

Current and potential distribution of selected savanna tree species in the South African Lowveld by applying agent-based modeling

Dissertation

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Abstract

In this dissertation, the impacts on trees by elephants in the Kruger National Park and the use of trees by firewood collectors outside the protected area were compared for a simulation period from 2010 to 2050.

A first research focus aimed at a deeper understanding of the ecological adaptation strategies of different tree species. For this purpose, partial order methods were applied to an existing data set. Three very different strategies were identified and each assigned to a representative tree species.

*Acacia nigrescens*¹ invests in the root system for nitrogen production, while *Combretum apiculatum* stores carbon in different parts of the plant as a defense strategy against browsers. Whereas, *Sclerocarya birrea* with its large average leaf area of easily digestible leaves, on the other hand, leads to a high photosynthesis rate and nutrient input due to the longer residence time of large browsers. At the same time, all these tree species are characterized by their ability to withstand drought, fire, and recurrent tree cutting.

To develop an agent-based model, the agents and the environment had to be conceptualized first. The three agent types, "Tree", "Elephant" and "Firewood collector" were defined. A so-called "Goal-Oriented Action Planning" (GOAP) approach for collecting firewood was adapted from game development to model human adaptive behavior.

Agent-based modeling made it possible to observe individual trees over time and to compare different tree species and age groups. Additionally, the two areas considered have been simulated with two different climate scenarios.

Particularly noteworthy here is the comparison between the pure consideration of aboveground biomass and the detailed information on age class and species level. Even before changes in the biomass values became apparent, effects such as species shift, loss of adult trees and scrub encroachment were visible in the simulation results. This is a clear difference to macroscopic modeling.

Even if trees react very slowly to changes, trends can be derived from the model results that resemble an early warning system. Thus, simulation results can be processed directly into the practice of decision-makers on-site in Africa.

Besides, the combination of computer science and geography has contributed to a reusable methodical workflow and adaptable model elements for the scientific consideration of current and potential distributions of certain tree species in different regions.

¹For the sake of consistency with previously published literature on this research (also included in this dissertation), the *Acacia* tree species is referred to using the older nomenclature *Acacia nigrescens* rather than its current name *Senegalia nigrescens*

Zusammenfassung

Für die vorliegende Dissertation wurden Untersuchungen zur räumlichen Vorhersage der jetzigen und zukünftigen Verbreitung ausgesuchter Baumarten der Savanne im Lowveld Südafrikas mittels Agenten-basierter Modellierung gemacht.

Ein erster Forschungsschwerpunkt zielte auf ein tieferes Verständnis über die ökologischen Anpassungsstrategien verschiedener Baumarten ab. Hierzu wurden Methoden der Partiellen Ordnungen auf einen vorhandenen Datensatz angewendet und damit drei repräsentative Baumarten für die Region ermittelt.

*Acacia nigrescens*² zeichnet sich durch ein Investment in das Wurzelsystem zur Stickstoffgewinnung aus. Die Einlagerung von Kohlenstoff in verschiedene Pflanzenteile dient *Combretum apiculatum* als Abwehr gegen Fraßfeinde. Eine dritte Strategie verfolgt *Sclerocarya birrea*, die durch eine große Blattoberfläche mit leicht verdaulichen Blättern eine hohe Fotosyntheseleistung erlangt. Gleichzeitig führt die längere Verweildauer der großen Pflanzenfresser zu einem erhöhten Nährstoffeintrag unter den Bäumen. Allgemein zeichnet alle diese Baumarten aus, dass sie auch Dürren, Feuer und wiederkehrendem Abholzen widerstehen können.

Um unterschiedliche Nutzungen im Lowveld abzubilden, wurden die Auswirkungen der Elefanten an den Bäumen im Kruger Nationalpark mit denen der Feuerholzsammler im ländlichen Raum verglichen. Hierzu war es notwendig, das geplante, selektive und adaptive Sammeln von Feuerholz abbildbar zu machen. Dafür wurde das aus der Spieleentwicklung bekannte „Goal-oriented Action Planning“ (GOAP) für das Sammeln von Feuerholz angepasst.

Das entwickelte Agenten-basierte Modell verfolgt über die Simulationszeit von 40 Jahren mehr als 500.000 individuelle Bäume mit den jeweiligen Interaktionen durch Elefanten und Feuerholzsammler. Die Ergebnisse können über den Zeitverlauf sowohl auf Einzelbaumniveau als auch auf Art- oder Altersgruppenniveau miteinander verglichen werden. Hierbei zeigte sich in den Simulationsergebnissen, dass Effekte wie Artenverschiebung, Verlust von erwachsenen Bäumen und Verbuschung zu erkennen sind, noch bevor diese in den aggregierten Biomassewerten auftreten.

Ergänzend sind beiden Gebiete jeweils mit zwei unterschiedlichen Klimaszenarien simuliert worden. Auch wenn Bäume sehr langsam auf Veränderungen reagieren, so lassen sich doch Tendenzen aus den Modellergebnissen ableiten, die einem Frühwarnsystem gleichen. Damit war es möglich, die Simulationsergebnisse direkt für die Praxis der Entscheider vor Ort in Südafrika aufzubereiten.

Zusätzlich ist ein wiederverwendbarer methodischer Workflow für die Agenten-basierte Modellierung und einer Wiederverwendbarkeit aller Modellelemente entstanden.

²Aus Gründen der Konsistenz mit früher veröffentlichter Literatur zu dieser Forschung (die auch in dieser Dissertation enthalten ist) wird die Akazienbaumart unter Verwendung der älteren Nomenklatur *Acacia nigrescens* und nicht mit ihrem aktuellen Namen *Senegalia nigrescens* bezeichnet.

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Abbreviations

A.n. *Acacia nigrescens*

ABM Agent-based modeling

ABS Agent-based simulation

aDGVM adaptive Dynamic Global Vegetation Model

AGB Aboveground Biomass

AI Artificial Intelligence

ALA Average Leaf Area

BBR BushbuckridgePlot

C.a. *Combretum apiculatum*

C.m. *Colophospermum mopane*

CSIR Council for Scientific and Industrial Research

DSL (MARS) Domain-Specific Language

DVM Dynamic Vegetation Model

EMSAfrica Ecosystem Management Support for Climate Change in Southern Africa

GOAP Goal-oriented action planning

GPS Global Positioning System

GUI Graphical User Interface

H Damage class **High**, 60-80 %

HAW Hamburg University of Applied Sciences

HD Hasse Diagrams

HI Hluhluwe (site)

IPCC Intergovernmental Panel on Climate Change

K2C Kruger to Canyon Biosphere Region

KNP Kruger National Park

L Damage class **Light**, 10-30 %

LCC Leaf Carbon Concentrate

LDMC Leaf Dry Matter Content

LiDAR Light Detection and Ranging

LNC Leaf Nitrogen Concentration

LPC Leaf Phosphorus Concentration

LTS Leaf Tensile Strength

M Damage class **Moderate**, 30-60 %

Ma Mapungubwe Sands (site)

MAP Mean Annual Precipitation

MARS Multi-Agent Research and Simulation, Group at HAW

MAT Mean Annual Temperature

Mo Makhohlolo (site)

N Damage class **Nil**, <10 %

Nh Nhlanguwini (site)

Nw Nwaswitshumbe (site)

ODD Overview, Design concepts, and Details

PFT Plant Functional Types

PO Partial Orders theory

Po Pongola (site)

POI Point Of Interest

poset Partially ordered set

RCP Representative Concentration Pathways

RQ Research Question

S.b. *Sclerocarya birrea*, Marula

SANParks South African National Parks

SB Satara Basalt (site)

SDM Species Distribution Model

SG Satara Granite (site)

SKU SkukuzaPlot

SLA Specific Leaf Area

SM Ship Mountain (site)

SR Mean daily Solar Radiation in January

T.s. *Terminalia sericea*

T.t. Generic tree type, *Tree tree*

TDMC Twig Dry Matter Content

VoS Value of Sensitivity

X Damage class eXtreme, >80 %

Chapter 1

Introduction

1.1 Motivation

Trees have been an immense value to human life since the very first beginning. They serve as an ecosystem service for humans (Scholes and Archer 1997) but also for the associated ecosystem. In savannas, mainly as nutrient hotspots, for water uptake, to provide shade, and by reducing the total amount of evapotranspiration in the surrounding area (Treydte et al. 2009).

In savanna ecosystems, trees are mostly deciduous, and often grow fast in the first life states to reach the fire escape height and to avoid feeding pressure of smaller browsers (Griffith et al. 2018; Higgins et al. 2012). As adult trees, they frequently stand singly and widely spaced or grouped in patches (Treydte et al. 2007). In this stage, they withstand fires if the thick protecting bark is without substantial damages (Lawes et al. 2013).

In general, savannas are landscapes where trees, together with grass, create a biome with a combination of a continuous grass layer and scattered trees (Moustakas et al. 2009). Therefore, savannas are neither grassland nor forest. They are a bi-stable ecosystems in tropical and subtropical regions with a clear separation of wet and dry seasons (Scholes and Archer 1997). In total, they cover over 10 % of the global surface and over half of the continent in Africa (Scholes and Archer 1997).

The current tree distribution in savanna ecosystems and especially the occurrence of large trees, is mainly the result of a complex and prolonged socio-ecological process (Osborne et al. 2018; Sankaran et al. 2005; Twine and Holdo 2016).

Trees in savannas are part of a complex, adaptive system, driven by disturbances, climate, and vegetation composition (Díaz et al. 2013). They have an enormous ability to recover by resprouting. Trees are keystone structures for savannas with an enormous impact to the entire system (Scholes and Archer 1997). However, even in southern Africa, 80 % of savanna areas are used as agricultural land (Kotze et al. 2015).

Especially in Africa, trees are an important social, ecological, and economic factor (Sankaran et al. 2005). At the same time they are under pressure because of land clearance and impacts of global change (Osborne et al. 2018) together with growing needs for settlement and rangeland. As a result communal sites for harvesting and livestock grazing decrease in size (Druce et al. 2008).



Figure 1.1: *Acacia nigrescens*: Intact tree (left) and with a broken branch by elephant damage (right)



Figure 1.2: *Combretum apiculatum*: Tree with seeds (left) and resprouting after fire-wood collection (right)



Figure 1.3: *Sclerocarya birrea*: Tree (left) and toppled over by elephant damage (right)

This thesis was done in the context of the research projects ARSAfricaE (BMBF, FKZ: 01LL1303b) and EMSAfrica (BMBF, FKZ: 01LL1801C). To separate changes because of land-use with more indirect changes of global change, the EMSAfrica project takes an innovative approach by building "paired sites". Under the same climatic and similar soil conditions, one near-natural and a cultivated location are compared.

For this study, the chosen representative biome is the so-called biome Granite Lowveld (Rutherford et al. 2006) in South Africa, a semi-arid zone with hot and rainy summer in combination with dry, mild winters. It is one of a variety of ecozones in the Lowveld which covers large parts of the Provinces of Limpopo and Mpumalanga with substantial parts in the Kruger National Park.

Even when the trees are growing on similar natural conditions there are detectable variations in the tree population. This is mainly driven by the different types of land-use. In the rural areas of the Bushbuckridge Municipality firewood collection is the key disturbance that negatively impacts trees (Banks et al. 1996; Matsika et al. 2013a; Twine and Holdo 2016; Mograbi et al. 2019). Inside the protected area of the Kruger National Park (KNP) elephants (*Loxodonta africana*) are the main disturber against trees (Asner et al. 2016; Baxter 2003; Guldemond et al. 2017; Helm et al. 2009; Jacobs and Biggs 2002a; Moncrieff et al. 2008; Nellemann et al. 2002; O'Connor and Page 2014; O'Kane et al. 2011; Rugemalila et al. 2016; Scholtz et al. 2014; Trollope et al. 1998).

These firewood collector-tree and elephant-tree interactions lead to damages on trees but at different times, in various intervals, through acts, and with varying tree preferences (see e.g., Figures 1.1-1.3).

Existing studies in this biome are e.g., done on single tree level with LiDAR (light detection and ranging) (Levick and Asner 2013; Mograbi et al. 2019), species level by data collection (Shannon et al. 2011) and on landscape-scale by satellite and LiDAR (Mathieu et al. 2018).

Future tree distribution is e.g., modeled on landscape-scale (Moncrieff et al. 2016), for changes in biomass because of harvesting (Matsika et al. 2013b; Twine and Holdo 2016), and for vegetation cover (Bunting et al. 2016).

However, a missing step stone to predict the potential distribution of specific tree species and their age distribution is an integrated model approach that can model individual trees but on a landscape level. This topic is significantly important because even small changes, such as unsustainable use of a specific trees on a local scale, can lead to the loss of this species in the species pool and a subsequently decreasing potential of resilience on the ecosystem level (Kaschula et al. 2005; Shackleton et al. 1994)). Agent-based modeling (ABM) is a useful way to detect changes on an individual level (Bailey et al. 2019; Bonabeau 2002; Kelly et al. 2013; Miller and Morissette 2014). Modeling a high number of single trees operating and interacting simultaneously is a micro-scale modeling approach. The agents share an environment within which they interact and communicate with each other. Furthermore, the data, produced by the high number of agents typically used in ABMs, can show emergent behavior (Crooks 2010) and one might be able to identify tipping points (Gillson 2015; Staal et al. 2016; Van Nes et al. 2014) within the modeled system. A significant decline in the popula-

tion of a tree species is an example of an emergent characteristic that only becomes apparent at landscape level.

To capture all different agents, scales, and interactions, the underlying framework must be powerful enough to handle thousands of individual agents. To facilitate this, the MARS (Multi-Agent Research and Simulation) framework (Glake et al. 2017; Hünig et al. 2016; Weyl et al. 2018), which is under continuous development by students at the Hamburg University of Applied Sciences (HAW), was chosen.

1.2 Objectives

The overall objective of this thesis is to present an integrated approach for modeling tree distribution of key species at multiple temporal and spatial scales in an assigned South African savanna study area. Here, the simulation time is from 2010 to 2050 with the time frame from 2010 to 2020, enabling calibration of the model. The present approach is the first simulation, including more than 500,000 individual trees and spanning a simulation time of 40 years. With regard to the uncertainties due to climate change, two extremely different scenarios were used.

Producing meaningful simulation results for different land-use and climate change scenarios, is divided into various phases like conceptualization, calibration, initialization, data aggregation, and visualization.

Hence, modeling and mapping of the direct human indicated distributions on trees, like firewood collection on the one hand side and elephant damages on the other hand side is related to a variety of relevant methodological research topics. The different requirements result in some specific objectives, serving the modeling steps to answer these research topics:

- **Conceptualization**

- Analysis of multi-criteria indicator systems including data organization, classification, sensitivity analysis, visualization, and clustering.
- Combination and comparison of social and natural sciences to differ between direct changes due to land-use changes and more indirect changes as a result of climate change.
- Designing a generic tree model with a complete life cycle, including the life states seed, seedling, juvenile, adult, and dead tree. As well as preparation of diverse interfaces for all kind of disturbances.
- Realization of three different tree species models with growth rates, maximum stem diameter, seed production, space to germinate, seedling survival rate, response to damages, life span of leaves, CO₂ adaptation, response to rain events, and days with frost.

- **Design of an human agent**

- Integration of adaptable human behavior under changing conditions in models, mainly for agent-based models. Here, finding a planning algorithm to cover individuality, social and environmental circumstances as well as the availability of tools.
- Integration of Artificial Intelligent (AI) in agent logic in combination with a simulation built by time-steps with a continuous updating of all agents and the environment to get an agile simulation outcome.

- **Modeling workflow and products**

- Realization of a model coupling with an elephant model on a different spatial scale and tick length.
- Up-scaling from single tree level to landscape level by data aggregation.
- Providing spatial relevant trends in species distribution for the South African Lowveld under various land-use and climate scenarios.
- Advancing visualization of results for stakeholder support by Graphical User Interfaces (GUI) facilitating e.g., elephant or firewood collector movement and open tools for tree growth and damages.
- Supporting decision-maker in the local Bushbuckridge Municipality and the SANParks Management by presenting and discussing the results in stakeholder meetings and via the internet as well as providing products they are asking for.

To advance long-term collaboration and access to all modeling and analysis tools as well as all products, a web-based platform using free and open-source software and tool was developed and hosted by following common international standards.

This thesis aims to increase the knowledge of spatial distribution and temporal variation of different tree species at different spatial scales (see e.g., Figures 1.4) which lead to the following research questions:

RQ 1 Which conceptual components are best to model with the multi-variant savanna system as accurately as possible to get answers about current and potential tree distribution?

RQ 2 Is it possible to include adaptable human behavior in an agent-based model to simulate different preferences and efforts in collecting various kinds of firewood?

RQ 3 How do different tree species evolve in different land-use and under two extreme IPCC climate scenarios?

The results aim at supporting decision-making in Southern Africa concerning climate change adaptation and mitigation, and the sustainable management of savanna ecosystems.

1.3 Outline of the thesis

The thesis consists of eight chapters. Following this introduction, Chapter 2 describes characteristics of the savanna ecosystem with a focus on firewood collector-tree and elephant-tree interactions. It summarizes the state of the art as well as the basic concepts in modeling complex systems with agent-based models. A short overview of the multi-variate analysis highlights the potential in this method to indicate key concepts for the model.

Chapter 3 introduces the study area of this work focusing on details of climate and land-use by comparing to sites within the same biome, so called Granite Lowveld but under different land-use types. Following this, the entire workflow of modeling in the MARS Framework is described gradually.

Chapter 4 (first article) focuses on information reduction by finding three different ecological strategies of savanna trees by applying a partial order algorithm to an existing data set. This Chapter is published as: *Lenfers, U.A., Bruggemann, R., Clemen, T., 2017. Exploring survival strategies of African Savanna trees by partial ordering techniques. Ecol. Inform. 42, 14–23. doi:10.1016/j.ecoinf.2017.08.008.*

Chapter 5 (second article) outlines the integration of human adaptive behavior in an agent-based model. As a result, the firewood collection is modeled as a goal-oriented action planning (GOAP) to be able to combine this approach with agent-based modeling. It is published as: *Lenfers, U.A., Weyl, J., Clemen, T., 2018. Firewood Collection in South Africa: Adaptive Behavior in Social-Ecological Models. Land 7, 97. doi:10.3390/land7030097.*

Chapter 6 (third article, under review) presents a comparison between firewood collector-tree and elephant-tree interactions based on agent-based modeling. One of the main goals is to identify the differences in age class distribution of three tree species in well-protected and rural areas over the next 30 years. Particular attention was paid to modeling purposeful human behavior in contrast to the more random, instinct-driven actions of elephants. It is under review as: *Lenfers, U.A., Ocker, F.J., Weyl, J., Clemen, T. Tree distribution as a result of disturbances by elephants and firewood collectors: An agent-based model comparison. Submission number: Applied Geography JAPG_2019_1084.*

Chapter 7 discusses the results in coherence with the formulated objectives and places them into scientific context. Here, the limitations of this model approach as well as missing indigenous knowledge are described. Additionally, the large-scale consequences of the findings are discussed, including resilience, cascading effects, and decision-support.

Chapter 8 provides the conclusion of the thesis. An outlook and possible next steps, to continue and to improve the model, are highlighted. A special focus is laid on transferring the knowledge back to the stakeholder in South Africa.

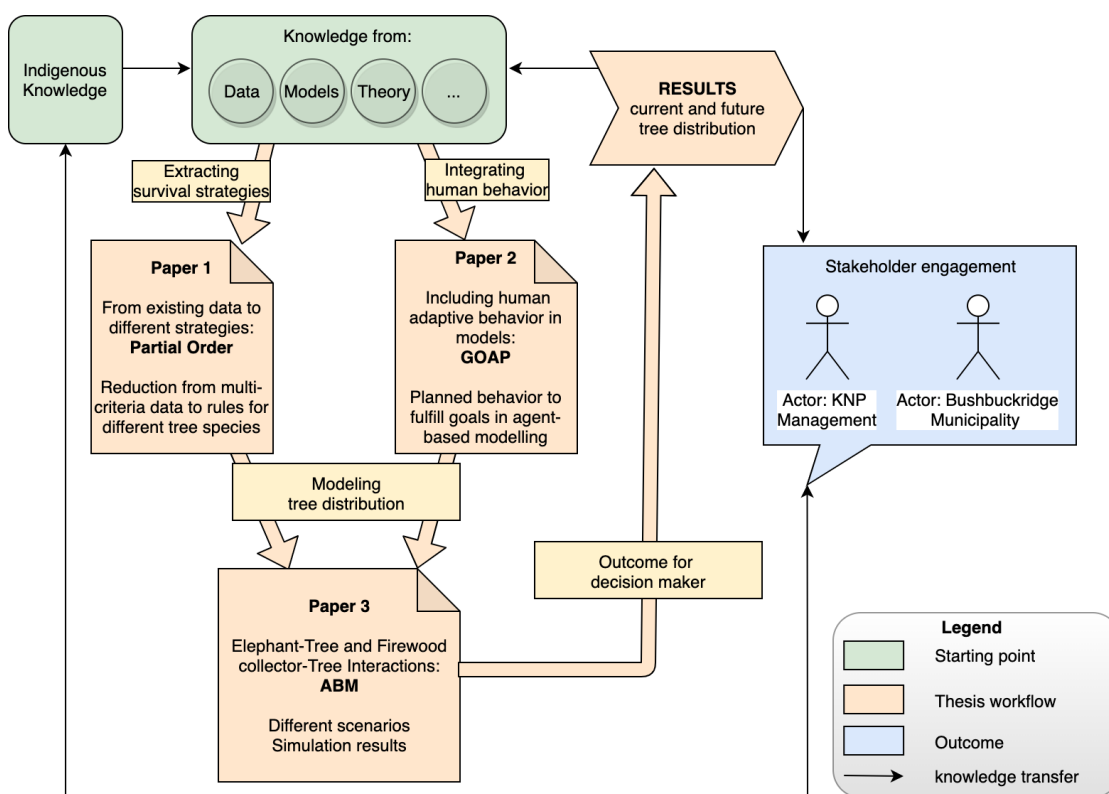


Figure 1.4: Thesis workflow in the overall context

Chapter 2

State of the Art

Although the term “savanna” has various definitions and classifications, the ecological and social relevance of this biome is undisputed (Gertenbach 1983; Rutherford et al. 2006; Venter 1990; White 1983). Savannas are one of the largest biomes on earth (Shorrocks and Bates 2014), covering almost 20 % of the land surface and 60 % of sub-Saharan Africa. They occur globally in tropical and subtropical regions, mostly in Africa but also in South America, India, Southeast Asia, and Australia. Until now, the dynamics of savannas are not entirely understood (Moncrieff et al., 2015; Sankaran et al., 2005; Scholes and Walker, 1993; Scholes and Archer, 1997; Vanak et al., 2012).

Here, savannas are defined as complex ecosystems in which woody species and grasses coexist, resulting in productive vegetation with very efficient photosynthesis (Shorrocks and Bates, 2014).

Another characteristic of these bi-stable ecosystems is a spatial-temporal dynamic in the vegetation composition, driven mainly by disturbances. Depending on the resilience and complexity of the ecosystem savanna, a disturbance can cause a stable or unstable equilibrium (Kutsch et al., 2001).

In South Africa, there are large conservation areas like the Kruger National Park with a near-nature savanna fauna and flora. Still, outside the parks, this landscape is home to over nine million rural residents (Twine et al. 2003).

Although the observation of trees represents only part of the bi-stable ecosystem, it can offer comprehensive insights into the system’s state because the survival of large trees is essential for the overall system (Manning et al. 2006; Shannon et al. 2008, 2011; Vanak et al. 2012). Trees are connecting points within a system of benefits and drivers (see Figure 2.1).

Even though generalizations about the drivers of tree demography are difficult to improve (Morrison et al. 2016), there are clear components in this complex and dynamic system. Inside conservation areas, the entire life cycle is driven by different combinations of **herbivory** (mostly elephant damages) interaction, **fire**, and **climate** (especially rainfall but also days with frost) (Archibald et al. 2005; Case et al. 2019; Holdo 2006; Lehmann et al. 2014; Mograbi et al. 2016; Morrison et al. 2016; Sankaran et al. 2005; Treydte et al. 2007; Wiegand et al. 2006). In human-modified landscapes, harvesting (especially firewood collecting) impacts the tree distribution in the savanna

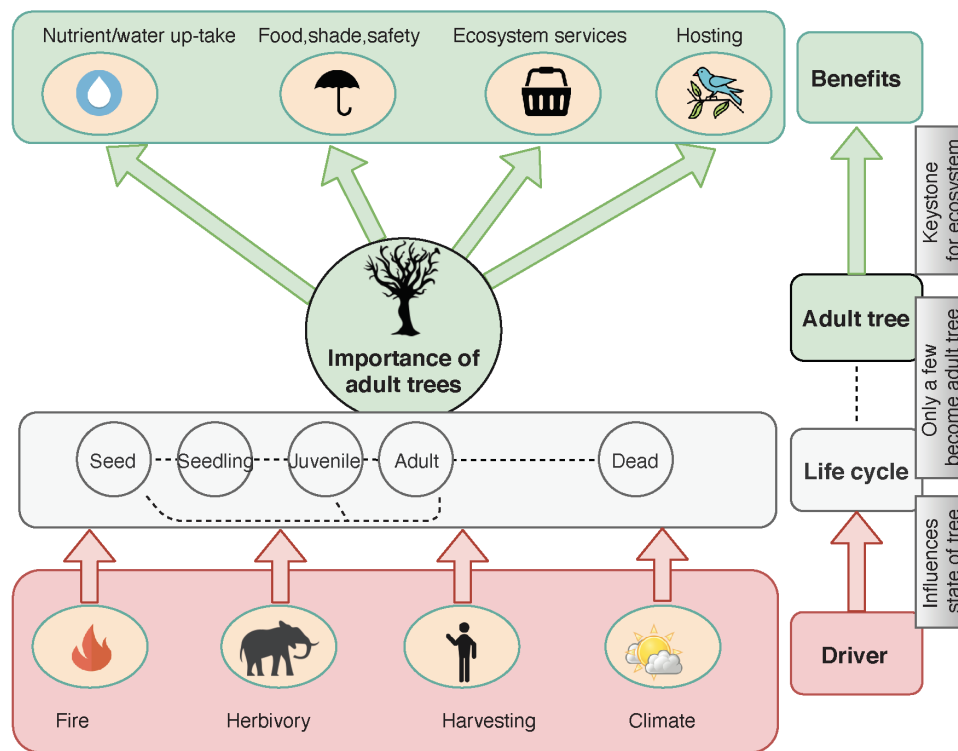


Figure 2.1: The importance of adult trees in savannas

landscape (Fisher et al. 2012; Matsika et al. 2013a,b; Mograbi et al. 2016, 2019; Morrison et al. 2016; Moyo et al. 2015; Twine and Holdo 2016; Verschure et al. 2014).

