 m, the tree shades' shapes cannot be modeled with high spatial accuracy. They are square regions around the tree and their size cannot increase continuously with the tree's growth.

In this model, very young trees have no shade (Figure 3.4.4a). As they exceed a user-defined age threshold, they provide a small shade (Figure 3.4.4b). Above another age threshold they provide a larger and darker shade (Figure 3.4.4c).

The light transmission value cannot vary inside a cell, so the area shaded by a single tree has to be made up of entire cells, i.e. its own cell and/or a neighborhood of cells around it. In this model, the shade of a young tree has the size of one cell (5 m * 5 m), while a larger tree shades has an area of 9 cells (15 m * 15 m) with a darker core shade and a lighter shade at the edges (Figure 3.4.4).

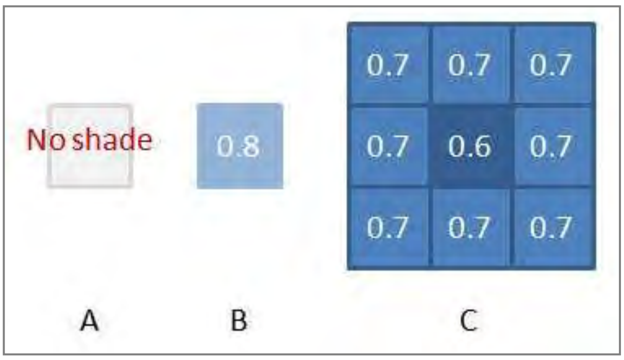


Figure 3.4.4 - The shades provided by trees of different ages. Very young trees provide no shade (A). Older trees provide small, light shades (B) and even older provide larger and darker ones (C). The ages of transition between the states A, B and C can be specified by the user. The light transmission

values written in the cells are example values. The user can specify the shade values.

The user can specify the ages of transition between the states A, B and C and the light transmission in these shades. The light transmission in a shade of state B, in the core of state C and in the edges of state C can be specified separately.

If trees are located close to each other or in the same cell, which is possible in the case of young trees, their shades overlap. Their light transmission values are thus multiplied to establish how much light passes through the *A. angustifolia* crown cover (Figure 3.4.5).

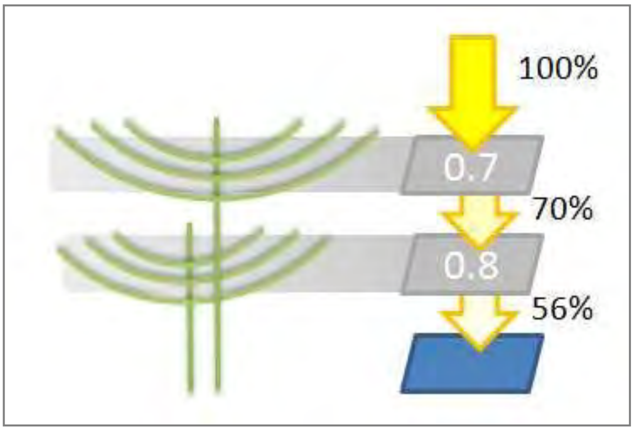


Figure 3.4.5 - Overlapping shades. When shades by neighboring trees overlap, their light transmission values are multiplied to establish how much light reaches the ground or the understory in a cell.

3.4.h) Understory

The understory is modeled as a value of light transmission in every cell, ranging from 1 (no understory, 100 % of the light passes) to a minimum value which is defined by the user. The light that passes through the *A. angustifolia* crown is multiplied by this value to determine how much light reaches the forest floor (Figure 3.4.6).

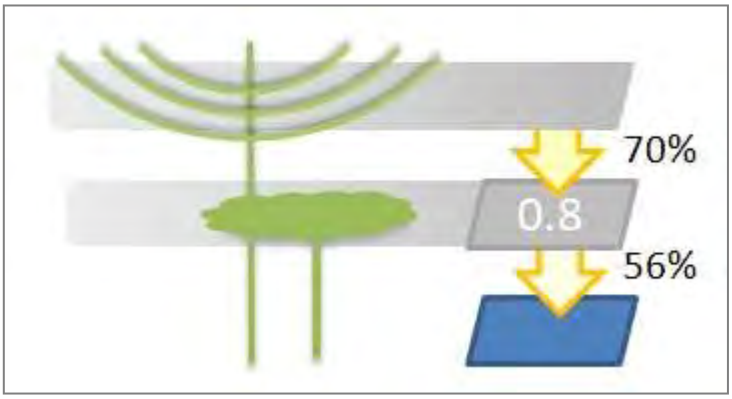


Figure 3.4.6 - Understory shade. This figure shows how the light that passes through the *A. angustifolia* crown cover is diminished by the understory before reaching the ground. In this example, 70 % of the sunlight reaches the understory, which has a light transmission of 0.8, so 80 % of the 70 %, i.e. 56 % reaches the floor.

The development of understory as a function of its own state and the light reaching its location is shown in Figure 3.4.7. There is no interaction between the understories in neighboring cells; the understory only depends on the light that reaches its very cell.