Additionally, the more indirect drivers of a changing climate will also influence the trees in different ways (Case et al. 2019; Kgope et al. 2010; O'Connor and Page 2014; Wiedner et al. 2007). In general, it must be considered that the combination of different drivers leads to higher damages on trees than a single disturbance. For example, a tree debarked by an elephant is much more vulnerable to fire for a period of time (Shannon et al. 2011).

Fire strongly affects the distribution and abundance of trees. In the tree-grass community, fire fueled by the grass biomass can suppress tree growth in the juvenile state and the tree establishment (Bond et al. 2003). Nevertheless, saplings generally survive fires by resprouting from root collars or they are protected by a thick-barked stem, like the large trees (Bond et al. 2003; Higgins et al. 2000).

Fire can reduce woody cover (Smit et al. 2016) mainly by killing young trees and by setting back the height growth with a start of resprouting until the fire escape height is reached (Bond et al. 2003). However, the frequency and intensity of fires is a function of the fuel accumulation built up by the grass layer. Therefore, frequent burning is not always possible (Smit et al. 2016; Trollope et al. 1998).

Herbivory impact on trees in African savannas has a long evolutionary history (Cumming 1982). This landscape has the most spectacular large mammal fauna in the world. From the smallest, the dik-diks (*Madoqua spec.*) with 3-4 kg, to a male elephant (*Loxodonta africana*) with 2,500 kg there are in total 92 herbivore species

in Africa (Cumming 1982). While they all are known to impact trees in several ways (Baxter 2003), elephants are evidently the major agent against trees (Eckhardt et al. 2000; Guldmond et al. 2017; Morrison et al. 2016). Elephant impacts on trees range from simple browsing leaves and twigs, to knocking branches and de-barking, to pushing down and up-rooting trees (Baxter 2003; Helm et al. 2009; Holdo 2006; Jacobs and Biggs 2002a; Moncrieff et al. 2008). After incurring damaged by elephants, all savanna trees have a high capacity to resprout (Vanak et al. 2012) but they are less resilient to repeated or combined disturbances (Morrison et al. 2016). Because elephant numbers in conservation areas are increasing, there is an ongoing debate on how many elephants can be tolerated in, for example, the KNP (Eckhardt et al. 2000; Henley and Cook 2019; Scheiter and Higgins 2012).



Figure 2.2: Elephants as landscape builders: different levels of elephant utilization

Harvesting takes place outside the conservation areas in the communal savanna landscapes (Giannecchini et al. 2007). Here, firewood collection, as selected wood removal, is the main driver of structural and compositional changes to trees in the human-modified savanna (Fisher et al. 2012; Matsika et al. 2013a; Mograbi et al. 2016, 2019; Twine and Holdo 2016; Wessels et al. 2013). Up to now, the majority of rural households near the KNP depend on firewood harvesting (Matsika et al. 2013a,b). Therefore, unsustainable firewood collection is often cited as the reason for deforestation in communal land (Wessels et al. 2013). However, this is also driven by reducing site for harvesting by land-use change for agriculture and settlement (Mograbi et al. 2019).



Figure 2.3: Traditional firewood collection

Climate and especially the mean annual precipitation (MAP) is the underlying cause of the woody cover of African savannas (Sankaran et al. 2005). Although, woody cover is or was a function of MAP, soil properties, and disturbances (Sankaran et al. 2005), consequences of climate change are now apparent. CO_2 is increasing, in turn, promoting an increase in woody plants (Kgope et al. 2010). It seems that CO_2 has a significant effect on tree recruitment in grassy ecosystems (Kgope et al. 2010). On the other hand, high temperature and little precipitation can increase droughts, which have a negative impact on the survival and growth rate of trees (Case et al. 2019).

To understand the future climate as an uncertain driver, a comparable dataset for all model approaches was needed. Therefore, the Intergovernmental Panel on Climate Change (IPCC) was established in 1988. Since 1990, the IPCC has produced reports, papers, and datasets to become a standard reference for policymakers and scientists (Davis 2010; Engelbrecht et al. 2015; Stocker et al. 2014).

Savanna tree species are well adapted to many kinds of disturbances with resprouting and regrowth from stores in their root system (Morrison et al. 2016). Without any disturbances and limits, an adult tree will produce seeds. Some of the seeds will germinate and become seedlings. After one to two years of undisturbed growing, these individuals will turn to the juvenile state. Depending on species growth rates and other specifics, they will be adults after a few more years and begin to produce seeds yearly. In savanna ecosystems, all stages of development in a tree's life are characterized by different needs, disturbances, and strategies (Morrison et al. 2019; Stevens et al. 2013). After disturbances, they can stay for much longer in a life state or even regress from an adult tree to a juvenile tree without producing seeds (see Figure 2.4). Although all savanna tree species vary considerably in terms of seedling productivity,

growth rate, maximum height, maximum age and other factors, all of them have to pass demographic bottlenecks while changing from one to the next state (Bond et al. 2017).

The characterization of state distribution for different tree species is useful in detecting population trends within a single species or on species level (Bond et al. 2017). In order to understand species geographical distribution capability, seed dispersal is a critical step as well (Thomson et al. 2010).



Figure 2.4: Different life stages (a-f) of the Marula tree (*Sclerocarya birrea*: a twig with leaves and fruits, b seedling, c juvenile, d juvenile back from adult, e adult, f dead)

Only adult trees can produce seeds and force seedling recruitment. Therefore, they have an important role in all landscapes (Manning et al. 2006). A loss of scattered adult trees in savannas can lead to missing size classes or a changing tree species composition in following generations. These trees are often prominent structures in the landscape, providing , for example, food, shade, safety, and nesting sites for birds (Treydte et al. 2007). They also play an important role in nutrient cycling (Treydte et al. 2007) and water up-take (Scholz et al. 2010).

Benefits are also provided as ecosystem services (Thijs et al. 2015) for rural South Africa. The marula tree (*Sclerocarya birrea*), for instance, provides many benefits to local communities, mainly via its fruits but also through its kernels, leaves, bark, and roots (Leakey et al. 2005; Shackleton and Shackleton 2005).

Answering questions about current and potential distribution of selected tree species is helpful in finding the most important forces that drive reproductivity, growth, and mortality of the tree community within the savanna landscape. Representative tree species and the driving environmental dynamics must be defined. Multi-variate analysis can help to deal with this complexity (Annoni et al. 2011).

Studies of complex environments are often producing multi-criteria datasets. Partial order (PO) theory is a discipline associated with discrete mathematics and graph theory. Objects, as a set of multiple indicators, can be compared and ordered by priority and rank (Bruggemann and Patil 2010). The concept behind the Hasse diagram (HD) is about incomparability, which orders objects by their sets of attributes. Hence, the data matrix needs a ranking aim, a clear orientation, and comparability of the objects. The resulting HD is the visualization of the ordered data set. Each element in the HD might or might not be connected to another element. Thereby, a clustering of elements can show similarities between those elements (Bruggemann et al. 1994; Bruggemann and Carlsen 2006). To solve such ranking problem, the software package PyHasse is still under development (Bruggemann et al. 2014).

Standard tools to project changes in species distribution and biodiversity are Species Distribution Models (SDMs) and Dynamic Vegetation Models (DVMs) with representative plant functional types (PFTs).

SDMs (also called statistical distribution model, niche model, or habitat suitability model) model the correlation of the current species distribution with present environmental factors. Based on present/absent outcome, a geographical map shows the statistical potential vegetation under different scenarios. One main limitation of this approach is that the observed species might not be restricted to the specific area in which they are currently distributed (Guisan and Thuiller 2005). Planting experiments with the savanna tree species *Colophospermum mopane* and *Acacia nigrescens* shows a much more complex potential distribution area (Griffith et al. 2018).

DVMs (also Dynamic Global Vegetation Models) are used to model global climate in an attempt to understand plant geography on a global scale (Moncrieff et al. 2015). Although Scheiter et al. (2019) adapted a DVM for Africa, the restriction of this model approach is that only patterns of distribution are modeled.

In contrast, agent-based modeling (ABM) considers individuals, representing the micro simulation approach. These so-called agents are acting in time and space with each other, influencing their environment and other agents. Hence, ABMs are able to handle a high degree of complexity and open systems (Heppenstall et al. 2012).

SWARM, MASON and NetLogo are among the first ABMs. Only by using ABMs, single trees and disturbances on single trees are trackable. With a powerful framework, a very high number of agents can be held within the simulation, producing simulation results that allow for an up-scaling to a landscape level (Grimm et al. 2010). Here, ABM has the advantage of dealing with the complexity of a geographical system at multiple scales and over different timescales (Heppenstall et al. 2019).

An ABM is a system of disaggregated individual components that can have their own characteristics and rules. The two main concepts are agents and the environment.

An **agent** consists of a block of code representing an autonomous unit, like one tree, elephant, or firewood collector which can process and exchange information to other agents in order to act. Agents have attributes like age, state, sex, species, growth rate, walking speed, or carrying capacity. Each agent is active and influences the entire simulation. They have goals to achieve, can sense their surroundings, supply knowledge, move, and learn. As a foundation for behavior, each agent has rules. These

rules are derived from literature, expert knowledge, and data analytics and are typical “if-else” statements (Heppenstall et al. 2019).

The **environment** as the space in which all agents operate is spatially explicit and build-up by different layers. These layers are similar to the way GIS data are structured (Hüning et al. 2016).

With these concepts, ABMs have the potential to detect emergence and non-average behavior (Bonabeau 2002). But, to capture this complexity, the use of a powerful framework is beneficial (Hüning et al. 2016).

For this thesis, the **MARS Framework** was used. MARS stands for the massive Multi-Agent Research and Simulation system which is still under development at the Hamburg University of Applied Sciences. It is designed to provide a “Modeling and Simulation as a Service” (MSaaS) solution to researchers all over the world. Following the trend of moving large-scale simulations to the cloud, MARS uses this advantage to offer a convenient web interface for creating simulations. End users can not only run simulations but also create their own with the newly created tool set. In addition, the simulation results can be analyzed in multiple ways, including 3D visualization and visual analytics (Dalski et al. 2017; Glake et al. 2017; Weyl et al. 2018).

Two of the main advantages of MARS are the possibility to model and simulate a massive number of agents as well as the layer construction which can easily integrate GIS files but also time-series layers.

Chapter 3

Study sites, Materials and Methods

This thesis, closely linked to the international research project EMSAfrica (Ecosystem Management Support for Climate Change in Southern Africa, FKZ: 01 LL 1801C), features two study sites in the Lowveld.

3.1 Study sites characterization

Skukuza and Bushbuckridge are placed in the southeastern part of South Africa. The area is made up of different biomes: the Highveld, the Lowveld, as well as the Drakensberg and Lebombo mountain areas (The Editors of Encyclopaedia Britannica 2019). With an altitude range from 150 – 600 m above sea level, the Lowveld covers large areas in the provinces Mpumalanga and Limpopo (see Figure 3.1).

The Vegetation Atlas of South Africa and other biome classification works (Rutherford et al. 2006; Powrie et al. 2012) define the Lowveld biome where the Skukuza and Bushbuckridge sites are located to the “Granite Lowveld (SVI3)” (see Figure 3.1).

Typical vegetation for this type consists of a few trees in tall shrubland up to dense thicket or open savanna. The tree cover is formed mainly by the following species: *Sclerocarya birrea*, *Acacia nigrescens*, *A. nilotica*, *A. exuvialis*, *A. gerrandi*, *Combretum collinum subsp. sulunse*, *C. imberbe*, *C. zeyheri*, *Ficus stuhlmannii*, *Peltophorum africanum*, *Pterocarpus rotundifolius*, *Terminalia sericea*, *Bolusanthus speciosus*, *Cassia abbreviata subsp. beareana*, *Dalbergia melanoxylon*, *Gymnosporia glaucophylla*, *Lannea schweinfurthii var. stuhlmannii*, *Pavetta schumanniana*, *Plectroniella armata*, *Terminalia prunioides*; tall shrubs: *Combretum hereoense*, *Dichrostachys cinerea*, *Euclea divinorum*, *Strychnos madagascariensis*, *Gardenia volkensii*, *Hibiscus micranthus*, *Tephrosia polystachya* (Rutherford et al. 2006; Powrie et al. 2012). Wigley et al. (2016) collected leaf trait data for five slightly differently important trees in this region:

***Acacia nigrescens* (A.n.)** is a tall, deciduous tree standing without leaves for several months. Its height commonly ranges between 8 and 10 m but can be up to 20m. The juvenile and adult tree is resistant to fire and drought but favorably used by

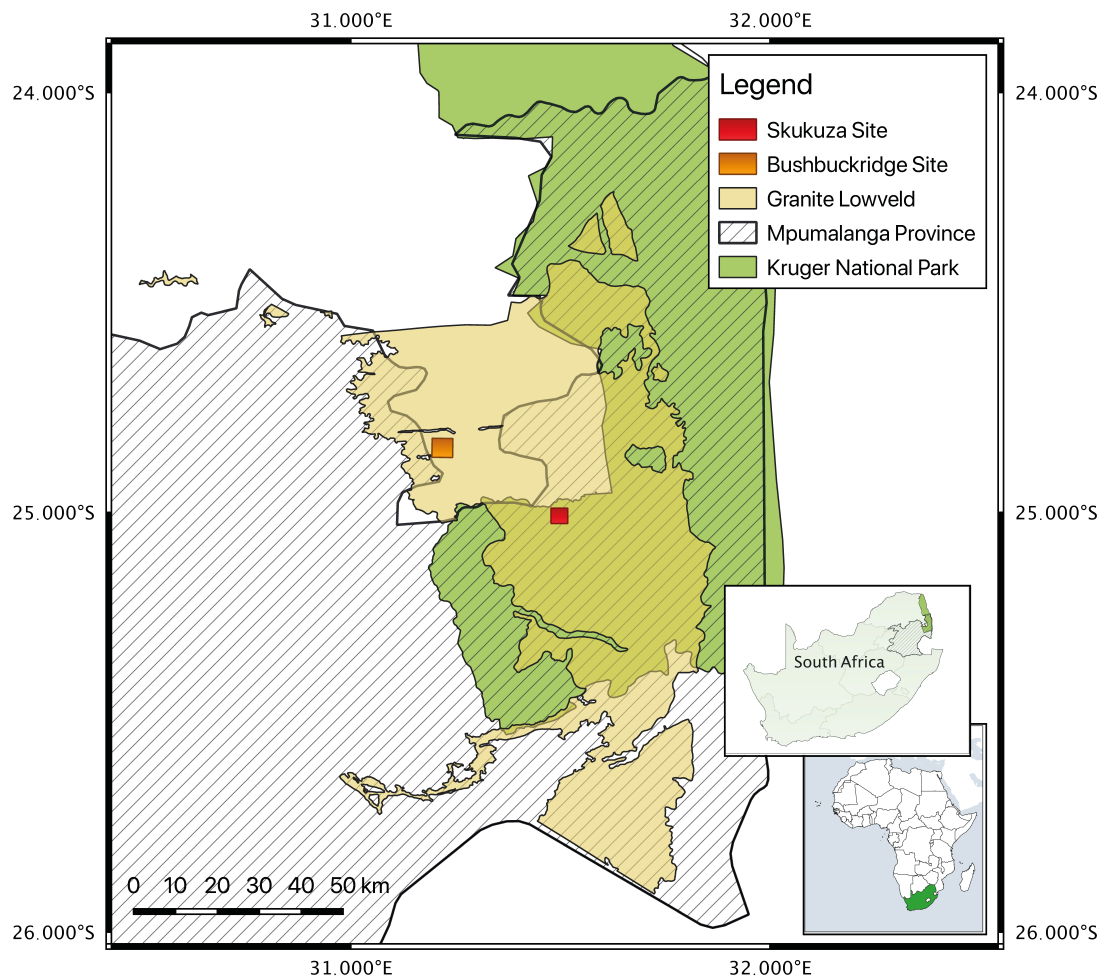


Figure 3.1: Location of study sites

many browser species, which have a high impact on the survival rate from seedling to adult trees (Coates-Palgrave 2002).

Colophospermum mopane (C.m.) is a medium to large-sized tree with a range of 4 to 18 m but usually 10 m. Without disturbances, they can become very tall. However, under elephant pressure, this tree forms the so-called mopane shrub. C.m. is dominated in hot, low-lying areas and can form mopane woodland (Coates-Palgrave 2002).

Combretum apiculatum (C.a.) is a small to medium-sized tree with a height between 3 – 10 m. This tree occurs in dry, open woodlands and bushvelds. The hard wood is resistant to borers and termites (Coates-Palgrave 2002).

Sclerocarya birrea (S.b.) is a 7 – 17 m medium-height, deciduous tree which is leafless for several months. Nevertheless, these trees are an essential forage source for many animals. Fruits, leaves, kernels, but also bark and roots, are attractive to several animals. The habitat ranges from medium to low altitude open woodland and bush (Coates-Palgrave 2002).

Terminalia sericea (T.s.) ranges in height from 4 – 6 m, making it a usually small to medium-sized tree. Nevertheless, it can sometimes become up to 10 m. It is often a pioneer occurring in open woodland and bushveld and can be very common locally (Coates-Palgrave 2002).

These five savanna tree species and their respective functional traits were compared at different locations in South Africa by using partial orders (see Chapter 4).

The climate at both sites is semi-arid and subtropical with hot, rainy summers and warm, dry winters (see Figure 3.2). The average yearly rainfall is interspersed with extreme precipitation rates below or above average. Drought years (less than 65 % of the average rainfall) in particular tend to have a high impact.

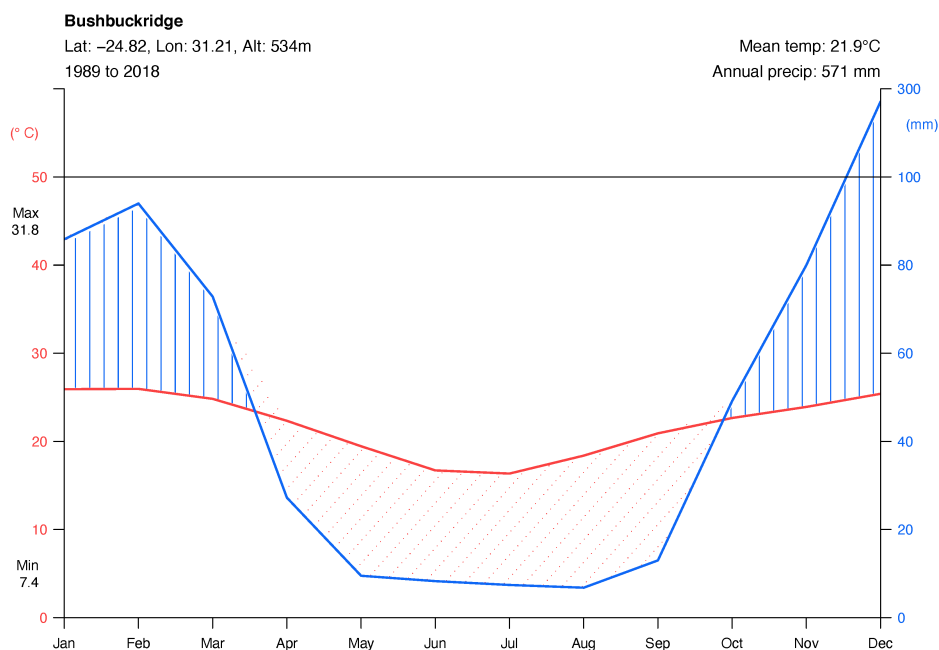


Figure 3.2: Walter-Lieth climate diagram Bushbuckridge Municipality (CRU data 1989-2018)

The rainfall patterns over the last 100 years indicates a cyclical trend with some having years above-average and others having below-average precipitation (Scholes et al. 2001).

Granite Lowveld has shallow sandy soil communities on granite. The underlying geology of the Archaean granite and gneiss of the Nelspruit suite forms the characteristically undulating landscape.

The main disturbances influencing the vegetation structure of this biome are fire, herbivory, and human influences. After droughts, wild veld fires can have an especially immense impact on the grassland. However, at the study sites, these wildfires occur very seldom. Areas affected by high collecting and grazing impact usually do not have enough dried biomass to fuel the fire. Within the protected area, there are mostly human-ignited fires with a return time between six and ten years (Scholes et al. 2001; Smit et al. 2016).

Herbivory, in particular, elephant damages on trees are restricted to the conservation areas. The severity of the impact is positively correlated with the number of elephants within the area (Cook et al. 2017; Levick and Asner 2013; Scheiter and Higgins 2012).

There are multiple disturbances indicative of human behavior:

First, large areas of the Granite Lowveld outside the protected areas are already transformed by cultivation and settlement (Coetzer et al. 2010). In Agincourt (town within the Bushbuckridge Municipality, SA), for example, the communal land is about 3,000 ha. Of these, 370 ha are settlements, 780 ha are fields, and only 1,850 are near-nature sites for grazing and resource harvesting (W. Twine, pers. comm.). Second, the harvesting of resources (mainly firewood collection) impacts the vegetation in this region (Fisher et al. 2012; Matsika et al. 2013a; Mograbi et al. 2019). Third, the more indirect impacts of climate change already affected and will affect the ecosystem and the municipality. First trends have already been measured (Engelbrecht et al. 2015; Mukuyu 2018):

- The annual mean temperature shows a significant warming trend.
- There has been a significant decrease in the annual number of cold nights.
- The maximum temperature is increasing, with the strongest warming signal occurring during spring.
- The strongest warming of minimum temperature occurs during summer and winter.
- The number of extremely hot days has increased.
- The 10-year average monthly rainfall data show variation but no specific trend.

To compare similarities and differences in a near-nature conservation area with a communal land, the EMSAfrica project selected two clearly defined sites (see Figure 3.1):

- The 25 km² study site is within the Bushbuckridge Municipality, south of Agincourt (-24.82°, 31.21°). As a result of Apartheid-era politics, this area is a consolidation of two former “homelands”. Monetary income continues to be low, the unemployment rate is high, and the region is densely populated and only marginally developed (Matsika et al. 2013b). Although most villages have access to electricity, collected firewood is the primary source of cooking and heating (Madubansi and Shackleton 2007).

Wood collecting and harvesting take place in the communal land. To build a realistic socio-ecological model with firewood collectors and a high number of single trees, a site of 100 ha in the middle of the 25 km² block is the study site “**BushbuckridgePlot**”. The agent-based model has 450,000 single individual trees, which are the harvesting source for 56 households, representing 336 inhabitants of Agincourt.

- The other EMSAfrica study site is inside the KNP (-25,02° 31,50°). Here, a nearly undisturbed savanna still exists. Additionally, a century-old history of data collection allows for reasonable estimations of the natural variances in this area. The EMSAfrica Project declares a 16 km² region to be the collaborative research area. In this near-natural site, the trees' primary disturbance agent is the African Elephant (*Loxodonta africana*). To model trees with elephant interactions, a 9 ha site named "SkukuzaPlot" with more than 50,000 single trees is linked with the "KNP elephant model" to model the entire KNP (Clemen et al., under review).

3.2 Predictions of changes

Many semi-arid ecosystems are currently affected by at least two different kinds of changes: land-use change and climate change. Based on this, it can be hypothesized that even very resilient ecosystems may not return to their initial state after disturbance but will instead adapt to a new steady state. Tree distribution can be seen as an indicator for savanna ecosystem resilience on a long-term trend (Aleman et al. 2016; Druce et al. 2008). Inside the Kruger National Park, tree distribution and recruitment are directly impacted by elephants (Cook et al. 2017).

With an undisturbed increase in the number of elephants, there will be an impact on the entire savanna ecosystem by losing big trees (Asner and Levick 2012; Eckhardt et al. 2000; Helm et al. 2009; Henley and Cook 2019; Moncrieff et al. 2008; Vanak et al. 2012). At the same time, bush encroachment will increase the woody biomass by shifting the species composition (Bond and Midgley 2012; Higgins et al. 2000; O'Connor and Page 2014; Skowno et al. 2017; Tews et al. 2006; Treydte et al. 2009). Outside the conservation areas, land-use change will have the most impact on the vegetation (Aleman et al. 2016). On the remaining harvesting sites, the firewood collection can have the most impact (Emanuel et al. 2005; Matsika et al. 2013b; Twine and Holdo 2016).

These processes can be further intensified by climate change. However, the future impact of climate is uncertain and is dependent in South Africa e.g. on the development of population growth, economic development, and development of new technologies. In order to standardize these uncertainties, scenarios for model comparison purposes must be defined. In the last decades, a variety of climate scenarios have been developed. New data sets were created due to the IPCC Fifth Assessment Report (AR5) with Representative Concentration Pathways (RCP) scenarios. RCP names different scenarios with time and space-dependent trajectories of human-made concentrations of greenhouse gases and pollutants. For this thesis, two of the existing scenarios were taken:

- RCP 4.5 (intermediate emission) represents a scenario with stabilization without overshoot pathways to 4.5 W/m² which is roughly equal to 650 ppm CO₂ eq and stabilization after 2100 (Meinshausen et al. 2011).

- RCP 8.5 (high emission) represents the most extreme scenario with three times today's CO₂ emission in 2100. The radiative forcing pathway leads to 8.5 W/m², which is roughly equal to 1370 ppm CO₂ eq by 2100 (Meinshausen et al. 2011).

Agent-based models are useful in learning about how different tree species in the savanna landscape will respond to increasing levels of CO₂, more droughts, hotter summers, and other impacts over the next decades (Calabrese et al. 2010). The complexity of different strategies against disturbances – but also against changes in temperature and precipitation as well as to increase levels of CO₂ – will determinate the regional distribution of individual species.

3.3 Modeling current and potential tree distribution

The model outcome should provide new insights into the potential tree distribution in the Lowveld, South Africa.

Each ABM has its specific workflow for defining the research question, agent types, the environment, and the spatial and temporal extent of the simulation, followed by aggregating simulation data analyzing simulation results. The workflow chosen for this thesis within the MARS system includes the following steps: define, realize, and implement the **modeling project**, create and calibrate the **simulation in MARS**, and select results to organize the **result processing** (see Figure 3.3). These phases, sometimes also called “model development”, “simulation”, and “analysis” (Castle and Crooks 2006) are not necessarily linear. Preferably, adjustments are made periodically or as needed (see Figure 3.5).

3.3.1 Modeling Project

The modeling project must reproduce the best approximation of the real world in the model. The main steps include defining the research question, devising the conceptual model, creating a domain model, defining the output and observables, generating the technical model, and implementing the model.

The research question focuses on the current and potential distribution of different tree species in the Lowveld. Different land-uses characterize the Lowveld particularly, making inclusion of this feature in the question essential to the modeling process. The most different land-use types with a savanna tree distribution are the areas inside the KNP (which have been protected for over 100 years) and the communal harvesting sites in the rural areas.