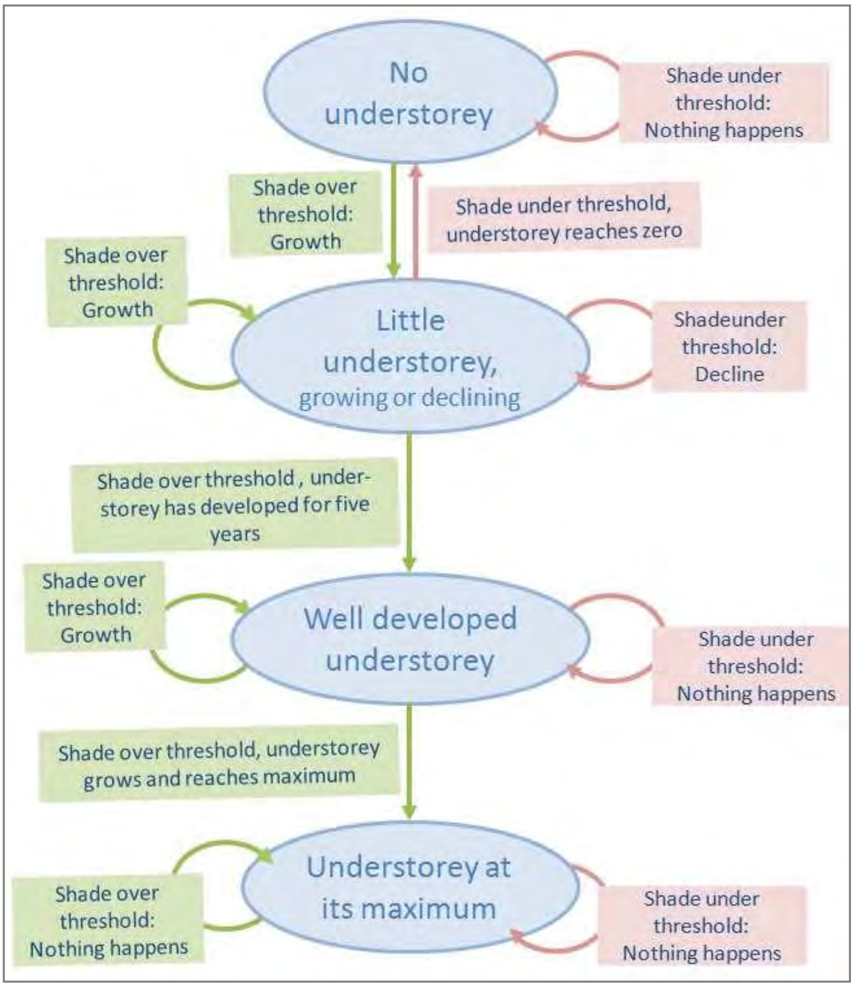


Figure 3.4.7 - Understory development. Diagram showing how understory responds to the amount of light that reaches it.

3.4.i) Tree-fall gaps

In this model, the crown gap is represented by a square region close to the location of the falling tree. All *A. angustifolia* trees that is growing in this gap region will die. The user can decide what should happen to the understory, whether it should be fully removed, partly removed or remain untouched. The root gap is limited to the cell in which the falling tree was growing. No (adult) *A. angustifolia* tree can be present in it because of the minimum distance between adult trees, so none are killed. The understory in the root gap can be fully or partly removed or remain untouched, like in the crown gap.

To cause a gap, a tree has to be an adult and above a certain minimum height (defined by the user). Also, an *A. angustifolia* that died by a gap itself will not create a gap. Otherwise, a domino effect would take place and kill many trees at a time.

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 (Figure 3.4.8).

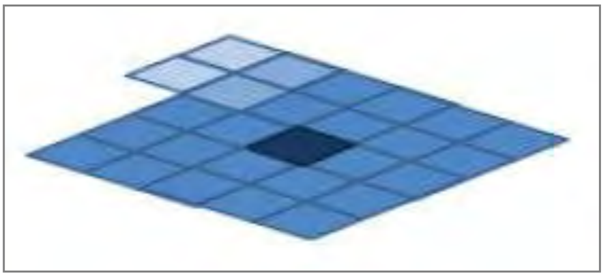


Figure 3.4.8: Gap size and position. The dark blue cell is the falling tree’s location, and its root gap. The blue region around it is the region where the center of the gap may be, given a maximum distance of 2 cells. Every cell inside this region has the same probability of becoming the gap’s center. The light blue square overlaid is a possible gap, given a gap size of 2 cells.

3.4.j) Fire disturbance

Fire disturbances are square patches of user-defined size, occurring at random locations in the simulation area. The understory and young trees beneath a certain fire resistance age (specified by the user) is completely removed in all disturbed patches. The percentage of older trees (trees above the fire resistance age) 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.

Besides that, the user can also define the time interval between disturbance years, how many patches appears in such a year and how large a patch should be. Furthermore, the percentage of patches that undergo a strong disturbance can be specified.

3.5 Technical details of the implementation

This section introduces the modeling environment TerraME and explains the outputs that allow users to evaluate the simulation results.

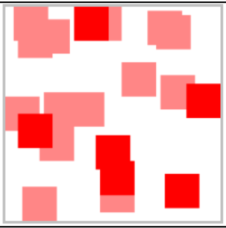
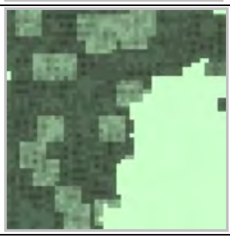
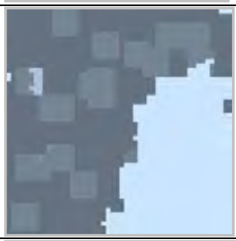
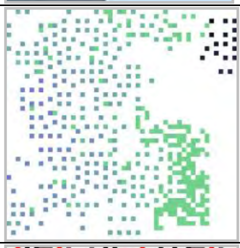
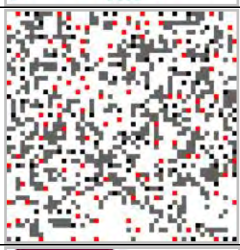
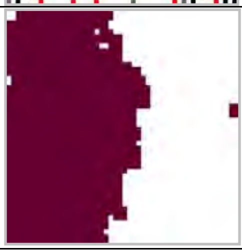
3.5.1 The development environment TerraME

The model was implemented using the open source modeling environment TerraME (www.terrame.org), developed by INPE and Universidade Federal de Ouro Preto (UFOP, Federal University of Ouro Preto) (Carneiro et al. 2013). TerraME is an environment aimed at supporting and facilitating spatial modeling using various paradigms (agent-based models, cellular automatons, map algebra etc.). It is an extension of the programming language Lua, providing data types and functions useful for (spatial) modeling, such as cells, cellular spaces, neighborhoods, automatons and agents. Some of the more computing-intensive behavior of these is implemented in C++, but the TerraME users does not have to use any C++. A (thorough) explanation of TerraME, including explanations of the paradigms, of the spatial data types and various examples, can be found in Carneiro et al. (2013).