Tree distribution in savannas is mainly affected by disturbances. In landscapes with people, humans tend to be the significant changing agent (Shackleton 1993), whereas, inside the KNP, elephants are the main disturber of trees (Helm et al. 2009).

This leads to the three agent types tree, human, and elephant to compare human-tree to elephant-tree interactions. Since trees in savannas have various strategies against disturbances, the selected tree species must represent a wide variety.

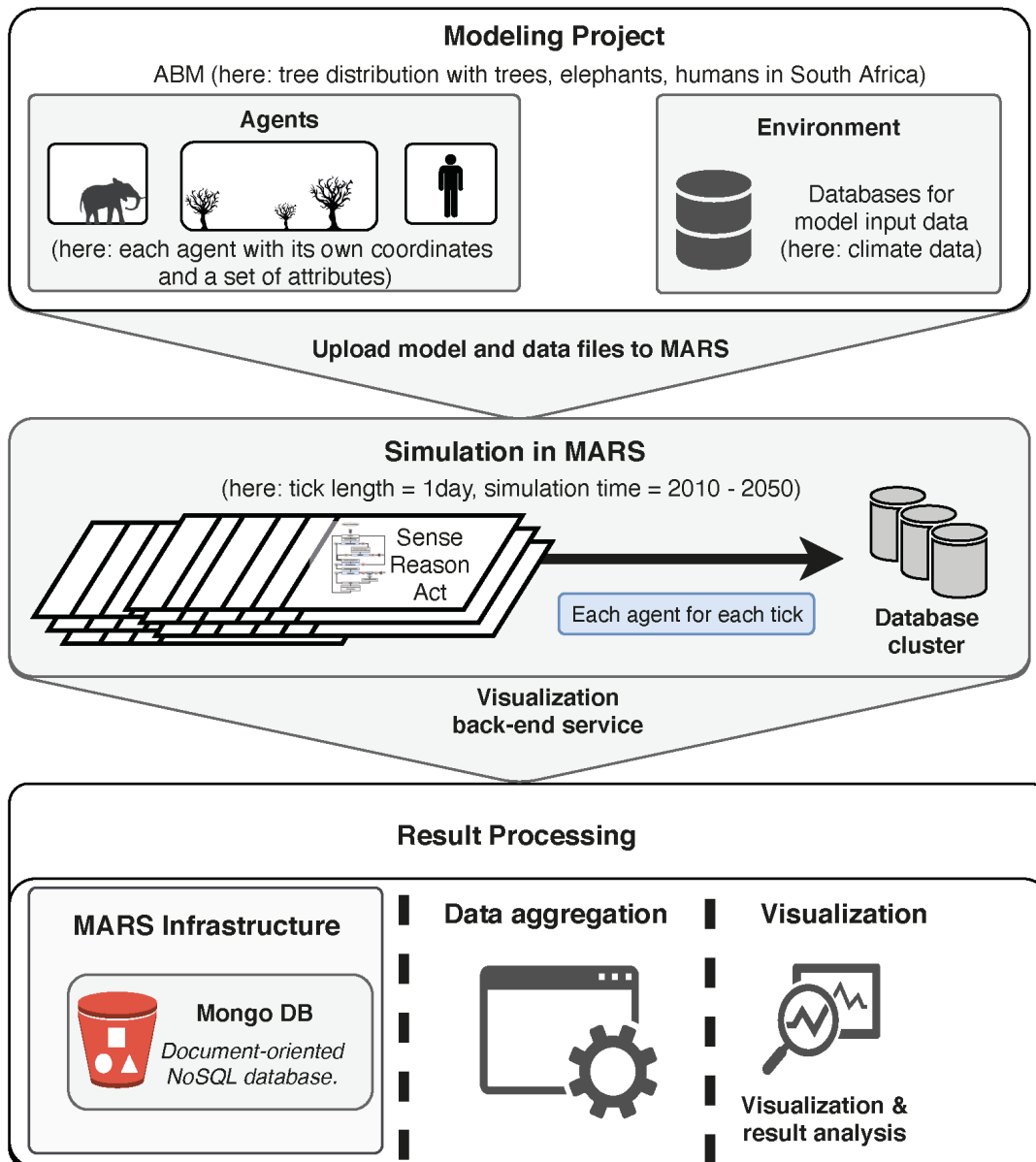


Figure 3.3: Modeling workflow utilized in this study

Much work is done to describe these differences (Charles-Dominique et al. 2018; Stevens et al. 2017; Wigley et al. 2016; Wright et al. 2004, 2005). Wigley et al. (2016) collected data about leaf traits in different savanna trees. This data set was the fundamental resource for defining tree species for the model.

The five main tree species of the Lowveld and their leaf traits were analyzed by applying multi-criteria analyses (see Chapter 4 for more details). After clustering, three different survival strategies emerged. For each strategy, the most abundant representative tree species were chosen:

- *Acacia nigrescens*, representing an investment in the root system,
- *Combretum apiculatum*, representing a defense strategy, and
- *Sclerocarya birrea*, representing a tree which invests in leaves to optimize photosynthetic outcome.

Additionally, to get a realistic density of trees in the simulation, a generic tree species was developed. This so-called “*Tree tree*” has attribute values mediated over the three selected tree species.

Savanna trees are characterized by their different life states, which sometimes have contradictory needs. Therefore, each Tree agent must have its own lifecycle from seed, seedling, juvenile, adult, and dead with corresponding attribute values. Each tree agent has the following attributes: state (age class), living and dead wood mass, maximum stem diameter, number of days with photosynthetic activity per year, damage type, growth rate juvenile and adult, first time of seed production, number of seeds, needed space for germination, mortality after drought for seeds, juveniles and adults, time span from seedling to juvenile, days of precipitation as a seed.

The human agent is represented by the agent type FirewoodCollector. One FirewoodCollector represents a household of six members and a daily demand of about 10 kg of firewood per day. Since the focus is on trees, FirewoodCollectors are mainly defined in terms of their goals, actions, and preferences in different firewood qualities (see Chapter 5 for more details).

Disturbances against trees by elephants are mostly driven by where the elephants are at what time of the day rather than by the number of elephants (Gaylard 2015). In order to simulate elephant behavior realistically, the model was coupled with an existing KNP elephant model designed and developed by the MARS group (Clemen et al., under review).

The Elephant agents are free to pursue their daily activities, driven by the needs defined in the KNP elephant model. If a “KNP elephant” or a “KNP elephant group” comes to the area of the “elephant-tree model” this specific Elephant or elephant group becomes, for one time step, part of the “elephant-tree model” and might interact with trees (see Chapter 6 for more details). The Elephant can damage trees within this time step and afterward disappear into the “KNP model”.

To summarize, agents are autonomous pieces of code. Their behavior is flexible and allows for different ways to act or react. Such actions and reactions are the outcomes of the sense-reason-act method (Weyl et al. 2019), a main ABM concept (see Figure 3.4).

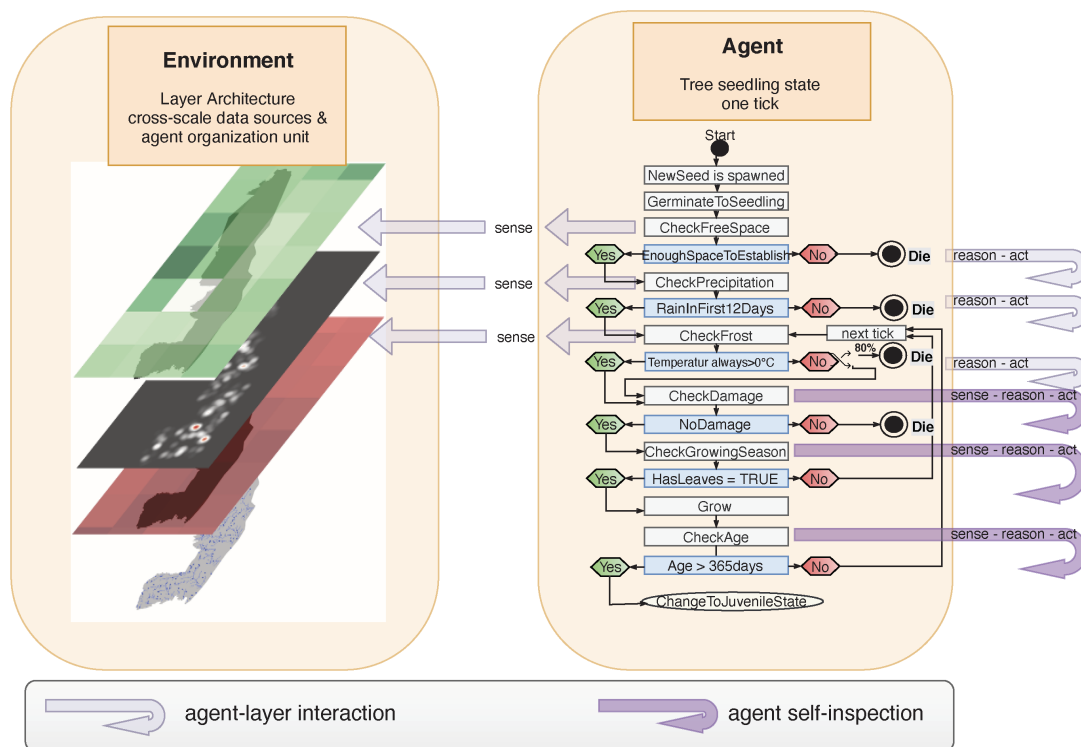


Figure 3.4: Sense-reason-act method of agents and their interaction with layers

The environment is the second part of an agent-based model. All agents' actions are documented and organized in the environment. The environment is made up of multiple layers. Each agent has a geo-referenced coordinate on the environment based on several TimeSeries layers with, for example, climate data. Through these TimeSeries layers, the agent can sense environmental attributes such as, for example, temperature, precipitation, and aggregated data like the sum of precipitation within the last 12 days.

In this model, the environment is made up of (for more details, see Chapter 6):

- ElephantLayer, FirewoodCollectorLayer, TreeLayer, as an organization unit
- TemperatureLayer with daily maximum, minimum, and average temperature
- PrecipitationLayer with daily precipitation and a function to calculate precipitation for a given interval
- DroughtLayer (resulting from the precipitation layer) to switch drought-relevant attributes in tree agents between average years and drought years
- HerbivorePressureLayer to simulate the average biomass reduction by other disturbers.

Uploading the model and all necessary files to the MARS framework is the link between designing the model project and the simulation. Workflows within the MARS group are based on a so-called **tandem approach**. The combination of domain

expert knowledge with computer science knowledge allows for this kind of large ABM and ABS.

Technical support, including programming in C# or the MARS domain-specific language (DSL, Glake et al. 2017), as well as model and data uploads, are performed by computer scientists of the MARS group. For a brief overview of the process, see Figure 3.5.

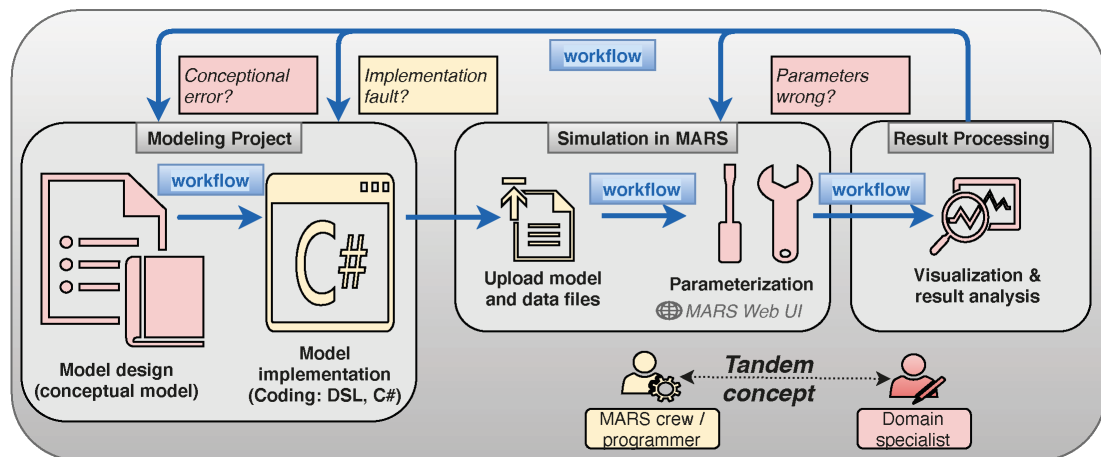


Figure 3.5: The MARS Tandem concept

3.3.2 Simulation in MARS

This study includes two sites with two different tree disturbance agents. Each site has a different tree distribution. Hence, two different tree initialization files were created. Data obtained from literature about AGB/ha, species distribution, and age class distribution were collected and transformed to inform the initialization. The numbers per hectare about tree species in different states with different biomass were randomly distributed over the simulation area.

The temporal frame of the simulation is from 2010 to 2050, with a daily tick length for the tree agent and FirewoodCollector agent types and a Δt of one hour for the elephant agent type.

Since the future climate is unknown, two different climate predictions are selected. In total, this thesis compares four different simulations in which all agent types are the same. Each simulation has the same start date (01.10.2010) and end date (30.09.2050). A simulation time of 40 years and a time step of one day results in 14,600 steps. For each day in the simulation, every agent goes through its own sense-reason-act methods defined by decision-trees (for more details, see Figure 3.4 and Chapter 6) and interacts with other agents and the environment.

The results of all agents and time steps during the simulation are stored in the MARS database cluster. Along with a unique identification number, each agent's attribute values for each tick are documented in CSV files. A separate file with all dead trees and their specific cause of death is maintained. In order to handle such

high volumes of data, MARS is designed to be highly scalable – by adding hardware, the performance can be extended to the required level (Weyl et al. 2019; Glake et al. 2017; Hüning et al. 2016).

Terabytes of data in a database cluster go through a data science pipeline before any analysis and visualization are possible. The visualization and back-end services lead to the third part “result processing” of an ABM.

3.3.3 Result Processing

In order to detect trends in tree distribution data, a tick-by-tick analysis of the data does not seem promising. Therefore, an initial data aggregation was done on a yearly basis. In South Africa, the vegetation year starts in October. Hence, the beginning of October is an excellent time for annual and inter-simulation comparison of tree distribution. A second data reduction was performed to compare only seedling, juvenile, and adult trees of each species.

The MARS simulation infrastructure incorporates and chains together by a steadily broadened multitude of processes and tools (including support for geographic data, 3D visualization, and context and logging services) to provide an approach to today’s simulation requirements.

The analyses and visualizations in this study were created by utilizing the programming languages Python (version 3.7.x), R (version 3.6.x), and kepler.gl. To extract the massive amount of result data from the Mongo database, a variety of tools has been applied.

Chapter 4

Exploring survival strategies of African Savanna trees by partial ordering techniques

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Highlights

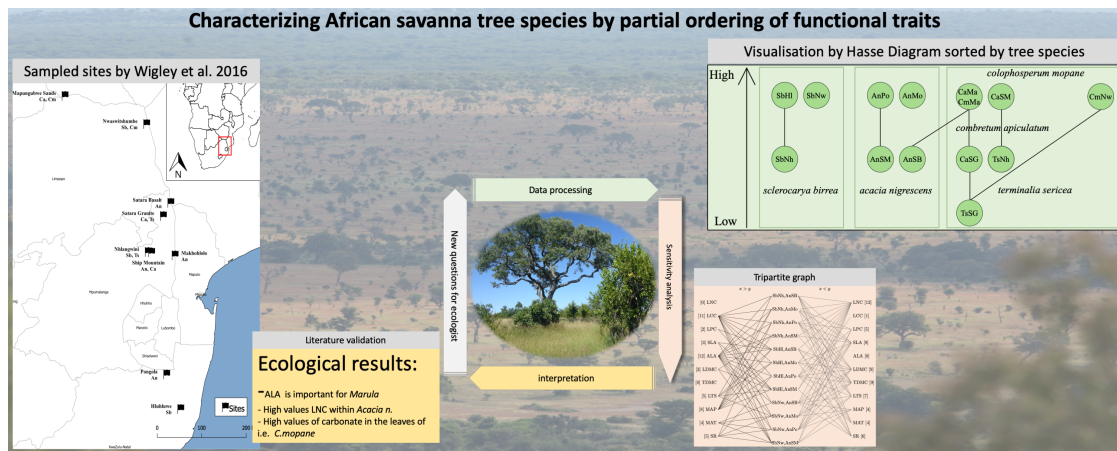
- Ecological strategies derived by partial order theory
- High average leaf area (ALA) typical in *Sclerocarya birrea*
- High leaf nitrogen concentrate (LNC) found in *Acacia nigrescens*
- High leaf carbonate¹ concentrate (LCC) within *Colophospermum mopane*

Keywords:

Sclerocarya birrea, Savanna trees, Resilience, Functional traits, Partial orders

¹Should be 'carbon' instead, carbonate is a translation mistake within the abstract, highlights, and graphical abstract of the manuscript

Graphical Abstract



ABSTRACT

The resilience of savanna ecosystems to climate and land-use changes is an important ecological and management question. The term 'resilience' is used to refer to the ability of a tree species to survive in a specific location, even under changing environmental conditions. In this study, vectors of functional traits of selected savanna tree species are studied by applying partial order algorithms to them. Some ecological interpretations are obtained and are compared to published research. One finding is the high rates of nitrogen fixation for the leaves of *Acacia nigrescens*. In opposition to this well-known fact, we discovered that *Sclerocarya birrea* has a bigger average leaf area than the other four tree species. Additionally, we found high carbonate¹ values within the leaf from *Colophospermum mopane*, *Combretum apiculatum*, and *Terminalia sericea*. These results correspond to different ecological strategies for the tree species in question. It became obvious that geometric structures gained from partial ordering show a very good correspondence to ecological strategies of these tree species. Concepts of partial order theory may therefore be helpful in ecosystem research.

4.1 Introduction

In order to survive, African savanna tree species have to deal with drought, fire, herbivores, and tree-grass competition (Archibald et al. 2005; Bohrer et al. 2014; Cardoso et al. 2016; Manning et al. 2006; Scholes and Archer 1997).

For this reason, the plant communities of savanna ecosystems change in a specific manner across time and space (Barbosa et al. 2014). Each species in the bi-stable savanna ecosystem (Staal et al. 2016) has its own strategy to respond to the variation of environmental configuration, disturbance, and climate conditions - the so-called ecological niches (February and Higgins 2016; Neyret et al. 2016; Stevens et al. 2013). In our study, we focused on large deciduous trees. They form a keystone structure (Helm et al. 2009; Levick and Asner 2013; Manning et al. 2006) and are functionally important for savanna ecosystems.

For the purposes of this study, we took data from Wigley et al. 2016 and selected five major tree species. All of them are common in many areas of the Lowveld in South Africa. The research focused on the comparison between *Sclerocarya birrea* (Marula) (Sb) with *Acacia nigrescens* (An), *Colophospermum mopane* (Cm), *Combretum apiculatum* (Ca), and *Terminalia sericea* (Ts).

Marula, ecologically speaking, is one of the most important trees in the South African savannas (Helm et al. 2009; Jacobs and Biggs 2002a), as it provides food and shade for several groups of animals. The leaves are browsed by mammalian herbivores and insects, the bark is stripped by elephants, and the fruits are eaten by several wild animals (Shackleton 2002).

Several investigations were also performed within the context of *Sclerocarya birrea* and provided a broad data basis (Emanuel et al. 2005; Helm et al. 2009; Jacobs and Biggs 2002a; Maroyi 2013; Shackleton 2002). All of this data was thoroughly analyzed with the use of conventional (multivariate) statistics. The key findings were, for example, the strong correlation between soil properties and spatial and temporal tree distribution (Wigley et al. 2016). The strong influence of precipitation within savanna ecosystems was verified as well (Sankaran et al. 2005).

In the context of ecological strategies and resilience, one of the key questions is to what extent tree species are able to optimize their growth and their stability within the savanna ecosystem. Additionally, the concept of inter-species competition has to be considered; i.e. which tree species is better adapted to which specific site or condition than another. This comparison is difficult to make because a singular (deterministic or even heuristic) goal function is unknown.

To perform this analysis, a multi-indicator system must be scrutinized. In this study, several leaf traits extended by climate data are used as a vectorial information base. We were thereby able to keep the single indicator information separated, avoiding information loss due to any heuristic aggregation process. Such processes unavoidably merge the valuable information provided by each indicator due to the aim of getting a reduced set of new indicators: in general, just a one-dimensional scalar. An appropriate analysis tool is provided by the theory of partially ordered sets (Brüggemann and Carlsen 2006).

Partial order theory has been applied toward many disciplines, e.g. on environmental chemicals, pollution, economic and socio-economic topics (Annoni et al. 2015, 2011; Fattore 2008; Sørensen et al. 1998).

To date, partial order theory has only been applied to few ecological studies (Patil and Taillie 1976, 1982; Solomon 1979). As far as we know, this study is the first attempt to combine elements of partial order theory with aspects of savanna ecology. In our study, we focused on the question of whether it is possible to extract different survival strategies of selected savanna tree species by applying methods from partial order theory or not.

The paper is organized as follows: The following section presents the origin and amount of data used here and gives a brief overview about methods of partial order theory. Applying these methods to the data led to a set of results that are described in section three. Various ecological strategies were derived from these results and

consecutively validated by a literature review. Finally, the last section of the paper summarizes our contributions and identifies areas for further research.

4.2 Material and methods

4.2.1 Study area

The study was conducted in the eastern part of South Africa (Figure 4.1).

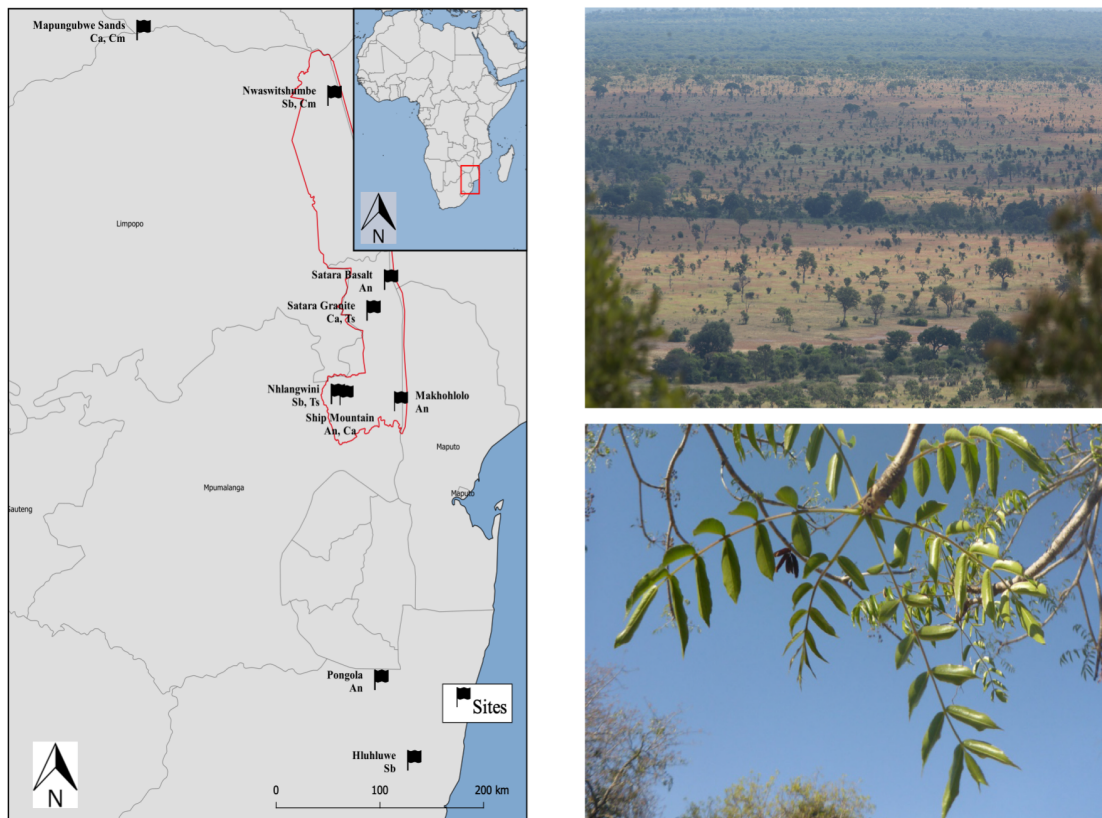


Figure 4.1: Left side: Data sites sampled by Wigley et al. 2016. All sites with at least one of our selected tree species. Right side: Typical savanna with tree-grass landscape (above), flushing leaf-let of *Sclerocarya birrea* in springtime (below)

All sites are located inside conservation areas within the coordinates -22°S , 29°W and -28°S , 32°W . The annual precipitation is between 300 and 900 mm (Table 4.1).

Functional traits data were obtained from (Wigley et al. 2016); please see the original paper for details.

Data analysis was focused on five tree species, which Wigley et al. 2016 identified as the dominating woody species in Kruger National Park, a representative savanna ecosystem in South Africa. In correspondence to the selected tree species, nine distinct sites were chosen as depicted in Figure 4.1 (left). We refer to Fig. 4.1 (left) for site locations. A typical tree-grass savanna landscape and a leaflet from *Sclerocarya birrea* in springtime are shown in Fig. 4.1 (right).

Table 4.1: List of sites of this study with climatic characterization (MAP: Mean Annual Precipitation, MAT: Mean Annual Temperature, SR: Mean daily solar radiation in January)

Name	Abbreviation	LAT (<i>decimal</i>)	LON (<i>decimal</i>)	MAP (<i>mm</i>)	MAT (<i>°C</i>)	SR (<i>mJ/m²</i>)
Hluhluwe	HI	-28.1067	32.0443	900	20	57
Makhohlolo	Mo	-25.2621	31.9137	550	20	60
Mapungubwe Sands	Ma	-22.2411	29.3779	314	22	64
Nhlangwini	Nh	-25.1991	31.2926	678	20	59
Nwaswitshumbe	Nw	-22.7781	31.2582	495	22	61
Pongola	Po	-27.4744	31.7201	660	21	54
Satara Basalt	SB	-24.2766	31.8154	525	21	54
Satara Granite	SG	-24.5257	31.6431	576	22	65
Ship Mountain	SM	-25.2134	31.3726	676	20	59

4.2.2 Data preprocessing

It is necessary to restructure, join, and classify the sampled data in order to provide a base for the application of partial order theory. Our approach avoids artificial (i.e. not deterministic, process based) aggregation by deriving a single but composite indicator.

4.2.2.1 Data organization

As we are interested in discovering the interplay between sites, their characteristics and tree species, the data is organized as follows:

- 1) Set of tree species $T := \{Sb, An, Ca, Cm, Ts\}$
- 2) Set of sites $S := \{HI, Nh, Nw, Mo, Po, SB, SM, SG, Ma\}$.