3.5.2 Outputs of the model

To evaluate the outcome of the forest simulation, the model provides several types of outputs. Seven different maps are created for every simulation year (or less frequently, as defined by the user) by TerraME's built-in map-making functionality. Each map shows a specific aspect of the forest evolution, as presented at Table 3.5.1.

Table 3.5.1 - Maps provided as model output during the simulation process

Model Output	Forest phenomenon
	Locations and sizes of disturbed patches. Lighter red means weaker disturbances, darker red the stronger disturbances.
	Light getting through the *A.angustifolia* crown cover. The darker the cell, the more shade.
	Light reaching the floor. It shows the shading by *A. angustifolia* and by the understory.
	Shade provided by the understory. The darker the cell's color, the less light can go through the understory cover, i.e. more understory has developed there.
	Locations of the *A. angustifolia* trees by age. Every dot stands for a cell occupied by a tree. Light green represents young trees, blue trees the old trees.
	Location of the *A. angustifolia* trees by sex. Black dots represent cells occupied by adult females, red dots are adult males. The grey dots represent juvenile plants that do not reproduce yet.
	The presence of understory. The color does not give any information about the intensity of the understory; it only shows whether understory is present in a cell.

Besides the maps, text files provide the age distribution of the *A. angustifolia* population. One of the files gives the number of trees per age class for every year of the simulation (every line represents one year). The other file gives the age of every single tree that is alive in that year. From these files the user can make age distribution diagrams such as the ones shown in the next section. The open source software R was used [3] to generate such distribution graphs, and the script is presented in the appendix A.

4 RESULTS

In this section we present two simulation scenarios and their outcomes to show the model functioning. The goal was to see whether it is possible to reproduce the forest dynamics behavior proposed by the theories explained in section 3.1. For this purpose, we simulate the evolution of *A. angustifolia* forest considering two scenarios: with and without disturbances.

Scenarios

If no disturbance at all occurs in a forest, Klein (1960) expects *A. angustifolia* to disappear after the first generation (see section 3.1.b). Disturbance allows the regeneration of *A. angustifolia* by removing understory biomass that inhibits seedlings' establishment. The Temporal Stand Replacement model (see section 3.1.a) claims that after a first strong generation, a second weaker generation would develop.

The simulations of these scenarios were run for 900 years in an area of 250 m by 250 m. 20 seeds were present in the beginning, located at random locations in the area. 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 *A. angustifolia* trees (< 15 years) and, in strong disturbances, 3 % of the adult ones.

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[3] http://cran.r-project.org/

The complete parameters used for these simulations are listed in the Appendix B. The outputs of the model (maps and age distributions) can be found on the additional file, attached to this report.

4.1 Simulation without disturbance (A)

In the simulation without disturbances, *A. angustifolia* trees reproduce and spread over the area (Figure 4.2.1 and Figure 4.2.2). After about 340 years, the area is mostly covered by *A. angustifolia* trees (Figure 4.2.3). 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 (Figure 4.2.4 and Figure 4.2.5). After about 750 years, the last individual dies.

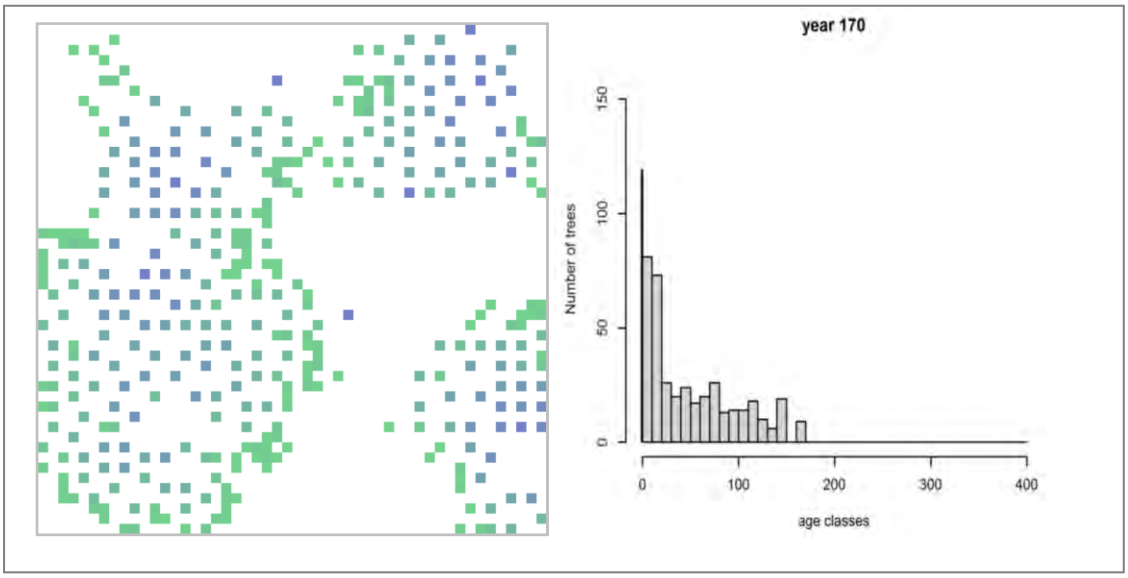

Figure 4.2.1 - State of the *A. angustifolia* population after 170 years (no disturbance). The map of the simulation space (left) shows locations of the *A. angustifolia* individuals color-coded from green (young) to dark violet (old). The age distribution plot shows the distribution of the individuals' ages. The area is being invaded starting from the several initial (female) trees, forming a kind of front. In the age distribution, a strong presence of young plants is visible.