Now, the Cartesian product of the two sets T and S is formed, with $(t,s) \in T*S$, which results in 45 pairs. However, we only take into account those pairs which are available in the original data matrix of Wigley et al. 2016. The resulting set $X \subset T*S$ thus consists of only 14 pairs and comprises eleven indicators (Table 4.2). We introduce the notation (Sb, s) and (An, s') to abstract from specific selected sites. Thus, for example $s \in \{HI, Nw, Nh\}$ and $s' \in \{Po, Mo, SB, SM\}$. Furthermore, we do not write e.g. (Sb, HI) but rather $SbHI$ for the sake of simplicity.

4.2.2.2 Indicators

The leaf trait data are leaf nitrogen concentration (LNC), leaf carbon concentration (LCC), leaf phosphorus concentration (LPC), specific leaf area (SLA), average leaf area (ALA), leaf dry matter content (LDMC), twig dry matter content (TDMC), and leaf tensile strength (LTS). The climate data includes mean annual precipitation (MAP), mean annual temperature (MAT), and mean daily solar radiation in January (SR). The eight leaf traits correlate well with the productivity of trees (Wigley et al. 2016). As the intention is to perform an order analysis, it is mandatory to assure the same orientation of all eleven indicators, i.e. a high value should represent good states, whereas a low

value denotes a bad state. The set of indicators LNC, LCC, LPC, SLA, ALA, LDMC, TDMC, LTS, MAP, MAT, SR is our base of information, abbreviated IB.

Table 4.2: Overview of the trait and climatic data used for the study

Spp	LNC (<i>mg/g</i>)	LCC (<i>mg/g</i>)	LPC (<i>mg/g</i>)	SLA (<i>cm²/g</i>)	ALA (<i>cm²</i>)	LDMC (<i>mg/g</i>)	TDMC (<i>mg/g</i>)	LTS (<i>N/mm</i>)	MAP (<i>mm</i>)	MAT (<i>°C</i>)	SR (<i>mJ/m²</i>)
SbHl	18.8	429	1.3	92.72	107.55	339.91	370	1.16	900	20	57
SbNh	10	440	1	70.4	83.3	361.5	372	0.61	678	20	59
SbNw	12.3	452	1	90.46	78.52	336.96	370	0.62	495	22	61
AnMo	23.2	390.1	1.3	111	25.4	638.9	606.8	0.01	550	20	60
AnPo	28.6	424	1.6	112.51	22.39	571.35	607.7	1.51	660	21	54
AnSB	26	421	1	92.7	14.2	475.9	582	0.71	525	21	65
AnSM	26	439	1	88.3	27.5	291.8	538	0.86	676	20	59
CaSG	17	472	1	90.9	20.1	469.2	708	1.16	576	22	65
CaSM	16	489	1	61.6	4.7	669.6	658	1.1	676	20	59
CaMa	19.3	462	1.1	86.22	18.19	408.12	708	1.52	314	22	64
CmMa	22.9	496	1.5	86.07	31.29	437.42	588	1.21	314	22	64
CmNw	18	478	4	46.2	9.3	460.4	588	1.46	495	22	61
TsNh	11	454	1	70.4	14.1	418.7	540	1.02	678	20	59
TsSG	15	461	1	70.7	17.9	429.7	652	0.89	576	22	65

4.2.2.3 Classification

The data (Table 4.2) is still too finely graduated for applying the \leq -relation to it. Small (and probably not relevant) differences would hamper the analysis. Therefore, a binary classification was performed, where each $x \in X$ is mapped to $x' \in \{0,1\}^m$, m being the numbers of indicators, namely 11. The set of original values is thereby separated into two groups on the basis of a classification rule as follows.

For a first attempt, we considered that the arithmetic mean (M) of the minimum (Min) and maximum (Max) values (Table 4.3) in a data set is a reasonable threshold for the classification rule.

Table 4.3: Minimum, maximum and mean values of the original data

	LNC	LCC	LPC	SLA	ALA	LDMC	TDMC	LTS	MAP	MAT	SR
Min	10.0	390.1	1.0	46.2	4.7	291.8	370.0	0.01	314.0	20.0	54.0
M	19.3	443.05	2.5	79.355	56.125	480.7	539.0	0.765	607.0	21.0	59.5
Max	28.6	496.0	4.0	112.51	107.55	669.6	708.0	1.52	900.0	22.0	65.0

The selection of M allows a generalization to more than two classes in an easy way. A reasonable alternative would be a distribution-based approach, such as a selection of quartiles or other characteristics of a statistical distribution. The resulting matrix with entries $\in \{0,1\}$ is shown in Table 4.4. For further consideration, it is convenient to speak of indicators having a value of 0 as “switched off”, and those having a value of 1 as “switched on”.

Table 4.4: Data matrix after binary classification (Indicator value $< M$: score 0 and indicator value $\geq M$: score 1

	LNC	LCC	LPC	SLA	ALA	LDMC	TDMC	LTS	MAP	MAT	SR
SbHl	0	0	0	1	1	0	0	1	1	0	0
SbNh	0	0	0	0	1	0	0	0	1	0	0
SbNw	0	1	0	1	1	0	0	0	0	1	1
AnMo	1	0	0	1	0	1	1	0	0	0	1
AnPo	1	0	0	1	0	1	1	1	1	1	0
AnSB	1	0	0	1	0	0	1	0	0	1	1
AnSM	1	0	0	1	0	0	0	1	1	0	0
CaSG	0	1	0	1	0	0	1	1	0	1	1
CaSM	0	1	0	0	0	1	1	1	1	0	0
CaMa	1	1	0	1	0	0	1	1	0	1	1
CmMa	1	1	0	1	0	0	1	1	0	1	1
CmNw	0	1	1	0	0	0	1	1	0	1	1
TsNh	0	1	0	0	0	0	1	1	1	0	0
TsSG	0	1	0	0	0	0	1	1	1	1	1

4.2.3 Partial order theory

4.2.3.1 Introductory remarks

In this section, we follow the description given by (Carlsen and Brüggemann 2017, 2016) closely. The basis for partial ordering is the \leq -relation among the objects, i.e. set X , to be ordered (Annoni et al. 2017; Brüggemann and Carlsen 2006; Carlsen et al. 2015; Sørensen et al. 2000). Thus, the " \leq "-relation is the basis for a comparison of objects. Two objects $x, y \in X$ are called connected if and only if the relation $x \leq y$ holds. However, since each object is characterized by a series of indicators q_j , the obvious question is how $x \leq y$ should be understood. As a given object x is characterized by a set of indicators $q_j(x), j = 1, \dots, m$, it can be compared to another object y , if and only if:

$$q_i(x) \leq q_i(y), \text{ for all } i = 1, \dots, m \quad (4.1)$$

The adjacency matrix for directed graphs, sometimes also called the ξ -matrix, can be derived from Eq. 4.1.

Eq. 4.1 is not the only way to obtain a partial order from a data matrix. It is, however, the most basic definition. Eq. 4.1 is the basis for a graphical presentation called the Hasse diagram (HD). We denote the set of objects X , having the mathematical structure of a partial order as a poset (partially ordered set) (X, IB) , IB being the set of indicators. For details, see (Bruggemann and Patil 2010; Brüggemann and Patil 2011; Davey and Priestley 2002). For the construction of a Hasse diagram it is mandatory that all indicators have a uniform orientation, i.e. high indicator values correspond to "good" objects whereas low values represent "bad" objects. Basically, a HD allows the identification of simple structures such as

- maximal elements, no other comparable element is located above them, the set of maximal elements is denoted as MAX,
- minimal elements, no other comparable element is located below them, the set of minimal elements is denoted as MIN and
- isolated elements, which are minimal and maximal elements simultaneously, the set is denoted as ISO and equals $\text{MIN} \cap \text{MAX}$.

4.2.3.2 Further structures of partially ordered sets

4.2.3.2.1 Comparable and incomparable elements. Let x, y be elements of a partially ordered set. They are comparable when $x \leq y$ or $y \leq x$ is true. Otherwise they are incomparable elements and denoted as $x \parallel y$.

4.2.3.2.2 Chains. Chains are totally ordered subsets of a poset where all objects in the subset fulfill Eq. 4.1. They are characterized by their height which equals the number of objects in the subset. Chains are particularly interesting as they constitute complete orders of some objects being co-monotony ordered by their indicators. The concept of co-monotony describes criteria with the same orientation for a ranking aim.

4.2.3.2.3 Levels. Levels are the horizontal arrangement of objects within a Hasse diagram. The number of levels is the height of a maximum chain in the poset (for more details, see Bruggemann and Patil 2010; Bruggemann and Patil 2011). Levels per definition constitute a set of elements mutually incomparable. The level structure gives a first approximation to a weak order (a sequence, where tied objects can occur) of the objects from “bad” (bottom) to “good” (top). However, this will lead to many tied orders because all objects in a level automatically will be assigned an identical order (Bruggemann and Carlsen 2015). It is convenient to enumerate the levels from the bottom to the top.

4.2.3.2.4 Antichains. Antichains are subsets of the object set where no object fulfills Eq. 4.1; i.e. all objects in the subset are mutually incomparable. Thus, for any two objects within an antichain there is at least one conflict in indicator values. Note, an incomparable pair x, y of objects must necessarily belong to one level. Whereas in Hasse diagrams objects belonging to antichain seem to provide no order relations, a detailed analysis can be performed by which the degree of conflicts can be quantified; the concept of tripartite graphs seems to be especially useful.

4.2.3.2.5 Separated subsets. Let X_1, X_2 be subsets of X . If $x \in X_1$ and $y \in X_2$ implies $x \parallel y$, then the sets X_1 and X_2 are called separated subsets. From a data analytic point of view, separated subsets are of interest for finding common properties for elements of X_1 and of elements of X_2 causing this separation. It is possible to introduce the degree of separation:

$$\begin{aligned} \text{Sep}(X1, X2) &:= (\| \{(x, y) : x \in X1, y \in X2, X1 \cap X2 = \emptyset, x \parallel y\} \|) / N \\ N &:= (\| X1 \| * \| X2 \|) \end{aligned} \quad (4.2)$$

By Eq. 4.2, separated subsets can be characterized by $\text{Sep}(X1, X2) = 1$, whereby disjoint subsets $X1, X2$ with $\text{Sep}(X1, X2)$ having almost the value 1 indicate a “weak separation”, which also demands a causal interpretation.

4.2.3.3 Sensitivity analysis

The sensitivity analysis aims at a quantification of the influence each indicator has on the structure of the poset. The analysis is based on the distance among posets formed by the full set of indicators and those where one after another indicator is left out. The distance between (X, IB) and (X, IB_{q_j}) is therefore determined by calculating the adjacency matrices and subsequently the (squared Euclidean) distance (Bruggemann and Patil 2010; Brüggemann and Patil 2011).

4.2.3.3.1 Tripartite graphs. Let $x \parallel y$ be two objects which are incomparable, taken the indicators q_j of interest. Then there must be a set of indicators causing $x > y$, and a disjoint set of other indicators causing $x < y$. A tripartite graph consists of three vertically arranged vertices, parallel to each other. In the middle the set of incomparable objects $\{(x, y) : x, y \in X' \subseteq X \text{ with } x \parallel y\}$, the left and right columns are vertices, representing the indicators. A line from q_j (left side) is drawn to (x, y) if and only if $x >_{q_j} y$, and a line is drawn from the right column of indicator vertices, if $x <_{q'_j} y$ with q'_j constituting the indicator vertices on the right side. This graph clearly shows which indicator pairs cause a conflict (for more details, see Brüggemann and Voigt, 2012, 2011).

4.2.3.4 Tooling

All partial order analyses were carried out with the PyHase software (Brüggemann et al. 2014). PyHase provides a portfolio of sophisticated Python programs analysis of partial orders based on of 4.1 . The modules used in our study are: `mHDC17_0.py`, `sensitivitysimp14_1.py`, `discretiz5_2.py` and `sepanalcoloured17_0.py`.

4.3 Results

4.3.1 Analyzing the structures of the poset

Each element $(t, s) \in X \subset T * S$ corresponds to a tuple of binary values 4.4 that represents, e.g.:

SbHI \rightarrow (0,0,0,1,1,0,0,1,1,0,0)

The pairwise comparison (according to Eq. 4.1) leads to the following distinction of cases:

4.3.1.1 Equivalence (\cong)

CaMa \rightarrow (1,1,0,1,0,0,1,1,0,1,1)

CmMa \rightarrow (1,1,0,1,0,0,1,1,0,1,1)

are pairwise identical regarding their values, they are called 'equivalent'. In our poset there is only this pair of equivalent elements (see also Table 4.5). From an ecological point of view, those elements can be considered ecologically similar with respect to the underlying multi-indicator system.

Table 4.5: Example for equivalence

	LNC	LCC	LPC	SLA	ALA	LDMC	TDMC	LTS	MAP	MAT	SR
CaMa	1	1	0	1	0	0	1	1	0	1	1
CmMa	1	1	0	1	0	0	1	1	0	1	1

4.3.1.2 Chain of comparable elements (\leq)

The following chains exist within the poset:

SbNh \rightarrow (0,0,0,0,1,0,0,0,1,0,0) $<$ SbHl \rightarrow (0,0,0,1,1,0,0,1,1,0,0)

So, SbNh $<$ SbHl is expressing the mutual comparability of SbNh with the orientation as denoted above. The set of indicators with bits "switched on" of SbNh is a subset of the set of indicators "switched on" of SbHl (see Table 4.6). The ecological relevance of chains arises from the fact that any chain represents co-monotony among the indicators.

Table 4.6: Example for a two-elements chain

	LNC	LCC	LPC	SLA	ALA	LDMC	TDMC	LTS	MAP	MAT	SR
SbHl	0	0	0	1	1	0	0	1	1	0	0
SbNh	0	0	0	0	1	0	0	0	1	0	0

4.3.1.3 Incomparable elements

The incomparability of SbHl with SbNw (SbHl \parallel SbNw) indicates a conflict namely with respect to the indicators LCC and LTS (SbHl has the bit "LCC" switched - off, whereas SbNw has this bit on); but with respect to LTS, the opposite is valid (Table 4.7). Similarly, there is a conflict between LCC and MAP. An ecological interpretation cannot directly be seen from the Hasse diagram, but tools are available to elucidate this incomparability relation in more detail (see Section 4.3.4).

Table 4.7: Example for incomparable elements

	LNC	LCC	LPC	SLA	ALA	LDMC	TDMC	LTS	MAP	MAT	SR
SbHl	0	0	0	1	1	0	0	1	1	0	0
SbNw	0	1	0	1	1	0	0	0	0	1	1

4.3.2 Visualization of the poset

4.3.2.1 Hasse diagram

The binary data matrix shown in Table 4.4 provides the input for the PyHasse program `mHDC17_0.py`. Figure 4.2 shows a first visualization of the poset.

It would even be generally possible to extract the same information from the poset directly; visualizing them by Hasse diagrams helps to get more information out more quickly.

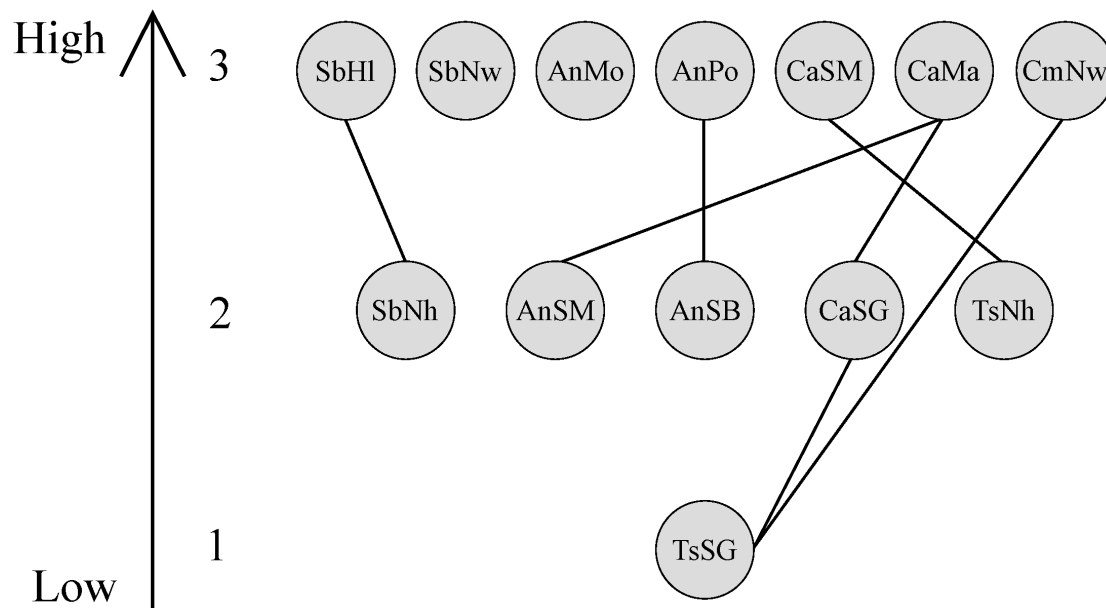


Figure 4.2: First visualization of the poset as a Hasse diagram ($\text{CaMa} \cong \text{CmMa}$, only CaMa is visible).

The following structural elements became distinctive from Fig. 4.2:

- **Chains:** Chains are represented as edges of a directed graph within the Hasse diagram. The co-monotony implies that moving from the bottom of a Hasse diagram toward the top, each bit already switched on is maintained and other bits are sequentially switched on, as well. As one can see in Figure 4.2, there are the following 11 chains: chains with four vertices: $\text{TsSG} < \text{CaSG} < \text{CaMa} \cong \text{CmMa}$, chains with three vertices (subsets of the four-vertices-chain): $\text{TsSG} < \text{CaSG} < \text{CaMa}$, $\text{TsSG} < \text{CaSG} < \text{CmMa}$, and $\text{AnSB} < \text{CaMa} \cong \text{CmMa}$, chains with two vertices (partially subsets of the three-vertices-chains): $\text{SbNh} < \text{SbHI}$, $\text{AnSM} < \text{AnPo}$, $\text{AnSB} < \text{CaMa}$, $\text{AnSB} < \text{CmMa}$, $\text{TsSG} < \text{CmNw}$, $\text{TsSG} < \text{CaSM}$, $\text{TsNh} < \text{CaSM}$
- **Antichains:** There are several pairwise incomparable elements. Each non-connected set is an antichain. These incomparabilities will be analyzed below.
- **Levels:** The poset comprises three levels because the maximum chain has a height of three. The bottom level, referred to as Level 1 (see Figure 4.2) consists of

TsSG, whereas the top level, i.e. Level 3 consists of *Sclerocarya birrea* SbHI, SbNw, the second level consists of SbNh. An evaluation on the basis of levels would lead in the case of Sb to the order: $SbNh < SbHI \cong SbNw$.

- Maximal elements: All eight elements of Level 3 are in this group. These include SbHI, SbNw, AnMo, AnPo, CaSM, CaMa, CmMa and CmNw.
- Minimal elements: The elements without a chain or in the lower level at the beginning of a chain are called minimal elements. In this Hasse diagram, SbNh, SbNw, AnSM, AnSB, AnMo, TsSG and TsNh are the minimal elements.
- Isolated elements: SbNw and AnMo are isolated elements and therefore deserve a more detailed analysis. The notion “isolated” for the object AnMo, as an example, expresses incomparabilities as follows: $AnMo \parallel AnPo$ and $AnMo \parallel AnSM$. Correspondingly, the set of bits switched on/off of AnMo is neither in a subset-relation to that of AnPo nor of AnSM.

4.3.2.2 Clustering by species

To get a clearer view, it is sometime helpful to re-order the Hasse Diagram preserving the given order relations (Figure 4.3). The sorting order of horizontal elements on the same level may be changed without consequences to the results. A goal is to minimize the number of edge crossings, but domain-specific issues can be considered as well. Here, the separation of tree species leads to a more structured Hasse diagram (Figure 4.3).

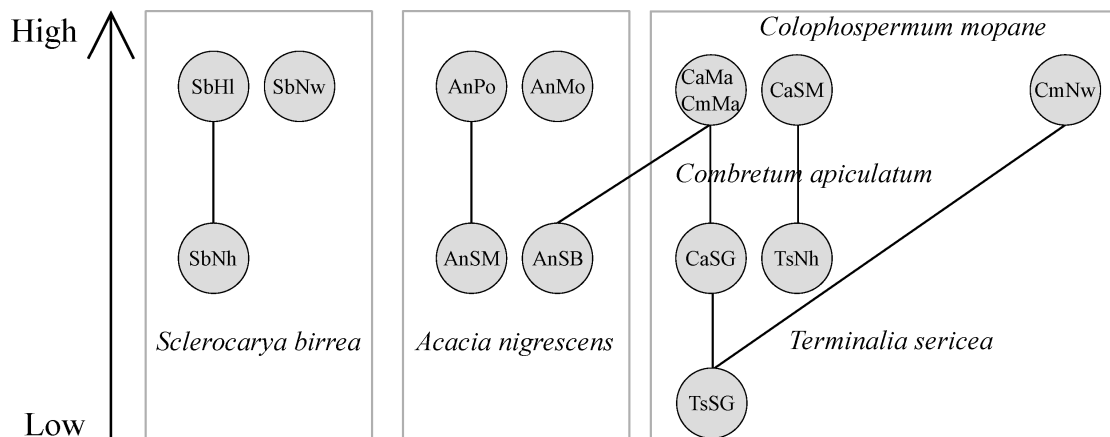


Figure 4.3: Hasse diagram clustered by species.

This clustering allows an easier ecological interpretation by species:

- *Colophospermum mopane* at both measured sites Mapungubwe Sands (Ma) and Nwaswitshumbe (Nw) is represented in the upper part, corresponding to Level 3 of the Hasse diagram. More values are greater than the arithmetic mean, so higher values in leaf traits and climate data are shown.

- *Terminalia sericea* at both sites Satara Granite (SG) and Nhlangwini (Nh) are in the lower parts, Level 1 and 2 of the HD. This tree species is known as a tree with low nutritional value demands (Grant and Thomas 2006).
- The whole Hasse diagram becomes separated into three different groups, characterized by:
 - *Sclerocarya birrea* (Sb),
 - *Acacia nigrescens* (An), and
 - *Colophospermum mopane* (Cm), *Combretum apiculatum* (Ca), and *Terminalia sericea* (Ts).
- *Sclerocarya birrea* is fully separated, without any chain to another tree/site combination. The corresponding degree of separability is one.
- The *Acacia nigrescens* group is almost completely separated from the group formed by Ca, Cm, Ts. The separability degree is close to one.

To find out why *Sclerocarya birrea* is separated, a closer look at the incompatibilities is carried out by sensitivity and antichain analysis.

4.3.3 Sensitivity analysis

The sensitivity analysis aims for a quantification of the influences each indicator has on the structure of the poset.

Based on the Value-of-Sensitivity (VoS) in Table 4.8, an order of indicators can be derived:

ALA > MAP > LNC \cong LPC \cong LDMC > LCC \cong SLA \cong SR > MAT > TDMC \cong LTS.

If the data matrix does not contain the indicator ALA, the poset would change most dramatically, hence its Hasse diagram; whereas omitting TDMC or LTS from the data matrix would have only minor consequences. It is not surprising that MAP has such a large influence, as precipitation is most crucial for savanna tree species (Sankaran et al. 2005). As we will discuss in more detail in Section 4.4, the high impact of ALA (Average Leaf Area) arises only from the presence of *Sclerocarya birrea* (Sb) in the current data set.

Table 4.8: Results of the sensitivity analysis (Value of Sensitivity)

Indicator	LNC	LCC	LPC	SLA	ALA	LDMC	TDMC	LTS	MAP	MAT	SR
VoS	4	2	4	2	9	4	0	0	8	1	2

4.3.4 Tripartite graphs

Incompatibilities can be further scrutinized by applying the concept of tripartite graphs. Figure 4.4 shows an example where Sb and its corresponding sites (Sb,s) are mutually compared with An and its sites (An,s') with $s \in \{Nb,Nh,HI\}$ and $s' \in \{SB,Mo,Po,SM\}$. By this, basically incomparable elements of a poset can be analyzed regarding the sensitivity of its attributes.

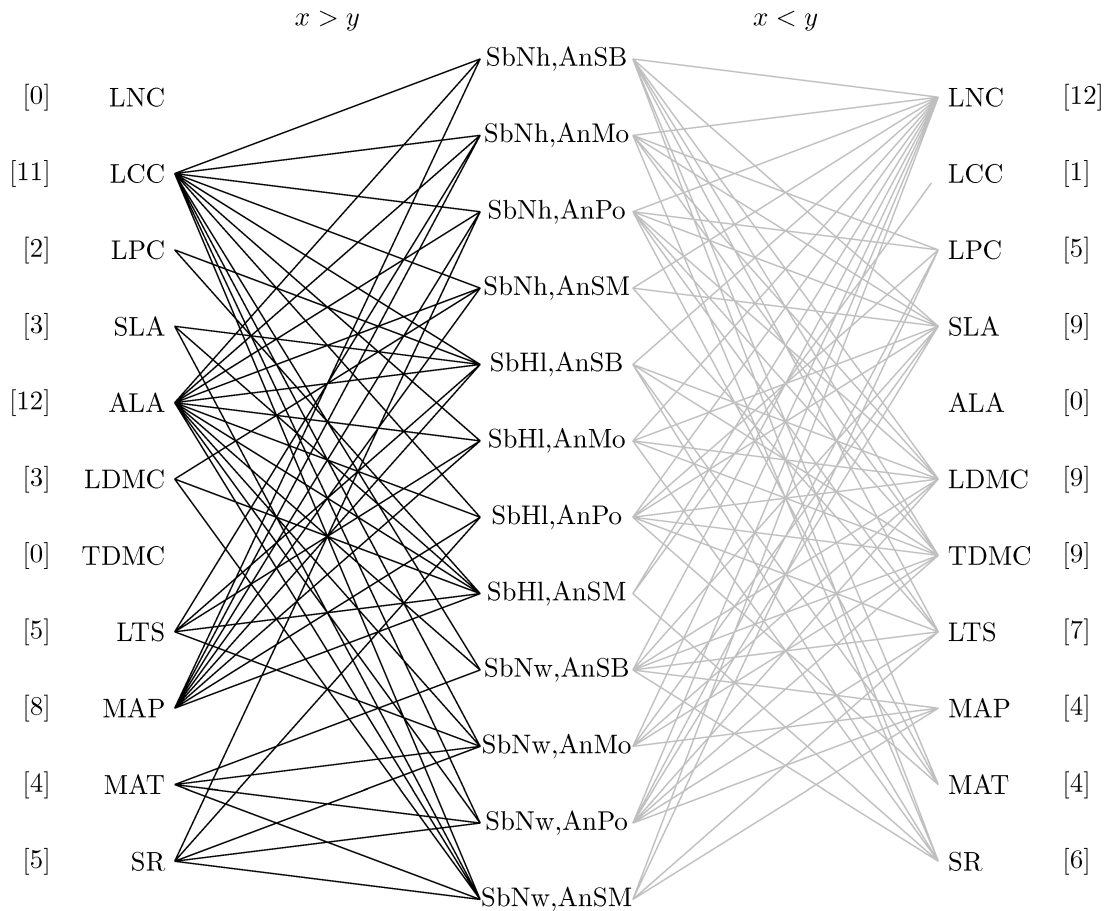


Figure 4.4: Tripartite graph of (Sb,s) , and (An,s') , where s and s' are representatives of different sites. The symbol x stands for the Sb with its sites and y for An with its sites, $[]$ stand for the orientations of the comparabilities.

As an example, it can be stated that MAT values are the reason that $(Sb,s) > (An,s')$ in four pairs, whereas LCC only causes $(Sb,s) < (An,s')$ once. MAP produces eight relations of $(Sb,s) > (An,s')$ and among all possible pairs of sites of *Sclerocarya birrea* and *Acacia nigrescens* (max =12), MAP favors An over Sb four times. All findings are summarized in Table 4.9, which we call the “Table of Champions”. Not only the combinations of *Sclerocarya birrea* versus *Acacia nigrescens* are shown here, but all *Sclerocarya birrea*-combinations with the tree-species *Colophospermum mopane*, *Combretum apiculatum*, and *Terminalia sericea* are also taken considered.

Sclerocarya birrea is clearly dominating other tree species when the focus is limited to the indicator ALA , whereas LNC causes a superiority of *Acacia nigrescens* over

Table 4.9: Table of champions

	max	LNC	LCC	LPC	SLA	ALA	LDMC	TDMC	LTS	MAP	MAT	SR
Sb vs An	72	0:12	11:1	2:5	3:9	12:0	3:9	3:9	5:7	8:4	4:4	5:6
Sb vs Ca	9	2:7	0:9	3:3	2:2	9:0	0:9	0:9	1:7	7:2	1:4	1:7
Sb vs Cm	6	1:5	0:6	0:6	2:1	6:0	0:6	0:6	0:6	5:0	0:4	0:5
Sb vs Ts	6	3:3	0:6	2:0	4:0	6:0	0:6	0:6	2:4	3:2	1:2	1:4

Sclerocarya birrea (see Figure 4.4). These are the main reasons why the subset of (Sb, s) is separated from the subset (An, s'). This fact can formally be expressed as follows:
Let

X1 be the set {SbHI, SbNw, SbNh} and

X2 the set {AnPo, AnMo, AnSM, AnSB} then

$ALA(X1) > ALA(X2)$ but $LNC(X2) > LNC(X1)$.

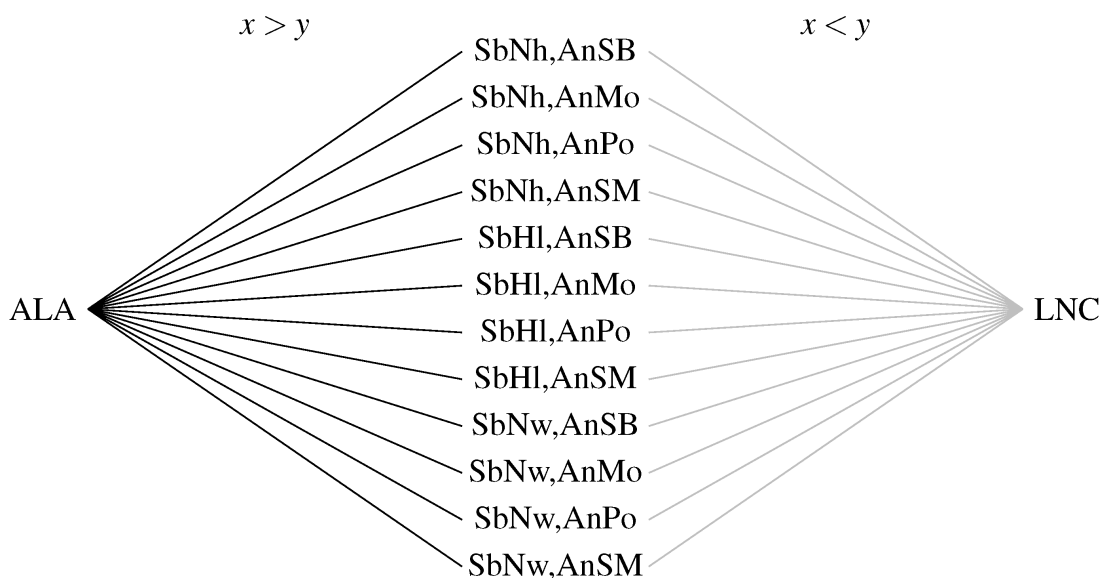


Figure 4.5: Tripartite Graph Sb vs. An. The most effecting indicators are ALA and LNC.

The simple presentation of separability in the Hasse diagram can therefore be associated with the role of indicators for the different subsets of interest. A similar analysis can be performed for any other combination of separated subsets (see Figure 4.3). In all mutual comparisons of (Sb, s) with other trees/sites, the indicator ALA plays a dominant role: *Sclerocarya birrea* wins over all other tree species if ALA is considered. For the indicator LCC, results are not as clear as for ALA. In this case, *Colophospermum mopane*, *Combretum apiculatum*, and *Terminalia sericea* win over *Sclerocarya birrea*. LCC favors *Sclerocarya birrea* only in the case of Sb-sites versus An-sites (see for the case Sb-sites vs Cm-sites Figure 4.6).

The separation between *Sclerocarya birrea* and *Acacia nigrescens* is most affected by ALA for $x > y$ and LNC for $x < y$ (Figure 4.5). For the separation between *Sclerocarya birrea* and the third group with *Colophospermum mopane*, *Combretum apiculatum*,

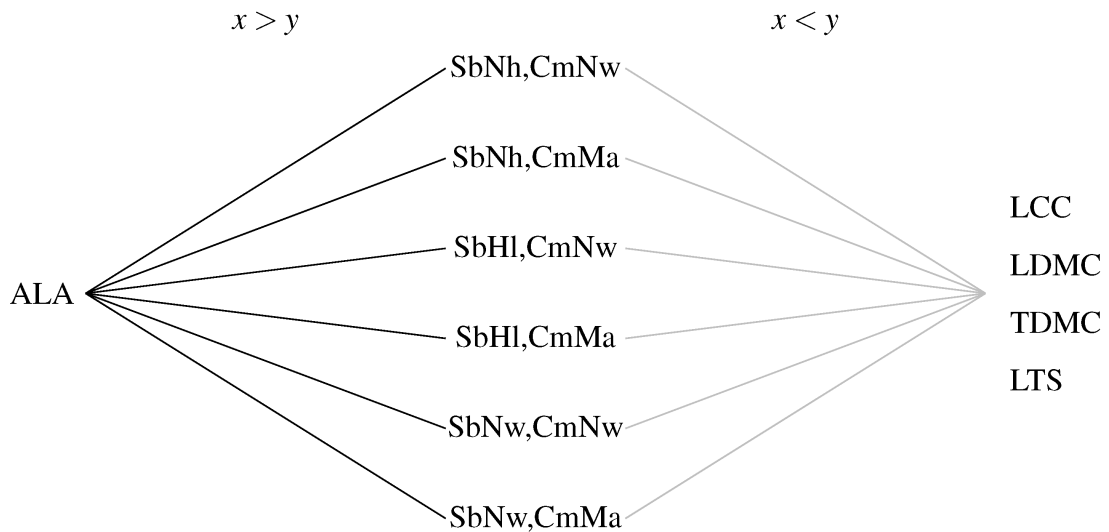


Figure 4.6: Tripartite Graph Sb vs. Cm with the most effecting indicators.

and *Terminalia sericea*, a tripartite graph for the comparison of all (Sb,s) and (Cm,s') combinations (Figure 4.6) is shown as an example. Here we see that LCC, LDMC, TDMC and LTS are the most effecting indicators for $x < y$.

4.4 Discussion

4.4.1 Strategies

The main aim of applying methods of partial order theory to functional traits of tree species was to discover ecological patterns or strategies. We compared our findings with evidence published elsewhere. The following ecological strategies were derived from the results shown above.

4.4.1.1 Strategy 1

Sclerocarya birrea (Sb) aims to have a bigger average leaf area (ALA) than the other species in the same area. Indicator ALA “switched on” means that each leaf is able to absorb a high amount of sunlight but at the same time has a high need for water (Wright et al. 2004). Looking for the description in (Grant and Thomas 2006) shows that Marula leaves are bigger (150 mm×300 mm) than the leaves of the other four species (35–120 mm×13–80 mm). Following Wigley et al. 2016, average leaf area (ALA) has definite consequences for the energy and water balance. As far as we know, however, the strategic advantage of big leaf areas is not studied in detail for savanna trees. As a result, the size of leaflet has advantages for *Sclerocarya birrea*. Well known is the early green-up of *Sclerocarya birrea* (Archibald and Scholes 2007; February and Higgins 2016), without waiting for precipitation after the dry season.

4.4.1.2 Strategy 2

The separateness of the subsets (S_b, s) ($s \in \{Nh, Hl, Nw\}$) and (A_n, s') with $s' \in \{SB, Mo, Po, SM\}$ shows that compared with *Sclerocarya birrea*, the species *Acacia nigrescens* has more nitrogen but lower carbon in its leaves than *Sb*. It is well known that *Acacia nigrescens* is able to use nitrogen through the bacteria species in its root system (Barbosa et al. 2014; Cramer et al. 2010).

4.4.1.3 Strategy 3

Colophospermum mopane, *Combretum apiculatum*, and *Terminalia sericea* are investigated in leaf and twig strengths by strong carbon content (LCC, LDMC, TDMC, LTS). A high value for LDMC is correlated with lower palatability through dense and tough leaves (Pérez-Harguindeguy et al. 2003). Both represent global strategies for plant survival and aim to protect against certain herbivores and abiotic stress exerted by fire, wind, and other forces (Díaz et al. 2001; Fortunel et al. 2009).

4.4.1.4 Strategy 4

Wigley et al. 2016 characterized the sites Nhangwini, Satara Granite and Mapungubwe Sands as relatively poor with respect to soil properties, whereas the other sites are considered as rich. This corresponds very well with the findings of the Hasse diagram where combinations of these sites with their tree species are minimal elements with the exception of CaSG, CaMa, CmMa. These tree/site combinations are all characterized by LCC “switched on”. The indicator LCC, however, does not depend on soil characteristics but on photosynthesis processes. It is interesting that the posetic approach is able to show this, even without explicitly considering soil properties in our study.

In summary, our findings show a strong correlation to ecological evidence. In particular, they separate survival strategies of *Sclerocarya birrea* from *Acacia nigrescens* in savannas: a contribution to the survival of *Sclerocarya birrea* is its amount of leaflets (= large ALA), whereas *Acacia nigrescens* has its advantages in its root system allowing to sufficiently fix nitrogen (LNC) (Archibald and Scholes 2007).

4.4.2 Limits

First, the impact of the data classification scheme used (in Section 4.2.2.3) needs still more exploration. We utilized a basic binary classification, through which the original information provided by measured values is lost; the basic numerical information of any single indicator separated is maintained, however. In future work, we are planning to apply fuzzy partial order (Kerber and Brüggemann 2015) to ensure data continuous in concept.

Second, we only included a small amount of data in this study. The reason for this was that we did not want to mix data from different origins where other measurement methods are potentially applied. Third, important points for the analysis by partial order theory are a) the range of data, b) the question of orientation, and c) the way

we preprocessed the data.

- a) Obviously, the differentiation of “good” and “bad” values of functional traits is only meaningful if data are in a certain biologically sensible range. A higher value of precipitation may be better than a lower one. However, if this value is extremely high, then the association with “good” is questionable.
- b) The question for orientation cannot be answered in a general manner; there may be properties which cannot be oriented uniquely. Here, we have to rely on expert opinion. Preprocessing requires two steps:
 - i) Minimal and maximal data values for each indicator are to be determined in order to perform a classification of $[0,1]$ -normalized data. This has the statistical consequence that the classification depends severely on outliers, i.e. the procedure is statistically not robust. We are aware of this problem but do not have a solution at hand.
 - ii) Classification into two values can also be carried out in a different manner. Here we selected the M-value, however, the mean or median would also be good starting points. A classification into more than two classes is possible, too. But the increase of complexity would hamper the interpretation of the results. Therefore, we started with a simple procedure.

Regarding data quality, we have to note that MAT only comprises three values in our data set. Nevertheless, we apply the classification into two classes. A MAT-value of 21 equals the mid-range value and hence was mapped to a score of 1. We checked this problematic point by performing the posetic analysis using the original data for the indicator MAT and found that in our case the results are not sensitive to that issue.

4.5 Conclusion

To our knowledge, this is the first time partial order theory has been applied to detect ecological strategies of tree species. Multi-indicator systems can be analyzed by tools of multivariate statistics such as cluster analysis, principal component analysis or artificial neural networks. Most of the techniques were applied by Wigley et al. 2016 and there is no question about the suitability of these methods. A possible alternative would be the application of deterministic, i.e. process driven mathematical models, which could provide a smaller set of model-based indicators. To our knowledge, such a mathematical model is unfortunately not at hand. For this study, we applied a relatively new method of discrete mathematics, namely partial order theory, on the original set of eleven ecological indicators.

Our technical question was: Is it possible to extract ecological information just by considering the $<$ -relations only? Our results validated this hypothesis. Besides the technicalities within the Hasse diagram (chains, antichains, levels etc.) we found that the incomparabilities in a partial order set are very important to consider in more

detail. Incomparable elements in a Hasse diagram are a bit similar to outliers in sampled data; they allow us to apply our research focus to issues worthy of further analysis. In the context of climate change and stability of savannas, we were able to deduce four different ecological strategies of tree species. Each was confirmed by literature. Future research will focus on the key properties of savanna tree species distribution. Our findings from this study suggest that strategies in leaf-forming, root systems, and carbon contents are crucial points for survival strategies of trees beyond soil and climate aspects. We will also focus on invasive species and their strategies to compete in the savanna ecosystem. We think that partial order concepts could here be supportive, too.

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Chapter 5

Firewood Collection in South Africa: Adaptive Behavior in Social-Ecological Models

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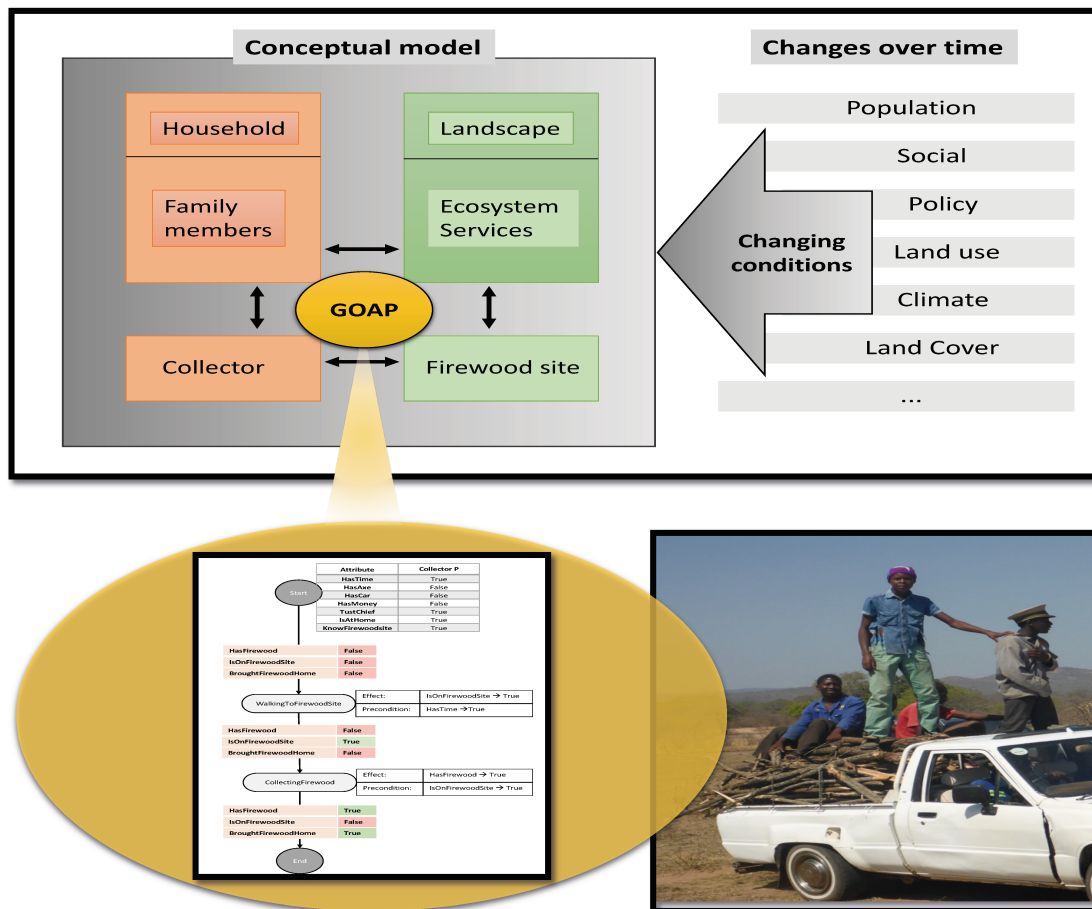
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Keywords:

firewood collection; savanna; Bushbuckridge; Kruger-to-Canyon Biosphere; goal-oriented action planning/GOAP; adaptive behavior; MARS; social-ecological systems

Graphical Abstract



ABSTRACT

Due to the fact that the South Africa's savanna landscapes are under changing conditions, the previously sustainable firewood collection system in rural areas has become a social-ecological factor in questions about landscape management. While the resilience of savannas in national parks such as Kruger National Park (KNP) in South Africa has been widely acknowledged in ecosystem management, the resilience of woody vegetation outside protected areas has been underappreciated. Collecting wood is the dominant source of energy for rural households, and there is an urgent need for land management to find sustainable solutions for this complex social-ecological system. However, the firewood collection scenario is only one example, and stands for all "human-ecosystem service" interactions under the topic of over-utilization, e.g., fishery, grazing, harvesting. Agent-based modeling combined with goal-oriented action planning (GOAP) can provide fresh insights into the relationship between individual needs of humans and changes in land-use. At the same time, this modeling approach includes adaptive behavior under changing conditions. A firewood collection scenario was selected for a proof-of-concept comprising households, collectors, ecosystem services and firewood sites. Our results have shown that, even when it is predictable what

a single human agent will do, massive up-scaling is needed in order to understand the whole complexity of social-ecological systems. Under changing conditions, such as climate and an increasing population, fair distribution of natural goods become an important issue.

5.1 Introduction

Savanna landscapes, as environments with the coexistence of grass, trees, and shrubs, are natural systems with strong resilience to natural disturbances such as fire, elephants, and other herbivores (Staver et al. 2011; Kruger et al. 2017; Beale et al. 2013). These bi-stable systems are important in regard to socio-economic and ecological questions (Scholes and Walker 1993; Scholes and Archer 1997).

South African savannas, with their unique and diverse flora, are characteristic in rural areas and millions of people benefit both directly and indirectly from these natural resources (Woollen et al. 2016; Findlay and Twine 2018).

One of the most frequented ecosystem services is the provisioning of wood, e.g., for fuelwood, construction materials, medical issues, and livestock forage (Woollen et al. 2016). Fuelwood, such as firewood or charcoal, is the most rural energy source in sub-Saharan Africa (Wessels et al. 2013). For savanna trees and shrubs, firewood collection is sustainable when the collected material is already dead or the collection rates are below the regeneration rates (Woollen et al. 2016).

To manage sustainable use, traditional authorities regulate firewood collection (Findlay and Twine 2018). However, increasing settlement (Coetzer et al. 2010), population growth, and a decline of natural resources (Ofoegbu et al. 2018) apply pressure to the social-ecological system. Additionally, changes of land-use in community areas, such as a mixture of various human activities (Aspinall and Staiano 2017; Giannecchini et al. 2007) and climate change, contribute to a more unsustainable use of this energy source. Extensive clearing of trees for cooking fuel (Kirkland et al. 2007), agricultural expansion, and charcoal production are destroying or at least fragmenting these landscapes (Woollen et al. 2016; Fisher et al. 2012). This increasing need and unsustainable use of firewood collection requires an adaptation in the firewood collection behavior. Covering those management questions in large scale simulation studies, human behavior and decision-making is a known challenge (Badmos et al. 2015).

Agent-based modeling (ABM) has a well-proven record on social-ecological systems (Badmos et al. 2015; Bakker et al. 2014; Cioffi-Revilla et al. 2011; Ralha et al. 2013; Le et al. 2008). Unfortunately, in most cases, these models are strictly fixed rule-based (Grimm et al. 2010) and therefore, are not able to represent a realistic picture of the adaptive behavior under changing conditions. Goal-oriented action planning (GOAP) is an artificial intelligence-based approach to overcome this obstacle (Orkin 2003; Bjarnolf et al. 2008; Thiel-Clemen and Klingenberg 2010). It is widely used in game development, but we are not aware of an application to social-ecological modeling.

The authors of this study designed the firewood collection process as a goal-oriented action planning (GOAP) behavior (Deadman and Gimblett 1994) and developed a

model for firewood collection in South African savanna landscape communities for this study.

5.2 Material and methods

5.2.1 Study Site

The Bushbuckridge district is in north-eastern South Africa next to the Kruger National Park (Figure 5.1).

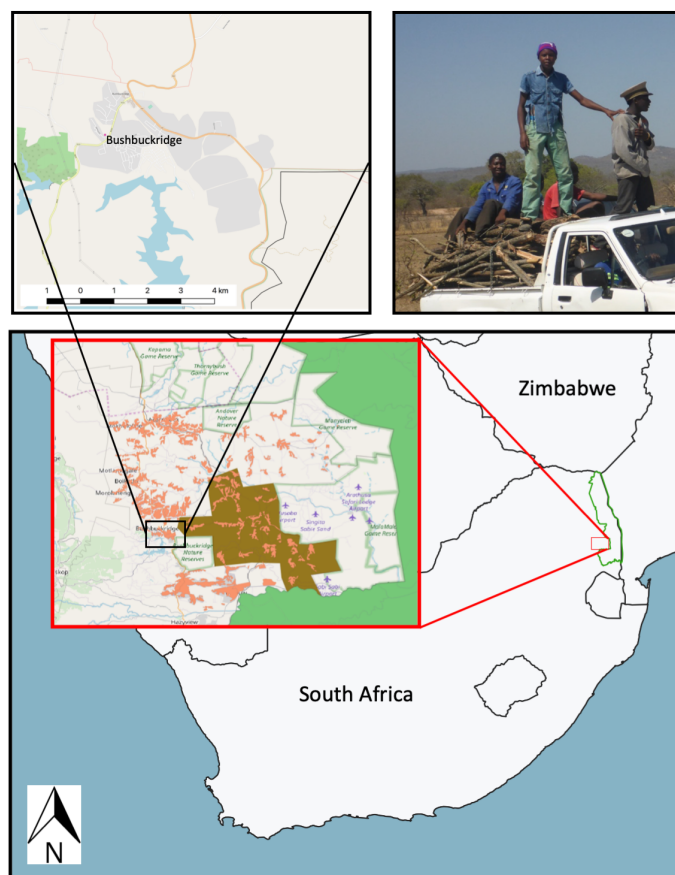


Figure 5.1: Location of the study site near the Kruger National Park (KNP) in the Bushbuckridge district. The picture shows transportation of firewood by car.

Many studies about firewood collection and savanna ecosystems were conducted in the Bushbuckridge area (Wessels et al. 2013; Coetzer et al. 2010; Madubansi and Shackleton 2007; Emanuel et al. 2005; Rutherford et al. 2006; Leakey et al. 2005; Mograbi et al. 2016; Coetzer et al. 2013; Coetzer-Hanack et al. 2016; Williams and Shackleton 2002; Matsika et al. 2013b,a), which is also a part of the Kruger to Canyon (K2C) Biosphere Region (Coetzer et al. 2010; Coetzer-Hanack et al. 2016; Williams and Shackleton 2002). The availability of excellent prior knowledge and existing long-term

data make Bushbuckridge a prime geographical region for social-ecological simulation models.

In this marginalized region, the population density is around 150–350 people per km²; unemployment is common, and the monetary income per household is low (Rutherford et al. 2006). Village residents use the communal land for cultivation, grazing, and wood harvesting (Shackleton et al. 1994). Using these ecosystem services is essential to rural communities (Rutherford et al. 2006). The vegetation is Mixed Lowveld Bushveld with some dominant trees species like *Acacia spp.*, *Combretum apiculatum*, *Terminalia sericea*, and *Sclerocarya birrea* (Emanuel et al. 2005; Rutherford et al. 2006; Powrie et al. 2012; Helm et al. 2009).

5.2.2 Data

In South Africa, firewood collection is mostly carried out by females and can take up to two hours daily to collect enough wood, especially in rural areas (Charmes 2006). The social regulation for firewood collection is traditionally done by local authorities (Findlay and Twine 2018). Collecting wood is free of charge (Boucher et al. 2011) and is used for cooking, heating water, and keeping warm (Madubansi and Shackleton 2007). Even with increasing electrification, firewood collection is done for cost saving and may increase levels of unsustainable wood harvesting (Wessels et al. 2013; Matsika et al. 2013b). Some households are able to buy firewood from local vendors (Madubansi and Shackleton 2007).

Based on the information from previous studies, we summarized some key factors in Table 5.1. These values will later be used to parameterize our model.

Table 5.1: Approximate data from selected sources for the model

Contents	Model Input Parameter	Source
Firewood consumption	8 kg/day	Matsika et al. 2013b
Meals	1–2 cooked a day	Matsika et al. 2013b
Trips to collect firewood per household	4 within a week	Matsika et al. 2013b
Time per trip	2 h	Matsika et al. 2013b
Female trips on foot	1 h–2 h 20 min	Charmes 2006
Social regulation	Authorities	Findlay and Twine 2018
Collecting preferences	Dead wood	Boucher et al. 2011
Energy preference	Firewood (for cost saving)	Mosa et al. 2016
Households with motor-car	19.3 %	Statistics South Africa 2016
Households with stove (electric/gas)	78 %	Statistics South Africa 2016

5.2.3 Multi-Agent Modeling and Simulation and MARS

Agent-based modeling incorporates artificial intelligence (AI) into modeling and simulation. Individual entities (“agents”) interact with each other and their surroundings (Gilbert and Troitzsch 2005), e.g., an agent who is cutting down a tree interacts directly with this specific tree agent located at a geographical position. Their behavior is

described on an individual level following a set of rules. It should be noted that agents can be individuals but also social groups, communities, or other entities that act and react to outer conditions (Helbing 2012). These actions and reactions on an individual level may lead to a higher state of complexity, i.e., self-organization and emergence (An 2012), which makes this approach especially suitable for research on social science (Axelrod 1997).