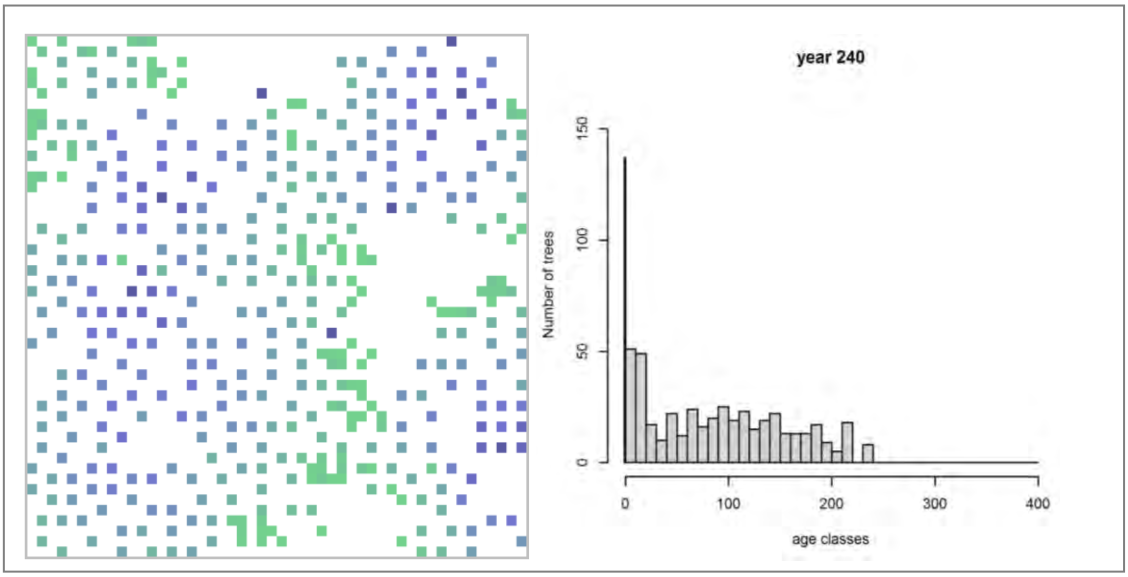

Figure 4.2.2 - State of the *A. angustifolia* population after 240 years (no disturbance). Recruitment has been visibly reduced, as less open space is available.

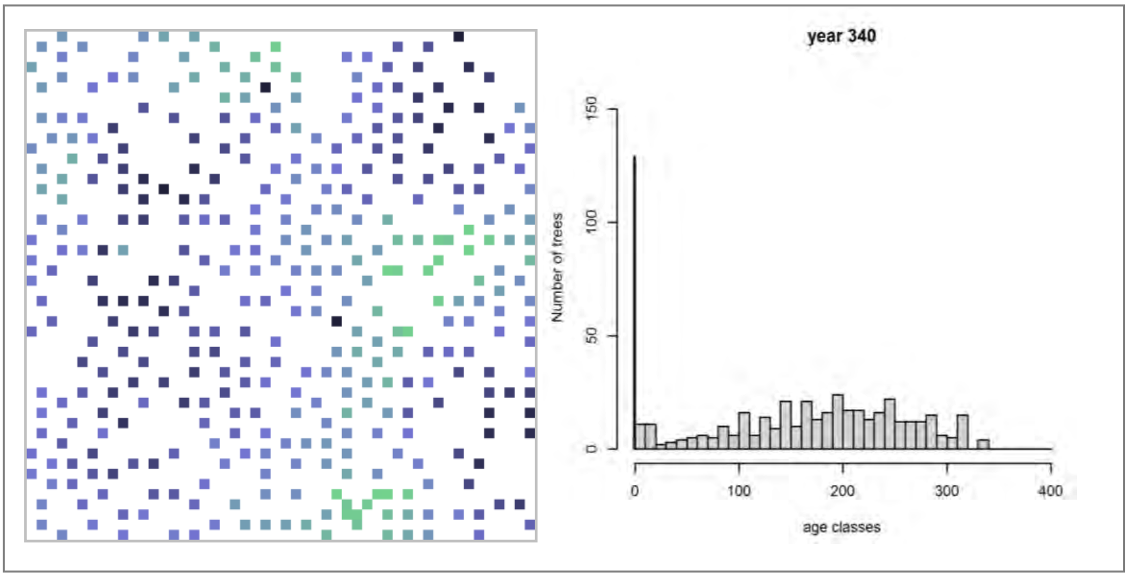

Figure 4.2.3 - State of the *A. angustifolia* population after 340 years (no disturbance). The area is covered by A. angustifolia-dominated forest.