The multi-agent framework MARS (Multi-Agent Research and Simulation) is under development at the University of Applied Sciences Hamburg (Hüning et al. 2016) and incorporates the newest concepts of both agent-based modeling and simulation. The frameworks target both simple and complex models by using specifically designed approaches tailored to the respective disciplines such as socio-ecological systems (Glake et al. 2017; Weyl et al. 2018).

5.2.4 Goal-Oriented Action Planning (GOAP)

Human behavior could be described as a sequence of decisions. Goal-oriented action planning (GOAP) derives from the field of AI and integrates adaptive decision-making into multi-agent models. Based on STRIPS (Stanford Research Institute Problem Solver), this planning algorithm aims to reach goals by executing a set of actions (Fikes and Nilsson 1971). Each agent keeps an inner state which is represented by a set of properties (attributes). These properties are often described as Boolean predicates that evaluate to either true or false, respectively. These properties change over time and are influenced by the inner or outer sensations of the agent.

A “goal” can be described as a desired state to be reached. A hungry agent, i.e., the “*IsHungry*” predicate results in true (“*IsHungry = true*”), might follow his individual goal to change his internal state to “*IsHungry = false*”.

Moving from one state to another is usually done by executing (“firing”) a sequence of “actions”. Before the “actions” are fired, a plan must be implemented to find the best sequence of actions to reach the goal (Pittman 2007). Each action contains a list of preconditions that need to be fulfilled before being executed, as well as a set of postconditions that are valid after successful execution. Additionally, an action might hold a “cost” value, indicating the necessary effort for a successful execution.

The planning algorithm calculates a way of minimal costs to reach the goal. We will show that this decision-making architecture allows the agents to adapt their behavior in correspondence to a changing environment (Le et al. 2008).

In general, GOAP would not need a software realization to work. The planning process could also be done on a sheet of paper and with a pen. If hundreds or thousands of humans are considered this task will become very time-consuming.

For this study, the MARS framework was technically extended by GOAP planning algorithms. That allows any MARS software agent to decide individually on base of an adaptive schedule.

5.2.4.1 State Model

The “state model” represents the individuality and personality of an agent. For example, an agent “Firewood Collector” may have a personal schedule, an individual set of experiences, personal traits, e.g., civil obedience, access to skills and equipment, living standards, or others.

By utilizing GOAP, each agent can plan his/her own sequence of actions as needed in order to reach a personal goal. Basically, these goals are represented by a set of values within the state model that should be achieved in the near future. The actual sequence of actions to reach that specific goal depends on the goal itself, the current state of the whole system (=world), and the individual state of the agent. Obviously, this means that even in the case of two agents sharing the same goal, their preferred sequence of actions to fulfill that goal might be without any overlap.

5.2.4.2 Planning

Planning is the process of thinking about the activities required to achieve a desired goal, often by considering constraints such as minimizing costs. If a cost value, e.g., the energy needed to execute an action, is assigned to each action, a sequence of actions will lead to total cost statement. By utilizing constraints, such as reducing total costs to a minimum value, the outcome of the planning process can be significantly changed. This can also be done on an individual level, i.e., different human agents may have individual planning constraints related to their personality or availability of resources.

The result of the planning process is a sequence of actions that transform the current state model of an agent into the desired state formulated by the goal description. So far, GOAP planning is not too dissimilar from other planning algorithms. The major advantage might become visible when considering a change of the environment, the social network of the agent, or within the agent himself during performing this transformation. As an example, the reader might think of driving to a location, e.g., a workplace or a supermarket, when an unexpected phone call suddenly interrupts the originally planned process. A change in the form described above would lead to a re-planning process in GOAP.

5.2.4.3 Actions

An action is something that the agent is able to do, bracketed by pre- and postconditions. A precondition is a condition or predicate applied to a set of state variables that must always be true just prior to the execution of an action. Analogously, a postcondition is a condition or predicate that must be true after the execution. By that, each action changes a part of a state model, either of the world or an individual agent.

Generally, to reach a goal, a sequence of actions is necessary. Every action is encapsulated and has no immediate impact on other actions. In some cases, actions must fulfill certain criteria to determine whether they can be run. For instance, if “CuttingFirewood” has the precondition “NeedAxe”, that will require a search of the immediate vicinity to see if there is an axe the agent can use. Thus, an action can trigger other actions (sub-processes) before again returning to the primary sequence.

5.3 Results

In this study, we aimed to describe the behavior of firewood collection under various changing conditions in Bushbuckridge, South Africa by using an agent-based simulation model incorporating GOAP planning. We combined existing data and knowledge of firewood collection behavior (see Table 5.1) and transformed this into a goal-oriented model.

The model itself is simplified in order to show that this way of modeling is suitable to express adaptive behavior under changing conditions.

5.3.1 Conceptual Model

The conceptual model is the first step in creating an agent-based model (Thiel-Clemen 2013). It describes, in a simple but not overly simplistic way (Lenfers et al. 2016), the complexity of a subset of the real world in a model. During the conceptual modeling process, modelers have to decide which subset of all concepts have to be included—and which do not. Obviously, this selection must be aligned with a specific research or management question.

In this paper, the conceptual model (see Figure 5.2) combines four different key elements for firewood collection. The selected components are *Household*, *Collector*, the *Landscape*, and *Firewood site*. A household aggregates one or more *Family members*. If the household needs firewood, one of the family members becomes a collector. The collector has to bring firewood to the household. The *Landscape* component provides several *Ecosystem Services*. One of them, firewood provisioning, is represented by a *Firewood site*. Collectors are able to interact with this service.

Figure 5.2 also shows constraints that might change over time. The steady growth of the human population certainly changes firewood collection behavior. Changes may also arise from social or political processes, land-use, climate changes, or other processes.

Therefore, the interaction between the conceptual components shown in Figure 5.2 needs an adaptive part. This is implemented by incorporating GOAP planning.

5.3.2 Domain Model

Following an initial conceptual model (Figure 5.2), the next step is to build the domain model. For agent-based models, this means defining the agents and the environment. An agent is typically represented by attributes and methods. Here, we limit ourselves to highlighting the interaction between the firewood collector as an agent and the firewood site as part of our environment.

The agent type collector has a list of attributes such as age, gender, health condition, wood carrying capacity, and personal time schedule, among others. The combination of attributes always depends on the exact research question. As a result, for this showcase, all of our agents are without personal settings and are all able to walk, drive a car, take an axe, and collect and cut firewood. At the same time, they have the same knowledge about the firewood sites and are able to go back to their home.

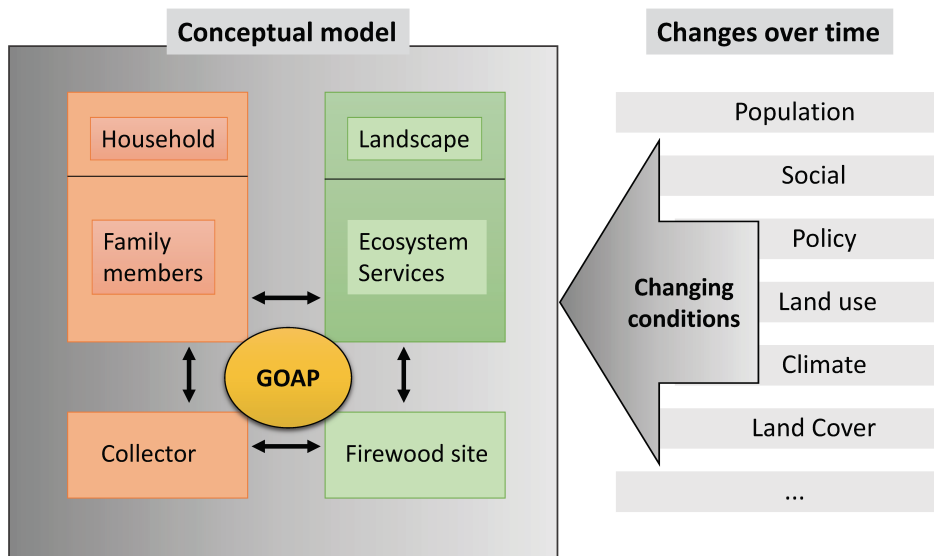


Figure 5.2: Conceptual model (left side) with changing conditions (right side)

For the goal-oriented action planning, in this approach, the collector agents plan their sequences of actions to bring firewood to their home. Each particular sequence of actions not only depends on the goal, but also on the different state variables of the agents and the world.

The environment here is the landscape defined by its geographical coordinates, spatial extent, and its biological diversity; it also provides several ecosystem services, e.g., firewood. In MARS scenarios, this environment is modeled by GIS files where firewood collection sites are marked points-of-interest (POI).

5.3.3 Scenarios

Simulation scenarios are a well-established approach to become aware of future challenges or changes in complex adaptive systems. For this study, the domain model described above was implemented in the MARS framework. In order to define relevant scenarios, we included possible changes over time, which actuate the system (Table 5.2).

Table 5.2: Changing conditions with examples and the effect on firewood collection, based on literature research

Changing Condition	Possible Trends	Effects on Firewood Collection	Source
Population	Increase	Higher demand for firewood	Wessels et al. 2013; Rutherford et al. 2006; Mosa et al. 2016; Mohammed et al. 2015
Social	Disobedience	Illegal firewood collection	Findlay and Twine 2018
Policy	Restriction of cutting	Fewer sites to cut firewood	Woollen et al. 2016
Land-use	Alternative sites	More effort to collect	Crews and Young 2013
Climate	Reduced resprouting capacity	Over-harvesting	Barbosa et al. 2014
Land cover	Species shift	Firewood quality	Crews and Young 2013

For firewood collection, there are several changing conditions coupled with a number of consequences of interest. Changes could be in e.g., population, the social system, policy, land-use, climate, and land cover.

With regard to the system considered in this study, this list of potential changes is certainly not comprehensive. However, the broad range of aspects and their importance should be visible.

5.3.4 GOAP

As stated above, a GOAP-based planning algorithm should make firewood collectors (agents) capable of reacting to changes in their individual, social and environmental contexts. In the first step, we enhance the state model of firewood collector agents by predicates to allow the evaluation of pre- and postconditions.

5.3.4.1 Firewood Collector

By analyzing the firewood collection process, we identified several aspects that have a vital impact on the individual behavior of collectors. The resulting list is shown in Table 5.3. Obviously, the availability of time, money, and the set of tools, e.g., axes, are important factors, but respect and obedience in social hierarchical groups are also of importance.

Table 5.3: Table of setting for the collector state model

Aspects	Predicates on States	Possible Values
Time schedule	HasTime	True/False
Equipment	HasAxe	True/False
	HasCar	True/False
Living standard	HasMoney	True/False
Civil obedience	TrustChief	True/False
Personal collecting conditions	HasFirewood	True/False
	IsOnFirewoodsite	True/False
	BroughtFirewoodHome	True/False
	IsAtHome	True/False

“Personal collection conditions” reflect the current situation of an agent in a set of logical values. Applying the GOAP planning algorithm to a firewood collector who has no money, no car, and no axe available achieves the action plan from Figure 5.3. Each action (green ellipse) is triggered by the set of preconditions and affects several state variables, as described in the “Effect” element. Figure 5.3 shows the “Happy Path”, a basic action plan that does not consider problems or changes: simply walking to a firewood collection site, harvesting wood, and walking back home.

However, in a non-uniform world, resources and skills are not equally distributed. That leads to different methods to acquire firewood for the household. Figure 5.4 shows five different action plans for firewood acquisition under variable circumstances.

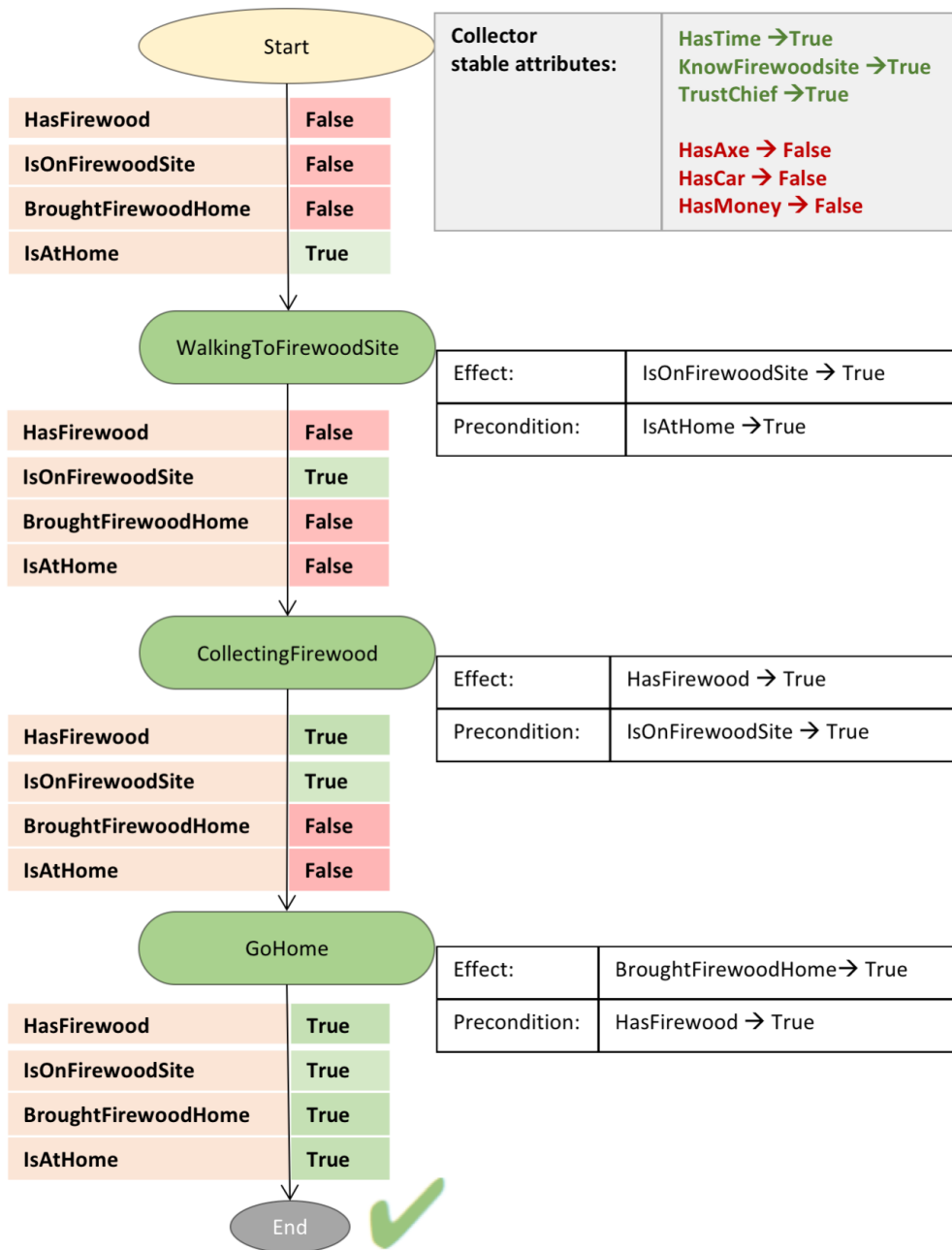


Figure 5.3: The “Happy Path”, i.e., the most basic action plan

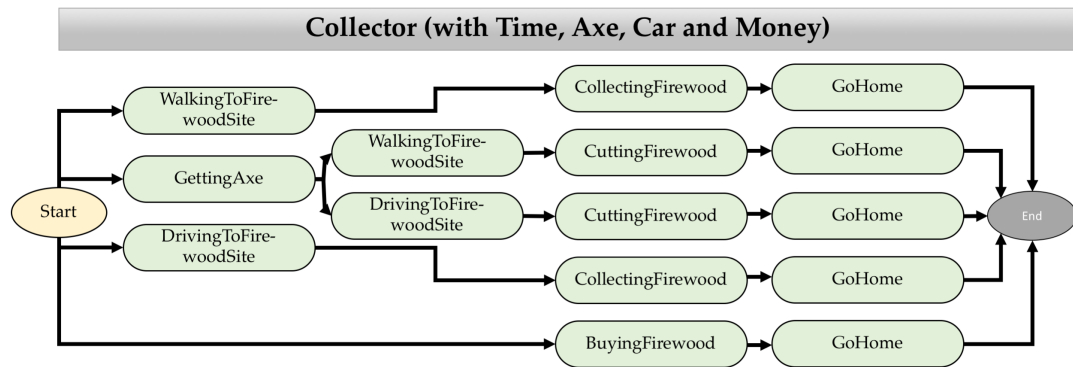


Figure 5.4: A composition of all possible action plans to acquire firewood for a collector with time, axe, car, and money

If the setting of the agent is different, e.g., the collector has no car and no money, there are fewer successful ways to fulfill the goal “*HasFirewood = true*” (see Figure 5.5).

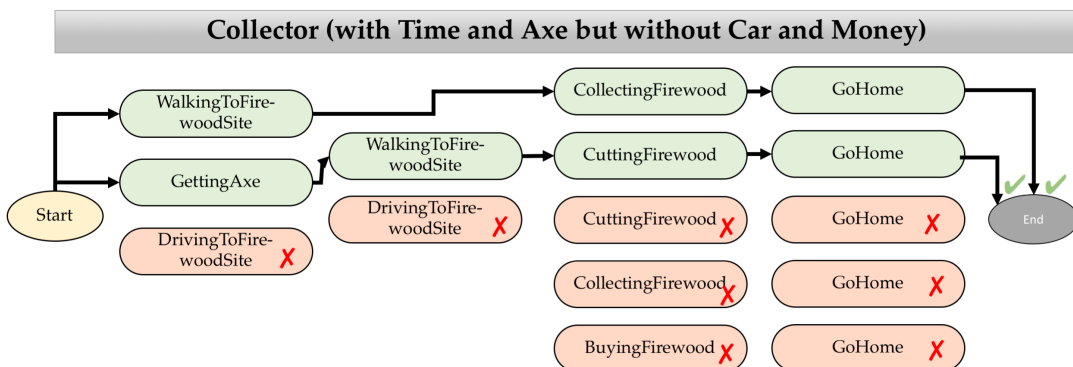


Figure 5.5: The composition of all actions: possible for this collector in green, impossible in red

GOAP is a complex algorithm to calculate the various ways to fulfill a goal by taking different steps, i.e., actions. It also offers optimization criteria, for example, to find the least time consuming one. If there are more than one “optimal” action plans resulting from the GOAP planning, a random or rule-based selection can be done.

5.3.4.2 Firewood Sites

In most regions of South Africa, firewood collection takes place on official firewood sites (Madubansi and Shackleton 2007). Because the actual location of true sites is not important for this study, we placed four fictive sites (a, b, c, and d) with different attributes (see Table 5.4) into the landscape around Bushbuckridge (see Figure 5.6 for map).

Table 5.4: Characteristics of firewood collection sites

Site	Walking Distance (m)	Time by Walkings	Reachable by Car	Driving Distance (m)	Official Firewood Site	Limitation
a	400	<3 h	No	-	Yes	No
b	800	<3 h	Yes	800	Yes	No
c	1500	<3 h	Yes	1500	Yes	No
d	2000	>3 h	Yes	2000	Yes	No

For the initial step of this study, we presumed that the sites are without any limitation on firewood. The three collecting sites (b), (c), and (d) are not only reachable by walking, but also by driving. Distance and time are important factors for calculating costs in this case.

5.3.5 Experiments

The preliminaries above were used to define more complex and integrated scenarios. The first experiment varied capabilities and resources of firewood collectors; the second, environmental factors; and the third, a combination of both.

5.3.5.1 Agents - By Changing Attributes of Collectors

Obviously, the most preferred site is site (a), which is both easy to reach and has plentiful collectable firewood.

We designed three different types of collector agents to represent three categories of human firewood collectors:

- I Presents a collector with unlimited time but without any equipment. This type could represent a child, for example.
- II Marks a stereotype for a collector which has only a maximum three-hour time limit, access to a car, and no civil obedience. Which could e.g., stand for a young man within a group who collects firewood by car.
- III In this type, the collector has a higher living standard but only three hours of time.

The result of the planning process is shown in the last row of Table 5.5. Only type III displays deviant behavior. Which action plan is executed depends on optimization constraints, e.g., costs or time consumption.

By considering only this setup, a high risk of overharvesting site (a) becomes obvious.

5.3.5.2 Environment - By Changing Attributes of Firewood Sites

After creating different collector types, we designed three different settings (A, B, C) for our four firewood sites (a, b, c, d), each representing a different state of overharvesting (see Table 5.6).

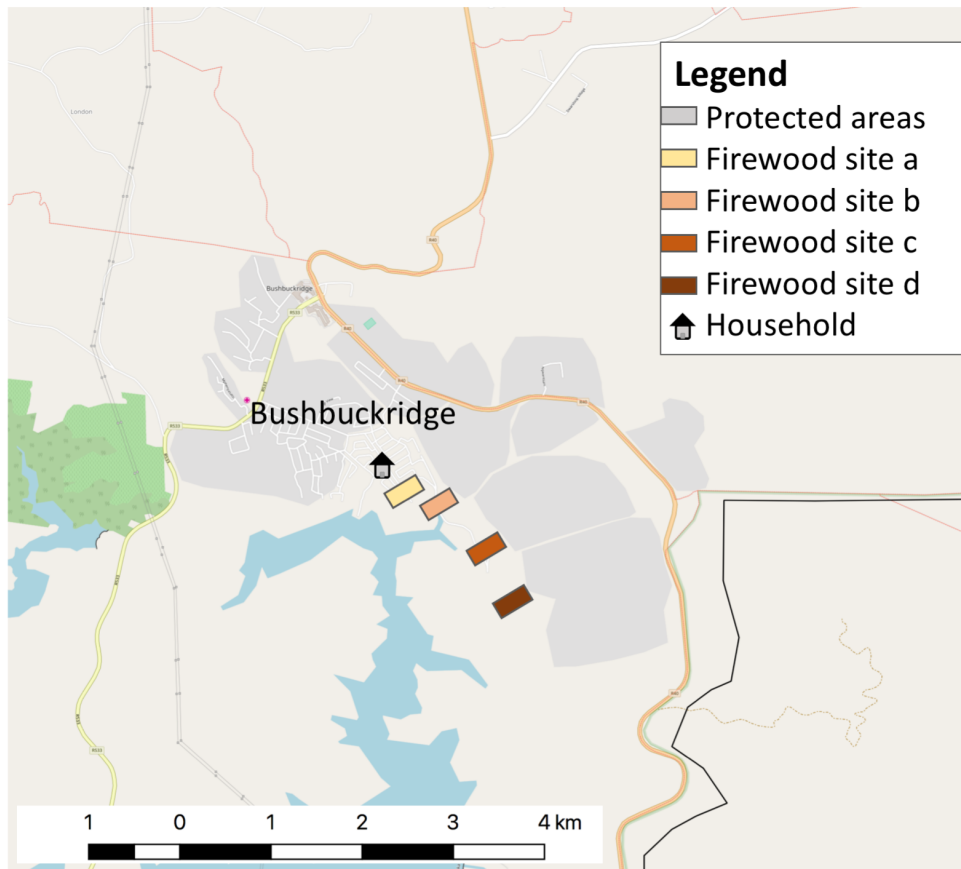


Figure 5.6: Map of the landscape with points-of-interest (POI) = firewood sites

Table 5.5: Attribute setting of the collector for three different scenarios and its model outcome

Collector Attribute	I	II	III
HasTime (> 3h)	True	False	False
HasAxe	False	True	True
HasCar	False	True	True
HasMoney	False	False	True
TrustChief	True	False	True
Outcome from GOAP ¹	<i>Collect on site a</i>	<i>Collect on site a</i>	<i>Collect on site a <u>or</u> Drive to site b and collect <u>or</u> Buy firewood</i>

¹ Depends on "costs" for a car, time, and money.

A Is a direct result after unlimited firewood collection. All dead wood on site (a) is gone, but there is living wood to cut on site (a). All other sites are still provided with dead and living firewood.

B There is no more firewood on site (a), (b), and (c), which are reachable within three hours. However, there is still both dead and living firewood on site (d).

C Here, we designed the opposite of unlimited firewood; there is no legal firewood on any of our four sites.

Table 5.6: Attribute setting of the firewood sites for three different scenarios

Firewood Site	Attribute	A	B	C
a	HasDeadWood	False	False	False
	HasLivingWood	True	False	False
b	HasDeadWood	True	False	False
	HasLivingWood	True	False	False
c	HasDeadWood	True	False	False
	HasLivingWood	True	False	False
d	HasDeadWood	True	True	False
	HasLivingWood	True	True	False

After designing three different collector types and three different firewood site scenarios (see Tables 5.4 and 5.6), we combined them to have a total of nine different scenario outputs (see Table 5.7).

Table 5.7: Combined scenarios and model output

Combination of Changing	A (No More Dead Firewood on Site a)	B (No More Dead or Living Firewood on Sites a, b, c)	C (No More Legal Firewood Available)
I (time, no equipment)	Walk and collect at site b	Walk and collect at site d	No plan possible
II (poor, less time, don't trust chief)	Walk and cut firewood at site a <u>or</u> Walk and collect at site b	Drive to site d and collect	No plan possible
III (has everything, but only less time)	Buy firewood <u>or</u> Drive to site b and collect	Buy firewood	Buy firewood

Even this basic scenario setting produced a variety of different strategies:

A/I: When there is no more dead firewood on site (a), the collector without an axe (I) has to walk a longer distance to collect firewood on site (b). A/II: If the collector has an axe but no car (II), he still can cut firewood on site a or walk to site (b) to collect there, like collector type I. A/III: A well-situated collector (III) can buy firewood, or if he has time drive to site (b), he may collect there.

For scenario B, time is a critical attribute. The only site with firewood to collect or to cut needs more than three hours to complete the goal.

B/I: The collector I has time and is therefore able to walk the longer distance to reach site (d) and collect there.

B/II: This collector type has only three hours to bring firewood to the household, but has access to a car and can drive to site (d) to collect there.

B/III: Because of time limitations, collector III has to buy firewood.

C/I and C/II: If there is no more firewood available (C), there is no plan possible for collector I and II.

C/III: Collector III can reach the goal by buying firewood.

By modeling with GOAP, it is plausible in this instance that there is no plan to fulfill the actual goal. However, this is not a dead end for the model; on the contrary, it serves as a way to find new solutions and to model adaptable behavior.

In this experiment, two cases did not result in a suitable sequence of actions to meet the demand. This may lead to “cascading” the problem back to the delegating entity:

C/I For collector I, there is no chance to fulfill the goal. Therefore, after the planning, no actions are executed. The design of the model must be able to account for this. Perhaps there are alternatives in the household level.

C/II Like collector I, collector II has no chance to bring back firewood to the household. Because of his lack of civil obedience, he may be able to change his behavior, e.g., by collecting firewood outside official sites. Even if it is not currently implemented in this model, the outcome shows the modeler that something is happening, and that the model needs an improvement for this scenario.

There are also visible results at the landscape scale. The modeling is about different behaviors and adaptive decision-making by people, but the results can change the landscape view; in this case, the different firewood places. Questions to be answered could be:

- Which of them are the most frequented and what will happen if these sites run out of firewood?
- What will happen if the demand for firewood increases?

For the first attempt, there is enough firewood on each collection side, so only the expenditure of reaching the area and collecting brings the decision which collecting place is best. This will be completely different when places nearby have no more firewood available. Here we are able to define a tipping point for overharvesting. If the firewood collectors need more time, money, or a vehicle, it causes changes in behavior between households with different social-economical standards.

This modeling approach also opens up options for new perspectives; for example, what happens if the collector type I gets access to electricity and an electric stove. Certainly, this will change the individual firewood collection behavior, but the question remains about how this will impact the entire system.

5.4 Discussion

Overharvesting and unsustainable fuelwood extraction are contributors for land-use and land-cover changes (LUCC) causing a significant impact on the overall savanna ecosystem (Wessels et al. 2013; Coetzer et al. 2010; Mograbi et al. 2016; Crews and Young 2013; Higgins et al. 2010). The aim of this paper was to show the capabilities of modeling adaptive human behavior under changing conditions with GOAP.

Starting with a very simple initial approach and unlimited resources, we showed that the firewood collector always collects firewood in a way that requires the least effort. In our experiments, this means collecting dead wood from the nearest firewood site or, if possible, buying firewood. By increasing the options and limitations, different collector stereotypes developed varying strategies for acquiring firewood. Other modeling approaches do not support this adaptation of social-ecological behaviors (Schlüter et al. 2017; Polhill et al. 2016; Moncrieff et al. 2015).

In some cases, it became quite obvious that no suitable planning was possible. This might indicate a gap in the model description, but could also point to a possible conflict in the real world.

Moreover, our modeling approach focuses predominantly on the landscape level. Overharvesting of firewood sites, tipping points for illegal harvesting, landscape fragmentation, and the need for alternatives are important topics in modeling savanna ecology (Coetzer et al. 2010; Mograbi et al. 2016). The complexity of ecosystems requires not only rule-based models (Le et al. 2008; Polhill et al. 2016; Moncrieff et al. 2015), but also adaptive agent-based models.

We found that individual firewood collecting behavior could be modeled in an acceptable manner with GOAP. The resulting behavioral patterns fit our own observations and published results. We showed using a basic example of overharvesting, that the behavior of agents has direct consequences at the landscape level. Even the synthesized model shows this cross-scale impact well.

We observed that defining costs and thresholds using a single rating system that combines monetary values, elapsed time, and performed activities is a challenge. This subjective task should be carried out by experts, a conclusion supported by the literature (Woollen et al. 2016; Matsika et al. 2013b,a; Boucher et al. 2011; Démurger and Fournier 2011; Joshi and Bohara 2017). In the near future, we intend enhancing and up-scaling the model by incorporating specific local conditions from Bushbuckridge, e.g., number of households and availability of firewood collection sites, together with limitations regarding more specific firewood quantities and different qualities for each firewood site (Matsika et al. 2013b, Chapter 4). Some of the extensions for achieving a more realistic model are:

- Collector: consider the effect of gender and age on different collection behaviors and distances covered; also incorporate fear of walking through potentially dangerous areas;
- Household: differentiate households based on different amounts of firewood needed, availability of electricity, income levels, and the number of household members;
- Landscape: include illegal firewood sites and locations of alternative energy sources, like dung;
- Firewood site: distinguish between different qualities of firewood.

However, it is expected that the greatest increase in knowledge will result from the massive up-scaling, i.e., by increasing the number of households and collectors

competing for firewood in a region. What will happen if all accessible collection sites are overharvested or if, due to climate change, there is a shift in tree and bush species? Exploring these scenarios will include thousands, perhaps millions, of individuals with high variability in intentions, goals and capabilities.

Dealing with the increasing complexity requires sophisticated and cross-scale simulation models. Only then can decision-makers and on-the-ground managers be better supported by scientists. The adaptive manner of this modeling approach also allows system experts to gain a better mechanistic understanding of the specific social-ecological system. Emerging behavior, and patterns of self-organization are worthwhile properties to look for as well as tipping-points in the system.

5.5 Conclusion

The understanding of human-nature interaction is an important step for achieving sustainable management solutions in the context of social-ecological systems.

Management decisions are often achieved by personal experiences, abilities, and within hierarchical structures. Under changing conditions, such as climate and an increasing population, the decision-making process becomes more complex. These experiences bring a high risk of ecological and social degradations.

For decision-makers it is predictable that, each single household will exploit the closest firewood site and travel further when the closest sites are exhausted. Consequently, the knowledge growth will come when the upscaling for hundreds, thousands, or millions of households is observed.

The MARS framework is exactly developed for these massive number of individual agents in highly complex social-ecological systems. To understand the processes that lead to emerging phenomena, tipping points, or self-organization decision-makers need such powerful frameworks.

Because of the higher demand and the potential loss of all ecosystem services, there is a high demand for suitable modeling approaches that cater for solutions for the worldwide problems.

The presented approach for adaptive planning of human behavior in agent-based modeling and simulation scenarios based on artificial intelligence are practical for all kinds of social-ecological modeling - especially, for limited natural resources like water, food, and fuel wood.

These promising results will lead to an expansion of the model in the near future.

Author Contributions: This work originated from the Department of Computer Science at Hamburg University of Applied Sciences. U.A.L. conceptualized the model and designed the study; T.C. and J.W. did the software design and implementation in MARS. U.A.L. conducted the experiments and did all analysis and visualization. T.C. and J.W. critically reviewed the paper and provided comments on its content and structure.

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Chapter 6

Tree distribution as a result of disturbances by elephants and firewood collectors: An agent-based model comparison

Ulfa A. Lenfers, Florian Ocker, Julius Weyl, and Thomas Clemen
Submitted to: *Applied Geography* (under review)

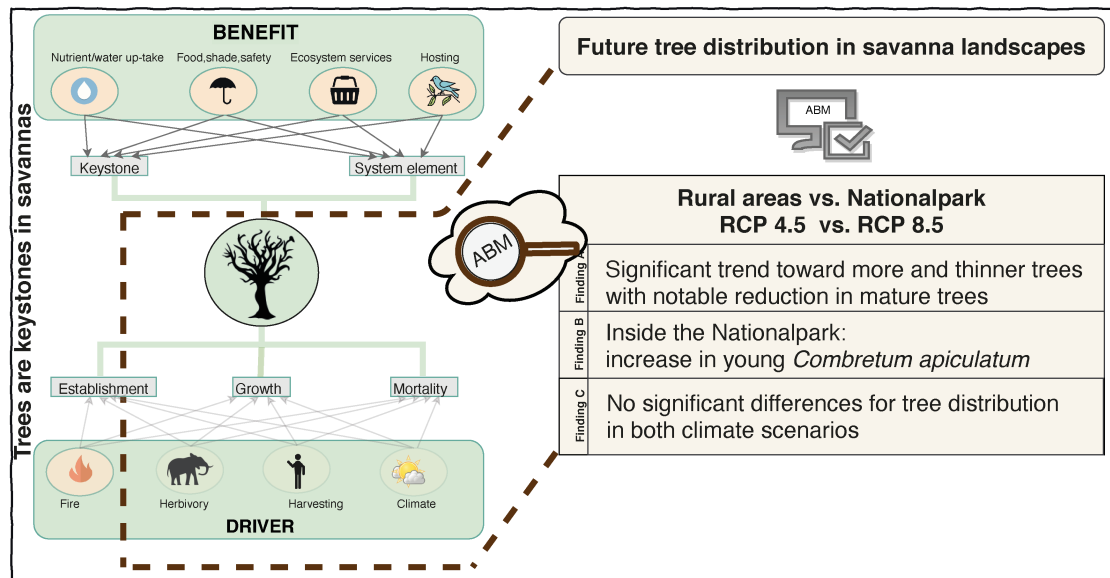
Highlights

- We developed an agent-based simulation model that covers more than 500,000 individual trees at two different sites in northern South Africa.
- Even the total aboveground biomass seems to stay more or less constant. Our results show a significant trend toward more and thinner trees together with a notable reduction in mature trees.
- The Kruger National Park scenarios show an increase in young *Combretum apiculatum*. That corresponds to bush encroachment.
- All simulations show no significant differences between the climate scenarios.

Keywords:

Savanna trees, Bushbuckridge, firewood collection, elephant, agent-based modeling, MARS

Graphical Abstract



ABSTRACT

In order to close the gap between social sciences and natural sciences, it is essential to explore how environments that were formed by natural processes are used by social groups. In the study of African savannas, understanding the dynamics of tree species and their demography is necessary for predicting future developments. In an effort to investigate these dynamics, we compared two plots, one located in the protected space of the Kruger National Park and the other in the rural areas of the Bushbuckridge Municipality. This paper presents a comparison of elephant-tree and firewood collector-tree interactions based on multi-agent modeling. We aim to identify the differences in tree-state distribution of three tree species in both well-protected and rural areas over the next 30 years. Particular attention was paid to modeling human, purposeful behavior in contrast to the more random, instinct-driven actions of elephants. The advantage of using an agent-based simulation was the ability to model individual trees with their species, age class, size, damage class, and life history; the similar level of detail applies to elephants and firewood collectors. Even when simulating the time span from 2010 to 2050 to predict future developments, we were able to do so with more than 500,000 single trees. We focused on answering the following questions: **Q1** How do the different tree species evolve in these differing land-use and under various RCP climate scenarios? **Q2** Are mature trees becoming rare?

6.1 Introduction

Trees are keystones in savanna landscapes (Figure 6.1) and are highly adaptable to changes in their surroundings (Blanco et al. 2014; Helm et al. 2011; Jacobs and Biggs 2002b; Manning et al. 2006; Stevens et al. 2014). These include not only soil conditions, temperature, and precipitation, but also disturbances like utilization and fire.

Therefore, savanna tree species can withstand droughts and fire and have developed different strategies to avoid over-utilization by, e.g., browsing animals (Accatino et al. 2016; Colgan et al. 2015; Higgins et al. 2012; Lenfers et al. 2017; Tomlinson et al. 2013).

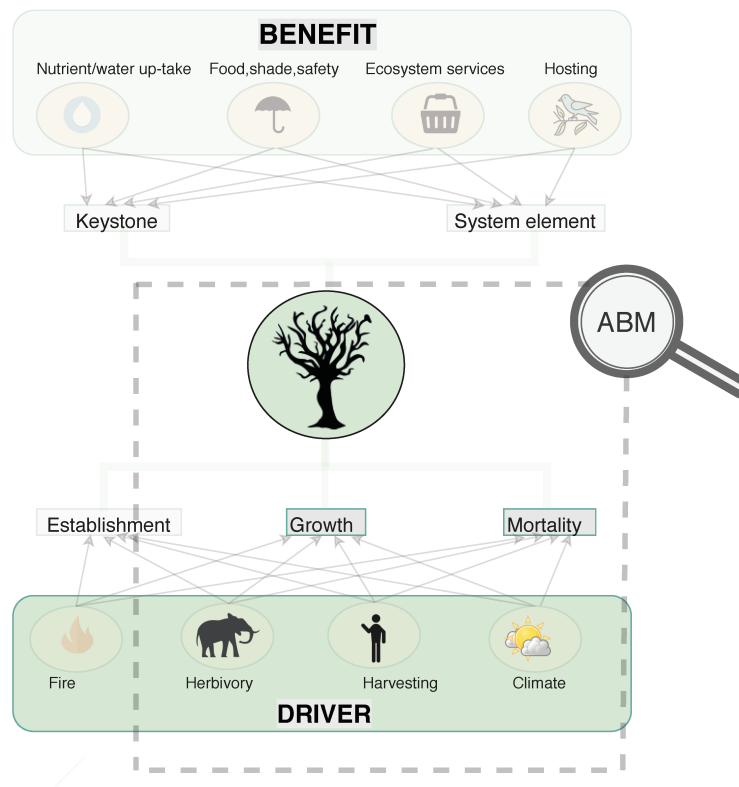


Figure 6.1: Trees as keystones in savannas, within dotted line is in ABM included

To get a model as comprehensive as possible, we took with *Acacia nigrescens*/*Senegalia nigrescens* (A.n.), *Combretum apiculatum* (C.a.), and *Sclerocarya birrea* (Marula) (S.b.) trees with different survival strategies (Lenfers et al. 2017). Additionally, the authors constructed an average tree called *Tree tree* (T.t.) to have the areas filled up acceptably with trees.

Next, two study sites in the most extreme land-use forms of the savanna were chosen: a plot in the rural area of the Bushbuckridge Municipality, and a plot inside the Kruger National Park (KNP) as a near-natural example in a protected area (Figure 6.2). Both sites have an enormous data base (Fisher et al. 2012; Kaschula et al. 2005; Lenfers et al. 2018; Madubansi and Shackleton 2007; Mograbi et al. 2019; Nickless et al. 2011; Odipo et al. 2016; Scholes et al. 2001; Statistics South Africa 2016) and belong to the EMSAfrica (FKZ 01LL1801C) study site system.

After the selection of sites, the main agent types beside the trees were identified: firewood collector and elephant (*Loxodonta africana*). Even if the treatment of trees is very similar, the planned and adaptive human behavior is very different from the random behavior of elephants. Furthermore, the two different climate scenarios RCP (Representative Concentration Pathway) 4.5 and RCP 8.5 (Engelbrecht et al. 2015) will be discussed.

Many existing models aim to make predictions about the fuelwood demand (Banks et al. 1996; Emanuel et al. 2005; Munalula and Meincken 2009; Scheiter et al. 2019; Twine and Holdo 2016; Wessels et al. 2013) or to calculate the aboveground biomass (AGB) of trees in savannas (Baxter 2003; Bonan et al. 2003; Jeltsch et al. 1998; Liedloff and Cook 2007; Moncrieff et al. 2015; Scholtz et al. 2014; Twine and Holdo 2016). To model non-linear systems with adaptable human behavior, which has been shown to be absent in current models (Mograbi et al. 2015), we take the advantages from the goal-oriented action planning (GOAP), see more in (Lenfers et al. 2018) and the KNP elephant model (Clemen, under review) to simulate non-linear interactions with single trees. Additionally, we modeled wood collection on the household scale with preferences in the quality of firewood. With the large scale agent-based model (ABM) (see ODD protocol (Grimm et al. 2006, 2010) in Appendix A) we were able to model each single tree's life cycle for three different tree species without losing too much information by aggregations to AGB and/or up-scaling from an average value per hectare.

6.2 Study area

To model tree distribution of specific savanna tree species, we placed our research areas (see Figure 6.2) in the Lowveld, one of the savanna biomes in South Africa with the vegetation type Granite Lowveld (Rutherford et al. 2006).

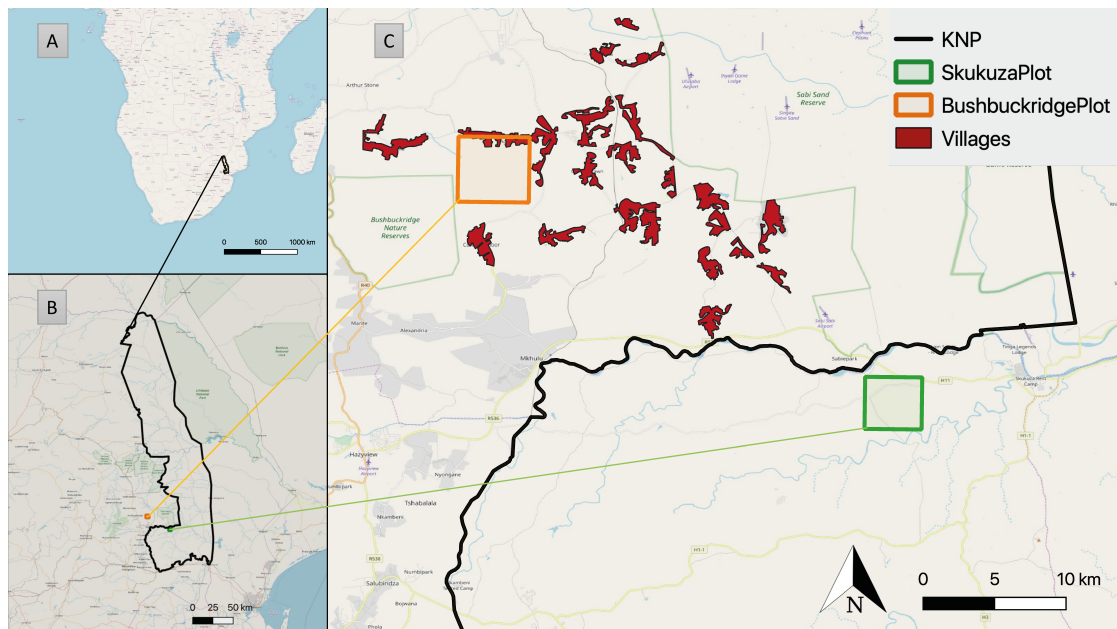


Figure 6.2: Study site: Overview of southern Africa (A), location of KNP (B) with both study sites (C)

The majority of rainfall occurs in the summer between October and May with a mean annual precipitation of 570 mm in the Skukuza site and of 640 mm in the

Bushbuckridge site. The rainfall is driven mainly by thunderstorms with a high inter-annual variability, causing droughts to occur regularly. The temperature profile is characterized by hot summers and mild and dry winters (Shackleton et al. 1994). Within this savanna biome, there are three main different land tenure systems: the state-owned communal areas (see Figure 6.2 BushbuckridgePlot), the state-owned conservation area KNP (see Figure 6.2 SkukuzaPlot), and a buffer zone that belongs to a system of privately-owned conservation areas.

6.2.1 Rural Area Bushbuckridge

One of the two main study sites of the EMSAfrica project (Berger et al. 2019) is located in the Bushbuckridge Municipality, south of Agincourt (-24.82°, 31.21°). The social structure is characterized by low-income households and the regular use of natural resources from communal lands (Matsika et al. 2013b; Mograbi et al. 2016; Twine and Holdo 2016). Since 40 % of the area is used for houses, streets, or agriculture land, an average of only 60 % of the land is used for firewood collection. Also, the first 1500 m south of Agincourt is less woody structure left because of the ongoing heavy firewood collection (Wayne Twine, pers. comm.). We took this into account while calculating the space required for firewood collection.

6.2.2 KNP Skukuza

The second study site of the EMSAfrica project is located 13 km southwest of Skukuza. Since 2000 there is an eddy covariance flux tower to measure mainly CO₂ fluxes. Fire is not a regular occurrence in this region and the elephant impact is differing between low and high (SANparks 2018).

6.3 Method

Agent-based modeling is an assessed approach to modeling interactions between individuals and their impact on the modeled system (Kelly et al. 2013). Each individual agent is defined as an autonomous entity. The access to all information of its environment and all surrounding agents allows the agent to make decisions. However, an agent can also be a group like an elephant family or a household. This rule-based behavior allows for the execution of various actions which represent the whole range of possibilities within the system (Bonabeau 2002). What each agent actually does can vary over time.

For the simulation, a run is built by time steps where all updates in the environment and interactions of the agents are recorded. The used framework, MARS (Multi-Agent Research and Simulation), is under development at the University of Applied Sciences Hamburg. The group has worked on different topics, but has focused mainly on large agent-based models (Glake et al. 2017; Hüning et al. 2016; Weyl et al. 2018).

6.3.1 Conceptual Model

To set up the ABM, we first built the environment with different layers and then realized the different agent types with all attributes and actions. Each agent type has an own layer as an organization unit. Additionally, we defined the two climate scenarios mainly to create minimum and maximum temperature, days of frost, precipitation per day, total amount of precipitation in a vegetation year (Oct. to Sept.), and days of precipitation within the first 12 days after seed germination (see Figure 6.3). (For more details see Figure 6.20 and Appendixes A and B).

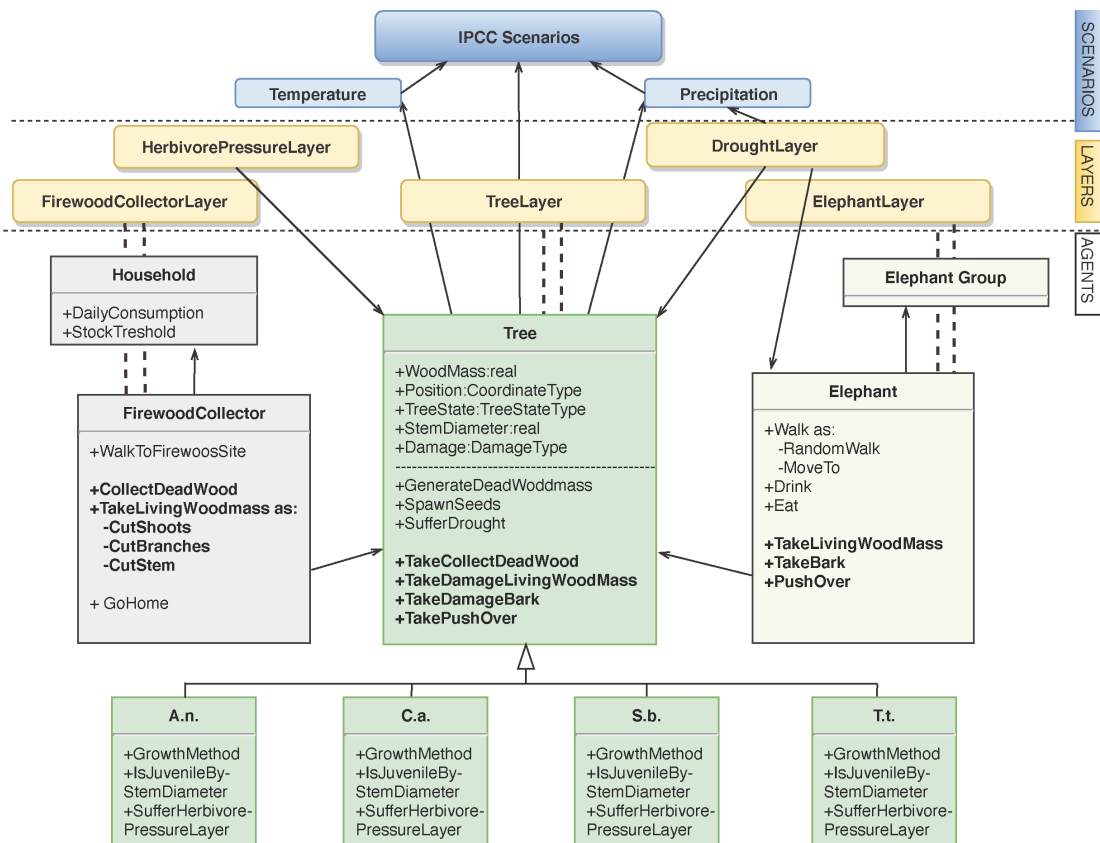


Figure 6.3: Conceptual model; in bright: FirewoodCollector-Tree and Elephant-Tree Interactions

6.3.2 Agents

Our two model scenarios share the same agent type “Tree“. In the Bushbuckridge model we also have the agent type “FirewoodCollector“. To manage the demand for firewood, there is also the agent type “Household“. Basically, each comprises six family members, one of whom has to collect firewood when there is a demand. Instead of tree damages by firewood collection, we chose the agent type “Elephant“ as the main driver of tree damages for the Skukuza model (Mogradi et al. 2016). Female elephants are organized in family groups with one leading cow. The "Elephants" are

being executed in their own model (Clemen, under review) and interact with nearby trees. This model coupling allows the "Elephants" to walk through the whole modeled "KNP" and interact randomly in the "SkukuzaPlot".

6.3.2.1 Tree

The agent type "Tree" is the key element of this study and is exactly the same in both models. Typical for savanna trees is their life cycle (see Figure 6.4) which sometimes returns adult trees back to a juvenile state upon damage. If there is too much or too frequent damage, the tree remains a juvenile without any seed production. In a perfect world, seeds receive water from rainfall within the first 12 days (Campbell 1996) and have enough space to germinate (for more details see Table 6.9) and thereby survive the first probability to die (Campbell 1996). Thereafter, the seed becomes an agent "Tree" in our simulation. The species for that single tree comes from the seed, produced by an adult tree. The first state is "seedling" and in this state, the tick-wise behavior (see Figure 6.22) brings the "seedling" to a "juvenile" if it is still alive at the start of next vegetation year (October 1st).

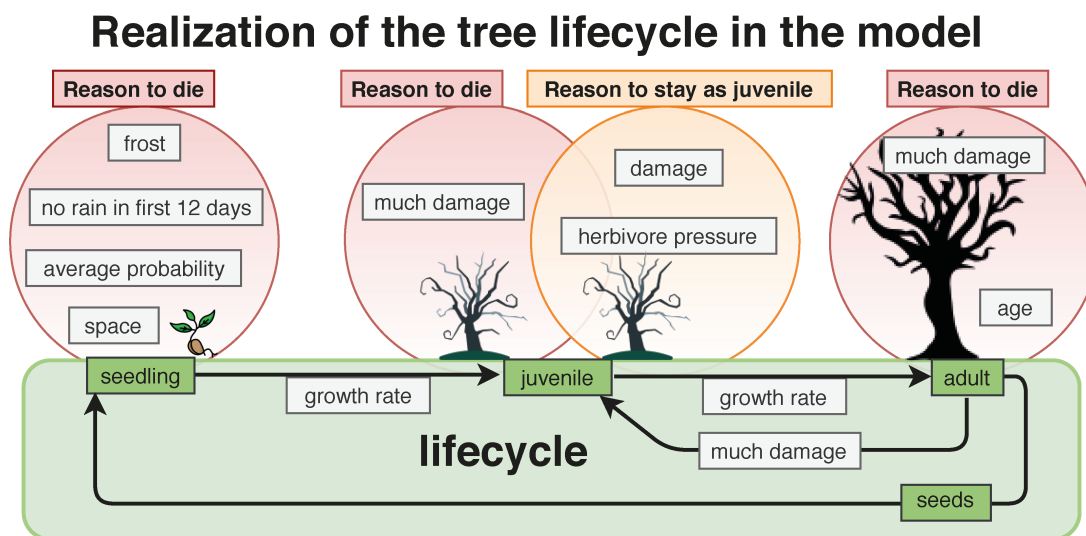


Figure 6.4: Tree lifecycle: From seed to adult tree or back to juvenile

In the states "juvenile" and "adult", each tree has the attributes: aboveground biomass (AGB), stem diameter, maximum growth rate, damage class, and the ability to switch from "LeavesOn" in photosynthetic active growing season to "LeavesOff". For each species, there is a threshold by stem diameter to change to the adult state. Only adult trees are able to produce seeds. In March, an adult tree spawns 50 seeds in its surroundings (Baxter and Getz 2008). With the first rainfall after spawning, the life cycle starts again. The daily tick routine of juveniles and adult trees (see Figure 6.5) starts with a check of new damages because damages have the most impact on the trees.