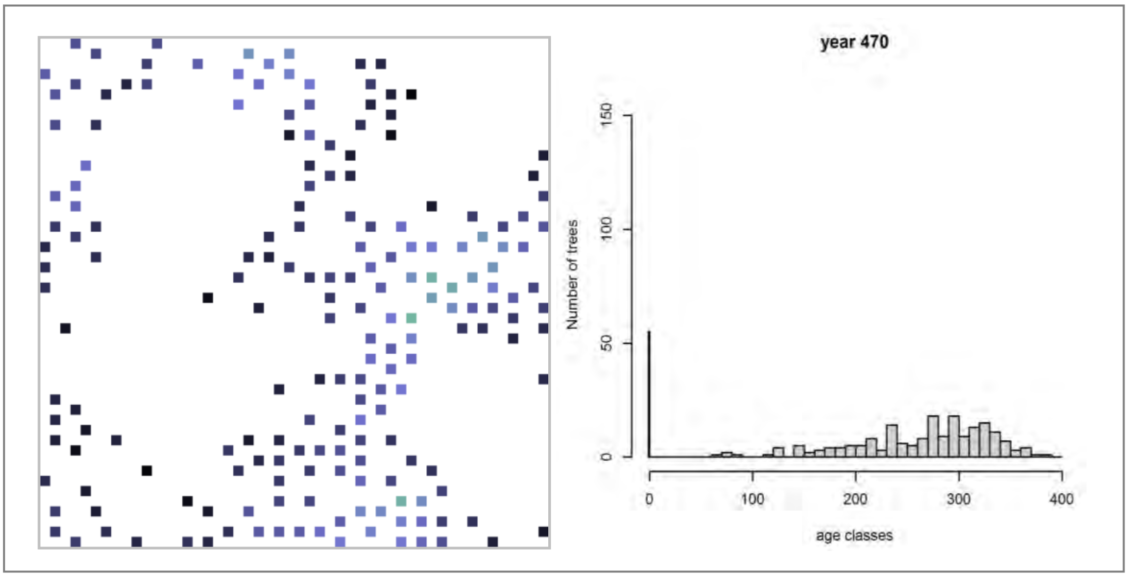

Figure 4.2.4 - State of the *A. angustifolia* population after 470 years (no disturbance). Large parts of the population have died. In the age distribution diagram, it is visible that regeneration is not taking place.

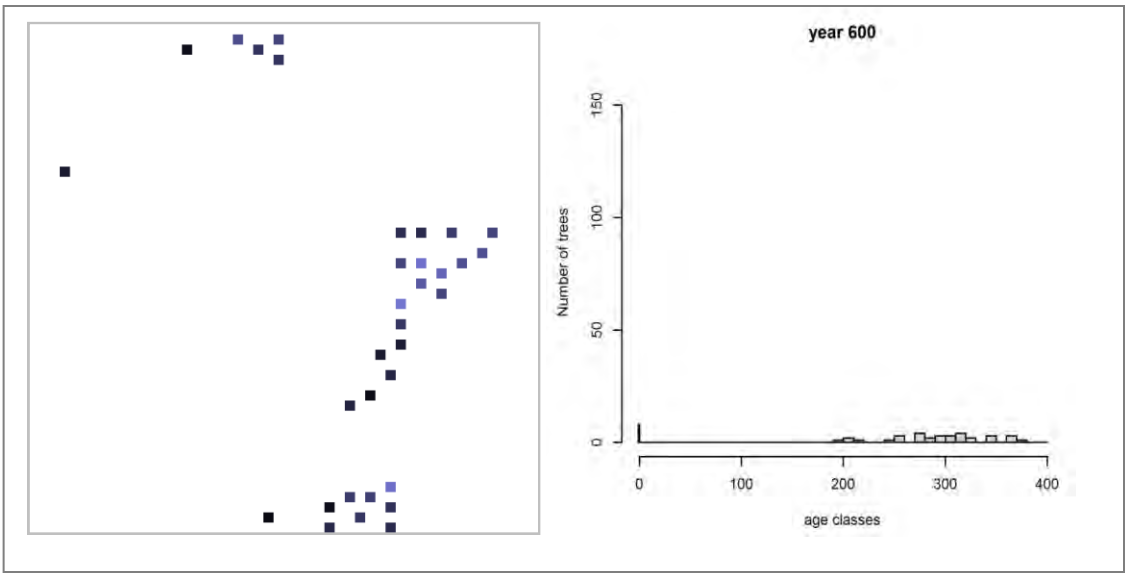

Figure 4.2.5 - State of the *A. angustifolia* population after 600 years (no disturbance). Large parts of the population have died.

4.2 Simulation with disturbances (B)

In the beginning, the development of the forest is similar to the one without disturbances: The *A. angustifolia* colonizes the area (Figure 4.3.1), 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 important, the population still decreases (Figure 4.3.2), until it only covers about a third of the area after 600 years (Figure 4.3.3). Then, the population decrease trend ends. With the disturbances, the population can regenerate and even slowly increase in number. This second cohort is developing very slowly, as it is depending on disturbance to open space for regeneration. At the end of the simulation (after 900 years, Figure 4.3.4), about two thirds of the area is covered by *A. angustifolia* trees again.

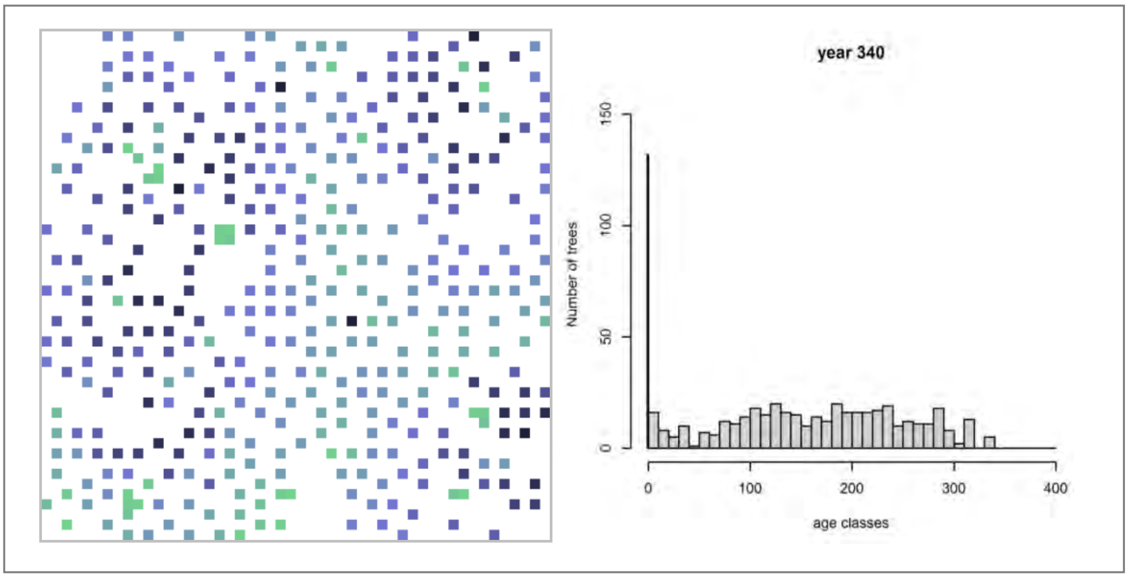

Figure 4.3.1 - State of the *A. angustifolia* population after 340 years (with disturbance). The population's state of development is very similar to the one in run A, without disturbances.

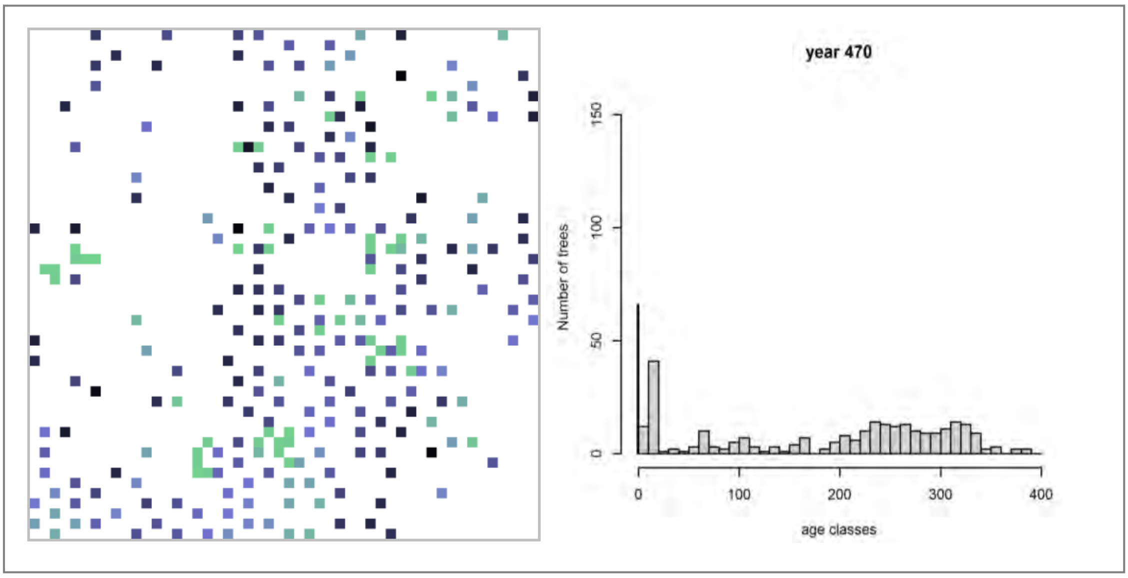

Figure 4.3.2 - State of the *A. angustifolia* population after 470 years (with disturbance). The population is slightly larger than in the simulation without disturbances and has more young individuals.

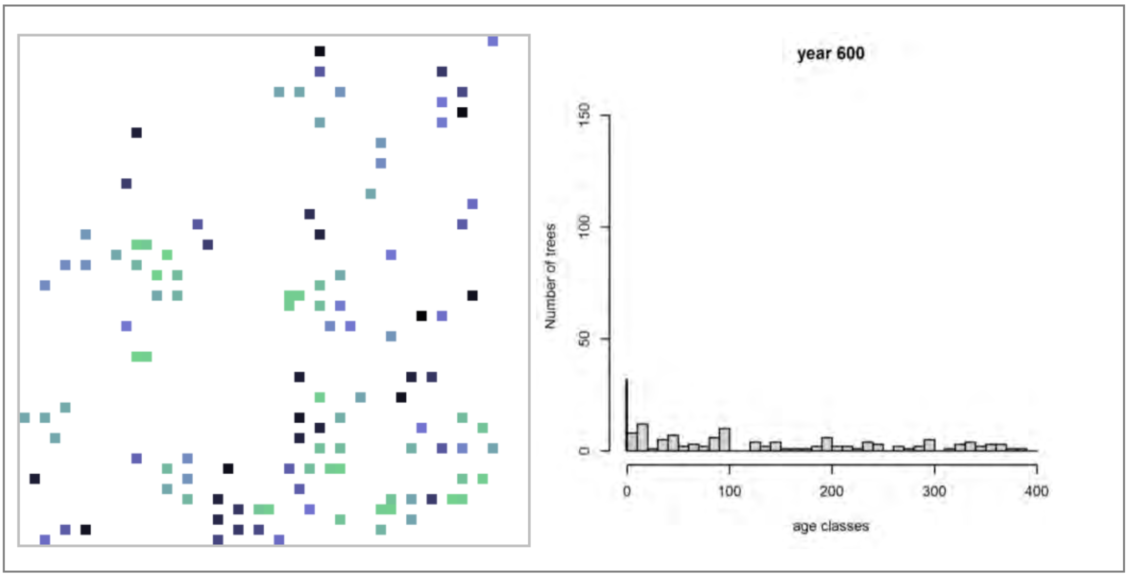

Figure 4.3.3 - State of the *A. angustifolia* population after 600 years (with disturbance). The population is at its lowest number, but still much larger than in the simulation without disturbances.

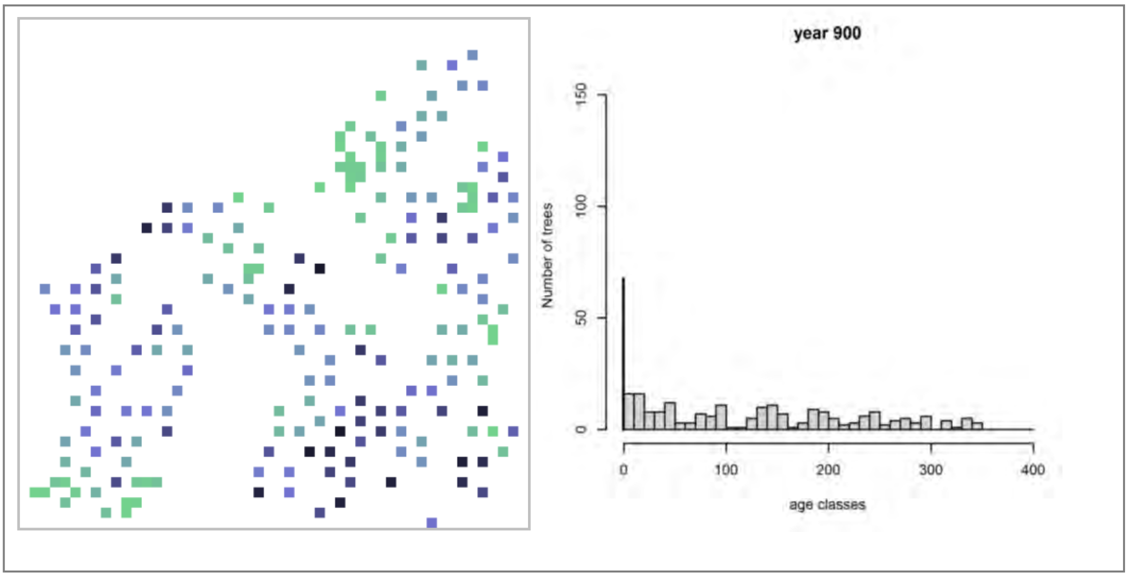

Figure 4.3.4 - State of the *A. angustifolia* population after 900 years (end of the simulation) (with disturbance). Compared to fig. 20, the population has slightly recovered.

5 FUTURE WORK

To improve the results presented in section 4, two aspects of the model could be adapted: The parameterization and the model itself.

5.1 Model evolution

Due to the restricted time frame of this project, the processes happening in the real world have been strongly simplified. Some of them, mainly understorey and disturbance, have been more simplified than others and could be refined to produce more realistic results.

Understory

Understory behaves in a very simple way in this model. It is represented by a single value for each cell (percentage of light transmission) and can have only few states, which determine its behavior: not present (→ it can grow), weakly developed (→ it can grow or decline), well developed (→ it can grow, but not decline) and fully developed (→ it can neither grow nor decline). If it grows or declines, it always does so in the same rate. While it might be too detailed to implement understory individuals as agents (this would make the model very complex and very demanding for computing resources), it would be possible to install a more complex behavior. For example, more states could be introduced, so that the understory could react more realistically to various situations, e.g. understory in gaps takes less time to redevelop than in free space. Another possibility would be to install various layers of understory, which would allow differentiating the behavior of functional groups, for example: understory that develops quickly after disturbance but does not become very strong, and understory that develops more slowly but lasts longer.

Disturbances

Fire disturbance was represented in this model as square patches occurring at fixed intervals in randomly chosen locations of the model space. This is very unrealistic, as fire disturbance are usually located closer to the forest edges and have linear shapes. This behavior could be added, as well as possibilities for the user to specify in more detail in which years what kind of disturbance should happen (e.g. irregular intervals, years with more or less / stronger or weaker disturbances).

Wind disturbance (windfall) and human disturbance (e.g. selective logging) could be as well added to the model.

Gap submodel

The gap submodel could be improved by better modeling what happens in a gap, e.g. not all the trees die, understorey behaves differently when being affected by falling tree than if it is removed by fire. As explained in section 3.4, the unrealistic "domino gaps", the death of one large trees causes many trees to fall because of a high tree density, that occurred in the simulations are prevented manually. It would be better to identify and remove the causes for this unrealistic behavior.

Other possible improvements

Other details that could be improved in the model would be to use the diameter at breast height (DBH) as a measure of growth instead of tree height, as more data on DBH is available. In this case, the growth curves would have to be adapted. The seed dispersal could be improved, allowing long distance dispersion, the determination of how many seeds should fall into which cells, and making the region where seeds can fall round instead of square. The effect of relief as an important factor for seed dispersal could also be considered.

Furthermore, the usage could be improved, for example, by making it easier to input the user parameters and making the model create necessary folders, so the user does not have to create them.

The randomness characteristics of the model could be improved by giving the user the possibility to choose a fixed or a varying random seed. So far, the random seed for each simulation run is the same, i.e. if the model runs several times with the same settings, the outcomes are exactly the same. This is an advantage if the influence of small changes in the settings should be examined, but makes Monte Carlo simulations impossible.

After the implementation work was finished, a bug was discovered which should be removed during the further development of this project. For details on this bug, see section 3.4.3.

5.2 Parametrization

The objective of this research project was not to perform a realistic simulation of the forest dynamics but to gain insight in the process of modeling. At this point, we didn't focus in parameterization and arbitrary numbers were used to run the model. To make the results more evidence-based and thus more scientifically meaningful and realistic, data collected in different study sites will be used to summarize information about recruitment, dispersion mechanisms, growth rates, mortality, light environment, seed dispersal and fire events.

6 CONCLUSIONS

The main goal of this research project was not to provide a new forest dynamics computer model better than existing models or to generate new knowledge about the dynamics of *A. angustifolia* populations. Instead, the goal was to gain insights in the modeling process.

In the iterative process of formulating, implementing and testing the model, we could see from the results what was missing or not well represented in our model. When the results diverged from what is expected, we tried to find the causes for this unrealistic behavior, which aspects were not well represented or what important properties were missing, and adapted the model. This way, we could find out which aspects of the forest had influenced he *A. angustifolia* population development and how.

For example, in early versions, once a tree reached adult age, there was no mortality until they reached old age. The simulation area was quickly colonized by dense *A. angustifolia* forest. The trees virtually occupied all the cells that the minimum distance settings allow them to occupy, causing a very dense and regular pattern, which then stayed completely unchanged for several centuries. This showed that mortality was not correct considered. Letting a small number of adult trees die every year opened some space and caused some dynamics, but gaps were immediately repopulated by new trees, so the dense pattern persisted. This was caused by the complete removal of understory in tree-fall gaps. If the understory is removed, gaps allow for recruitment of A. angustifolia. Although Jarenkow and Batista (1987) claim that tree-fall gaps allow *A. angustifolia* recruitment, this was not observed in a permanent plot set up in an well preserved area in Campos do Jordão State Park (Valeriano 2010) as well as in other preserved areas in the southern plateau of Brazil (Souza et al. 2008). By not entirely removing the understory in gaps restricted recruitment to disturbance patches, so the forest density decreased.

The simulation outcomes presented show that, despite its shortcomings, the model in its current status is able to depict the chosen theories. Thus, we assume that we managed to represent the most important aspects of its behavior. However, the outcomes do not realistically represent existing *A. angustifolia* forests. For example, the simulated density of *A. angustifolia* trees in the area is still quite high. Also, the time needed for colonizing an empty area is faster than expected. A further model adjustment and calibration process could remove these flaws, after which the model might be considered appropriate to generate new knowledge, support or confirm theories or make up new hypotheses.

The primary goal was to gain insights about the process of modeling a forest ecosystem. We consider this objective reached. During the iterative process we could clearly see the influence of the modeled properties on the forest, thus we gained a deeper understanding of the ecosystem. The work was a good exercise in formalizing knowledge about a complex system. Formalization shows how well you really understand a system and where the gaps in your knowledge are.

All the members of the team improved their interdisciplinary communication abilities – biologists and computer scientists do not always speak the same language, and both parties had to learn to think a little bit in the other party's concepts.

We are now more familiar with the process of simplifying complex systems, formalizing their behavior and identifying their relevant aspects. This knowledge is crucial not only for developing new models but also for applying existing models in a competent way, being aware of their limitations and abilities.

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Appendix A. R Script to create age distribution graphics

The open source software R is freely available at the website http://cran.r-project.org/.

```
setwd("C:\\araucaria\\results\\ageplots\\")
filename = "C:\\araucaria\\results\\ages08.02.2013_12_31.txt"
file = read.csv(file=filename, header=TRUE, dec=",", sep=";", skip=1)
# make plot for every year
years = 1:nrow(file)
# or make plot for every x years
#x=5
#years = seq(from=1, to=nrow(file), by=x)
# age classes
br = seq(from=0, to=350, by=20)
br = c(-1,br)
# max number of trees
overallmaxval = 0
for (i in years){
	ages = as.vector(file[i,], mode="numeric")
	ages <- ages[!is.na(ages)]
	maxval <- max(table(ages))
	if(maxval > overallmaxval ) {
	overallmaxval  <- maxval
    }
}

# make plots
for (i in years){
	ages = as.vector(file[i,], mode="numeric")
	outputfilename = paste(sprintf("agehistogram_%04d", i), ".jpg", sep="")
	title = paste("year", i)
	jpeg(outputfilename, quality = 80, bg = "white", res = 500, width =5,
height = 5, units = "in", pointsize=7)
	par(pin=c(3,2.5))
	hist(ages, breaks=br, col="lightgrey", freq=TRUE,
ylim=c(0,overallmaxval), main=title, xlab="age classes", ylab="Number of
trees", plot=TRUE)
	dev.off()
}
```

Appendix B. Parameters used in the simulations

Duration of the simulation	900 years
Size of the area	250 m · 250 m (50 cells · 50 cells)
Initial number of trees (seeds)	20, randomly placed and with random gender
Transition ages	Juvenile to reproductive: 20 years Reproductive to senile: 300 years Death of old age: between 310 and 390 years
Percentage of trees dying every year because of reasons (e.g. disease) that were not explicitly modeled	Seed: 96 % Juvenile: 2 % Reproductive: 0.1 % Senile: 0.1 %
Minimum percentage of sunlight needed for A. angustifolia germination	76 %
Maximum distance of seed travel:	17.5 m (seeds land in square area of 35 m · 35 m)
Number of successful (i.e. not predated) seeds produced every year by adult female tree	15
Percentage of females in the population	50 %
Which A. angustifolia trees cause gaps when they die?	Trees with height > 20 m
How large are the crown gaps?	10m x 10m
How far away from the falling tree's location can a crown gap (i.e. its center) be located?	10 m
How much of the understorey is removed in a gap?	30 %
At which age do the trees start to have a shade? How much light is intercepted?	10 years; 7 %
At which age do the trees start to have a larger shade? How much light is intercepted?	20 years; 25 % in the core shade, 15 % at the edges of the shade
What is the maximum percentage of light that the understorey can intercept?	60 % of the light that reaches it
After how many years does the understorey (in a specific cell) reach this level?	50 years, if the development is not stopped / declined
How much light has to be intercepted by A. angustifolia trees for understorey to develop?	85 % of the sunlight has to be intercepted
Every how many years do disturbances take place? (Simulation B only)	Every 50 years
How large are the disturbance patches? (Simulation B only)	20 m · 20 m
How many patches are disturbed in a disturbance event?	20 patches (possibly overlapping, then the intensity is stronger)
In how many of the disturbance patches do strong disturbances occur? (Simulation B only)	50 %
What percentage of "well fire resistant" trees is killed in disturbances?	Weak disturbance: 0 % Strong disturbance: 3 %
What is the age from which on a tree is considered to be "well fire resistant"?	15 years
How is the growth of the trees?	Until 45 years old: Growth per year (in meters) = $3.279 \cdot age^{-0.7}$ m Afterwards: Growth per year = 0.0143 m