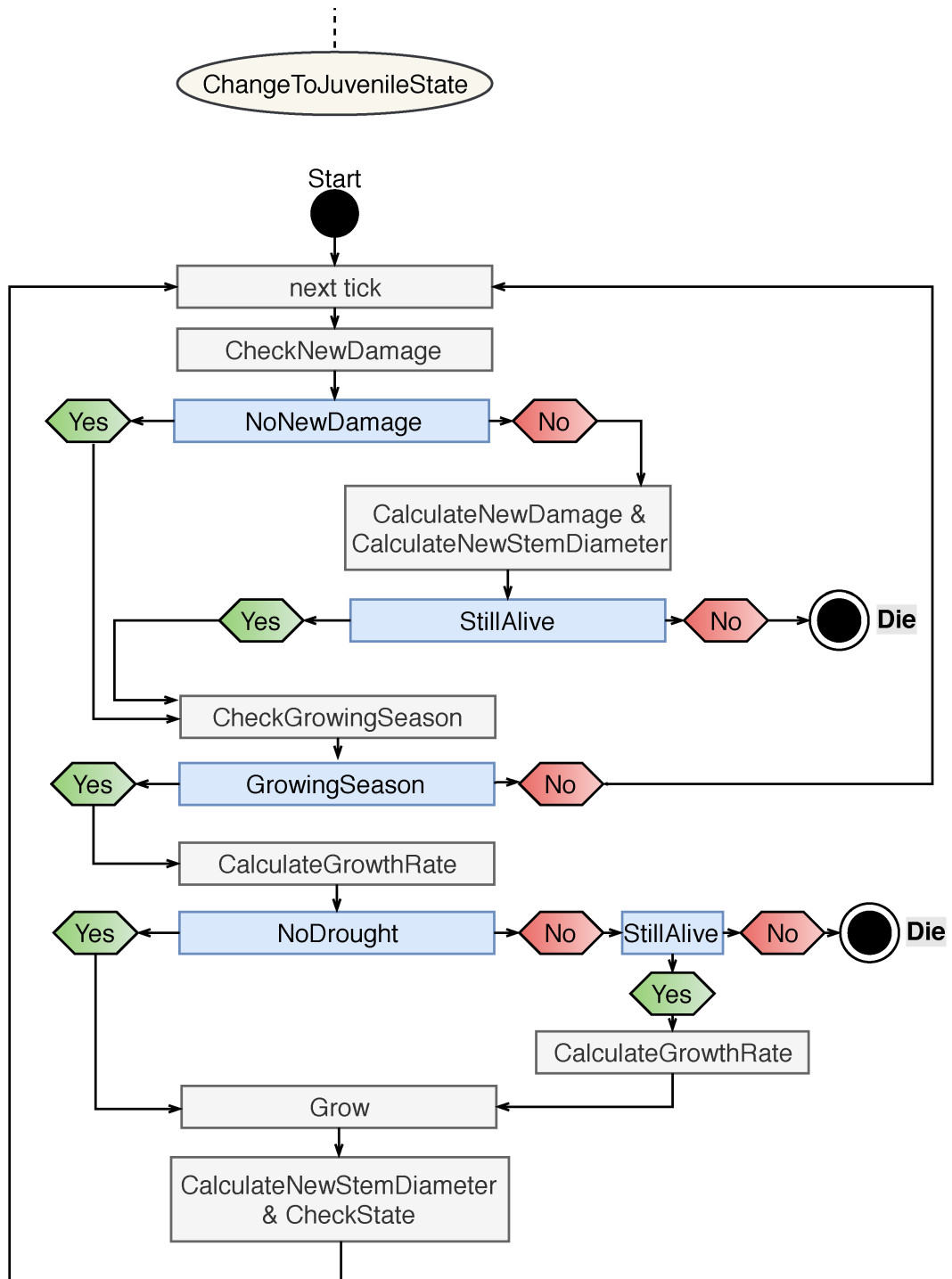


Figure 6.5: Daily tick routine for juvenile and adult Tree

Damage can be caused by "FirewoodCollectors" or "Elephants". The damage classes, modified after (Jacobs and Biggs 2002a) are N (< 10 %), L (10–30 %), M (30– 60 %), H (60–80 %), X (>80 %). For Figure 6.19, we classified "Low" for all light damages, "Medium or High" for damages between 30 and 80 %, and "Extreme or Dead" for the extreme damages as well as dead trees by damages like push-over or ringbarked.

When a tree is alive, the deadwood production is 1.7 % of the AGB (Shackleton 1998). Even when there is no firewood collection or damage by elephants, the AGB is regularly reduced by herbivores, pastorals, and insects (Fornara 2005; Scholes et al. 2001). Therefore, we included a "HerbivorePressureLayer" to be able to reduce the biomass for each tree once a year. To balance between the different strategies of the trees (Lenfers et al. 2017) we implemented rule-based probabilities for each species and their states (see Figure 6.21). The "DroughtLayer" is needed to simulate the massive changes that occur during a drought. In a drought year, all seeds and seedlings die and juveniles die at a random probability between 7 % and 15 % (Case et al. 2019).

6.3.3 Firewood Collector

A "FirewoodCollector" (see Figure 6.6) is an independent agent that are part of a "Household". These households have a daily firewood consumption, causing the collectors to have to refilling their stock as needed. On pursuing this goal, a collector has different wood gathering actions at his disposal like collection dead wood or cuttings shoots (see Lenfers et al. 2018). All these actions are weighted by preferability and cost to reach the site of action (see Table 6.9). Depending on the location of the agent, the surroundings are explored and the most preferable action is chosen until the capacity for a return is reached. The collector starts by moving to a reasonable position within the firewood site, then orientates himself, and begins to collect. If no reasonable action is available due to overcut or distance, the collector might return without reaching his collecting goal. For more details of the GOAP actions (see Lenfers et al. 2018) and more information about data for modeling, see Chapter 6.8 and 6.9.

6.3.4 Elephant

The elephant distribution of the "KNP elephant model" was adapted to helicopter counts in the KNP. If single elephant or herds are about to cross the SkukuzaPlot is mostly a matter of available water together with a random factor (Clemen, under review). As Figure 6.7 and 6.21 show, damages to the trees varies depending on the month, tree species, droughts, and state of the tree (Cook et al. 2017; Jacobs and Biggs 2002a; Moncrieff et al. 2008; Shannon et al. 2008).

6.4 Data

Due to the favorable quantity and quality of data in both research areas, we did not collect our own data and instead used existing data for the parametrization and initialization of the model.

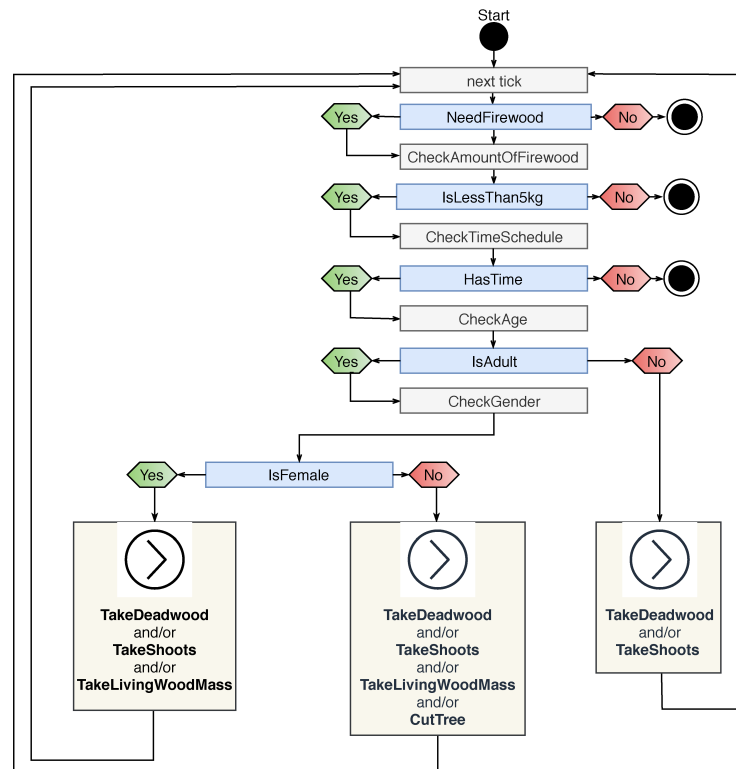


Figure 6.6: Daily tick routine for FirewoodCollector

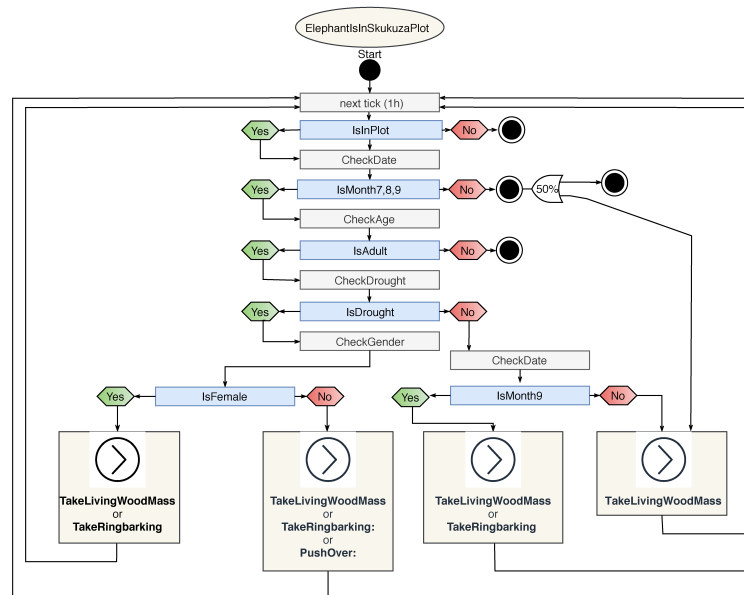


Figure 6.7: Hourly tick routine for Elephant inside the SkukuzaPlot

6.4.1 Model parameterization

The three tree species *Acacia nigrescens* (A.n.), *Combretum apiculatum* (C.a.) and *Sclerocarya birrea* (S.b.) with their different defense strategies (Lenfers et al. 2017) represent only part of the total tree population at our sites. After having parameterized them (see Table 6.1, also Chapter 6.9), we defined an average tree, named *Tree tree* (T.t.) to fill up the rest of the site with this more generic tree. We decided that this would give the most realistic model. For this, we sum each parameter of the three tree species and then divide it by three.

Table 6.1: Tree parameter for species (Allen et al. 2010; Baxter and Getz 2008; Campbell 1996; Jacobs and Biggs 2002a; Helm et al. 2011; Nickless et al. 2011; Shackleton 1998)

<i>Acacia nigrescens</i>	
seedling	< 1 cm stem diameter, frost tolereant
juvenile	< 8 cm stem diameter
growth rate juvenile	$\text{StemDiameter} = \text{StemDiameter} + (-0.068 * \text{StemDiameter} + 0,9) / \text{DaysWithLeaves}$
first time seed production	after 12 years
adult	> 8 cm stem diameter
max stem diameter	20
<i>Combretum apiculatum</i>	
seedling	< 1 cm stem diameter, frost sensitiv
juvenile	1-10 cm stem diameter
growth rate juvenile	$\text{StemDiameter} = \text{StemDiameter} + (-0.068 * \text{StemDiameter} + 1,2) / \text{DaysWithLeaves}$
adult	> 10 cm stem diameter
first time seed production	after 10 years
max stem diameter	20
<i>Sclerocarya birrea</i>	
seedling	< 1 cm stem diameter, frost sensitiv
juvenile	< 20 cm stem diameter
growth rate juvenile	$\text{StemDiameter} = \text{StemDiameter} + (-0.068 * \text{StemDiameter} + 1,9) / \text{DaysWithLeaves}$
adult	<= 20 cm stem diameter
first time seed production	after 18 years
max stem diameter	50

For the parametrization of firewood collection, we tried to map the conditions of Agincourt. The collecting area is located south of the village. The 5 x 5 km study sites of the EMSAfrica project correspond to the collection area for half of the inhabitants. In total, only 40 % of the area is suitable for firewood collection (pers. comment Twine) and the first 500 - 1500 m are already strongly over-harvested (Twine and Holdo 2016). Therefore, we modeled 100 ha in the center of the study site. Here, we calculated that 56 "FirewoodCollector", representing 336 inhabitants of Agincourt for these 100 ha.

This corresponds to 4104 people in 684 households, half the population of Agincourt in 2017 (pers. comment Twine).

Table 6.2: Firewood collecting parameter (Dube et al. 2014; Madubansi and Shackleton 2007; Twine and Holdo 2016)

FirewoodCollection	
households	684 (4100 person)
demand of firewood per household	10 kg/day
household members	6
hours per collection	3
per hour collection time	5 km distance; 20 kg dead wood; 15 kg shoots; 10 kg living wood
demand per collection (kg)	15 - 40
most stem cut	4 - 10 cm must > 3 cm
frequency of collection per week	3
species preferences	C.a. > A.n. > S.b.
wood collecting preferences	dead wood > coppicing > cutting branches > cutting down living trees

Since the elephant model is a coupled model, other requirements apply here. The elephants can move freely throughout the park and live their daily lives there (Clemen, under review). Only if they come close to the “SkukuzaPlot”, they change into the elephant-tree interaction sub-model. Thus, the parameterization for this model is limited to what the elephants do when they are in the plot (see Chapter 6.3.4). Due to the high complexity of the model coupling, we also had to limit the study area to 9 ha.

6.4.2 Initialization

Tree distribution of the given aboveground biomass stands in relation to the measured distribution of tree species and their age classes for both sites (Holdo 2006; Mograbi et al. 2016, 2015; Nickless et al. 2011; Odipo et al. 2016; Shackleton and Scholes 2011; Twine and Holdo 2016). We generated trees only once for the BushbuckridgePlot and once for the SkukuzaPlot by applying the data from Table 6.3 and 6.4. That process produced a “csv.file” with all generated trees including their geo-referenced position, species, stem diameter, and age state. The total AGB differs from 10 t/ha (Mograbi et al. 2015) in the rural area to 23 t/ha (Nickless et al. 2011) inside the national park.

6.4.3 IPCC-Scenarios

In South Africa the temperatures have been already increased over the last decades. Further climate change will lead to temperature increases up to 6°C and changing

Table 6.3: Tree Initialization BushbuckridgePlot

Bushbuckridge site		A.n.			C.a.			S.b.			T.t. (98 %)			total
state	seedlings	juveniles	adults	seedlings	juveniles	adults	seedlings	juveniles	adults	seedlings	juveniles	adults		
individuelles	8	2	0	31	131	3	31	73	7	3546	638	38	4508	
AGB t/ha	0	0.2		0	0.445		0	0.765		0	8.78		10	

Table 6.4: Tree Initialization SkukuzaPlot

Skukuza site		A.n.			C.a.			S.b.			T.t. (33 %)			total
state	seedlings	juveniles	adults	seedlings	juveniles	adults	seedlings	juveniles	adults	seedlings	juveniles	adults		
individuelles	683	130	7	2888	550	26	89	17	1	1817	300	46	6554	
AGB t/ha	0	3.9		0	5.4		0	6.1		0	7.6		23	

precipitation pattern (Archer et al. 2018). In order to have a first comparison that is as meaningful as possible, the two extreme climate scenarios based on contrasted representative concentration pathways, RCP 8.5 and RCP 4.5, were selected.

But the strongest differences in temperature and precipitation do not start until 2050. Therefore, we modeled a growth boost and a higher seedling survival rate for the RCP 8.5 scenario (Possell and Nicholas Hewitt 2009) to emphasize the higher CO₂-level (see Table 6.5). In order to make the experiments within the research project comparable, we gathered input data from aDGVM (Engelbrecht et al. 2015; Scheiter et al. 2019). The threshold value for a drought was set at 65 % of the average precipitation within a vegetation year.

Table 6.5: IPCC Scenarios (RCP 4.5 & 8.5)

RCP 4.5	
Seedling mortality	88 – 100 %
Growth rate	Max. growth rate _{species} = 100 %
Drought years Bushbuckridge (<435mm)	2019; 2020; 2025; 2027; 2029; 2031; 2032; 2034; 2042; 2048; 2050
Drought years Skukuza (<370mm)	2020; 2027; 2029; 2031; 2042; 2048; 2050
RCP 8.5	
Seedling mortality	85 – 100 %
Growth rate	Max. growth rate _{species} = 130 %
Drought years Bushbuckridge (<435mm)	2020; 2027; 2029; 2031; 2042; 2048; 2050
Drought years Skukuza (<370mm)	2018; 2020; 2028; 2029; 2038; 2042; 2049

6.5 Results

All simulation results were scaled down to 1 ha in order to ensure better comparability. The variable year represents the vegetation year which starts on October 1st of the current year.

Altogether, we compared four simulation runs with each other. In numbers this means for two climate scenarios more than 500,000 individual trees, which go through their daily routine over 40 years, which is equal to 14,600 simulation steps each.

All results show that there are only marginally differences between the two climate scenarios. That leads to the fact that the climate scenarios start to differ more in the last years of our experiments. Additionally, the response to changes in climate by trees takes decades because of their long lifecycle.

6.5.1 Trees

In this study, we highlighted the differences between two extremely different land-use forms (Figure 6.8).

The Bushbuckridge scenario starts with a biomass of about 10 t/ha, which stays relatively stable in the first years of RCP 4.5. Biomass increases moderately in the RCP 8.5 scenario. Continuous firewood extraction decreases the total amount of AGB remarkably. However, after that, the amount keeps robust at a lower level.

Both Skukuza scenarios developed differently to one another but converged after a couple of years. This effect is caused by the elephants that visited the site earlier in the RCP 8.5 run. After that point, both time series show a similar development with a slightly increasing trend.



Figure 6.8: Aboveground biomass by trees in t/ha (sum of all species)

In Figure 6.9, all four scenarios show a rise in total numbers of trees in the first seven years. Because of a stable AGB, this must be a trend to more but thinner trees. For Bushbuckridge, our analyses showed that even in times when there is nearly no AGB, still, a serious number of trees exist in the scenario. That means the diameter must be minimal.

The differences in the RCP scenarios are mostly driven by the different droughts that cause the death of many trees. The same happened in the Skukuza scenarios, but the numbers always recovered after a couple of years.



Figure 6.9: Number of trees in one hectare (sum of all species)

By classifying the results according to age classes (see Figure 6.10 - 6.13), the reasons became more apparent. Both amounts of AGB and the number of trees are mainly driven by the age class “Juvenile”. Here, we were not able to distinguish between juveniles that become adults and juveniles that remain in their current state (see Figure 6.4).

However, our results (see Figure 6.14) show under the prediction of our scenarios, that we will lose all adult trees under ongoing firewood collection in the rural area. Inside the Kruger National Park, a high loss of big trees over the last years was observed. Nevertheless, it seems that the number of adult trees is stabilizing.

6.5.2 Species

For the three tree species considered (see Figure 6.15 - 6.18), we found heterogenic results. For *Acacia nigrescens*, we have only two individuals/ha in both scenarios in Bushbuckridge. Even with the total number of trees, which is more than 450,000 in this plot, it is hard to detect a clear trend. In total, a rare species become even rarer.

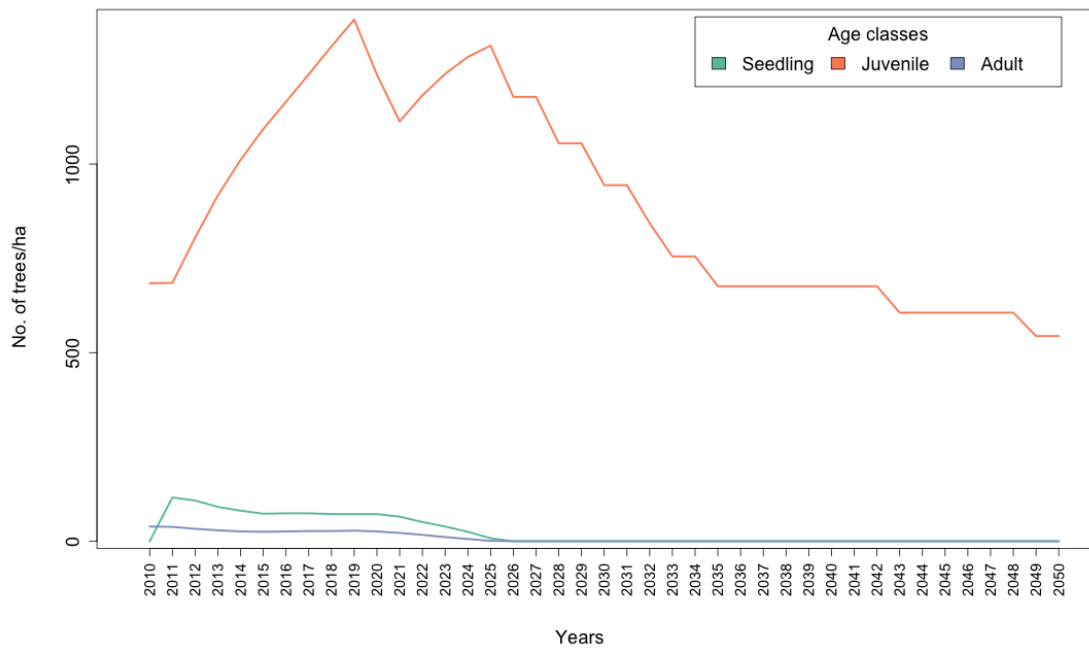


Figure 6.10: Bushbuckridge (RCP4.5) scenario results grouped by age class per hectare (sum of all species)

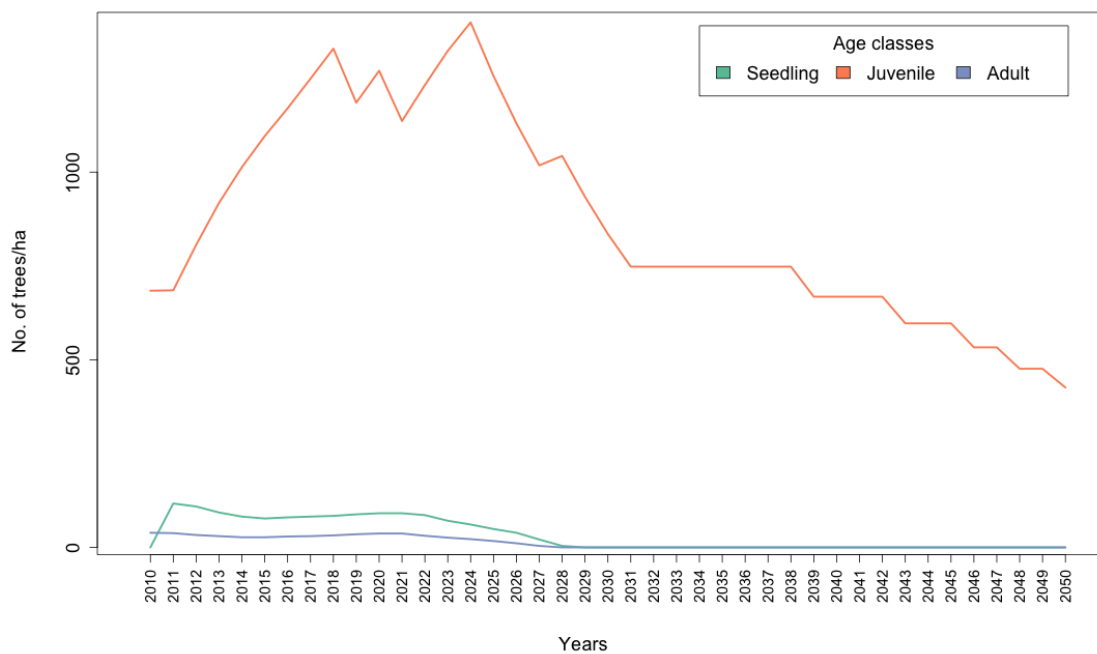


Figure 6.11: Bushbuckridge (RCP8.5) scenario results grouped by age class per hectare (sum of all species)

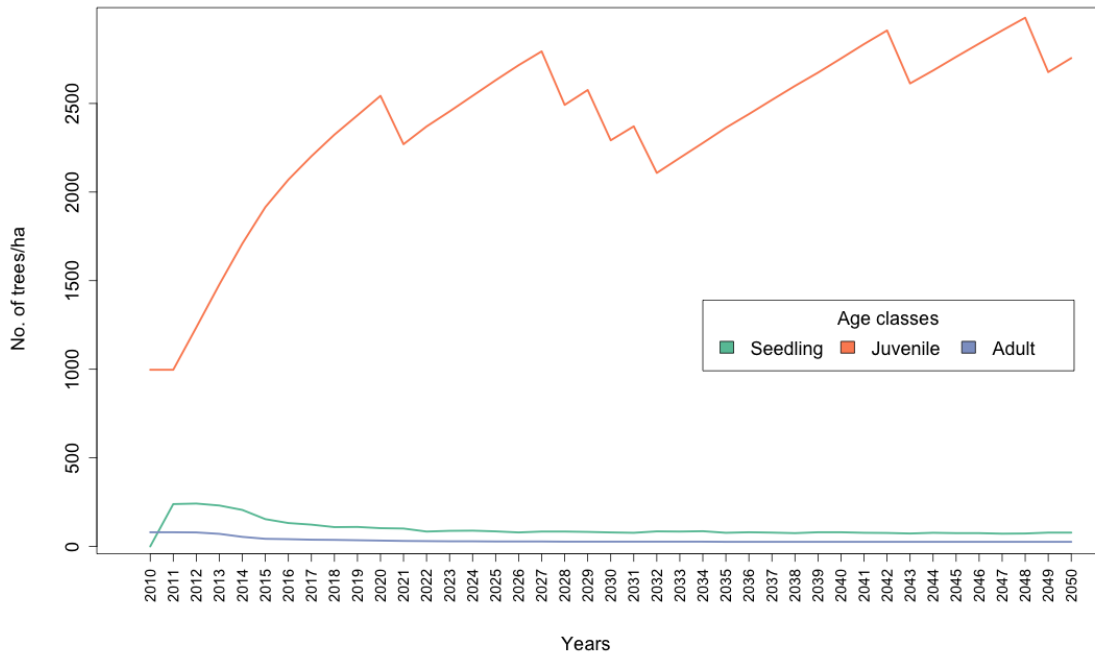


Figure 6.12: Skukuza (RCP4.5) scenario results grouped by age class per hectare (sum of all species)



Figure 6.13: Skukuza (RCP8.5) scenario results grouped by age class per hectare (sum of all species)

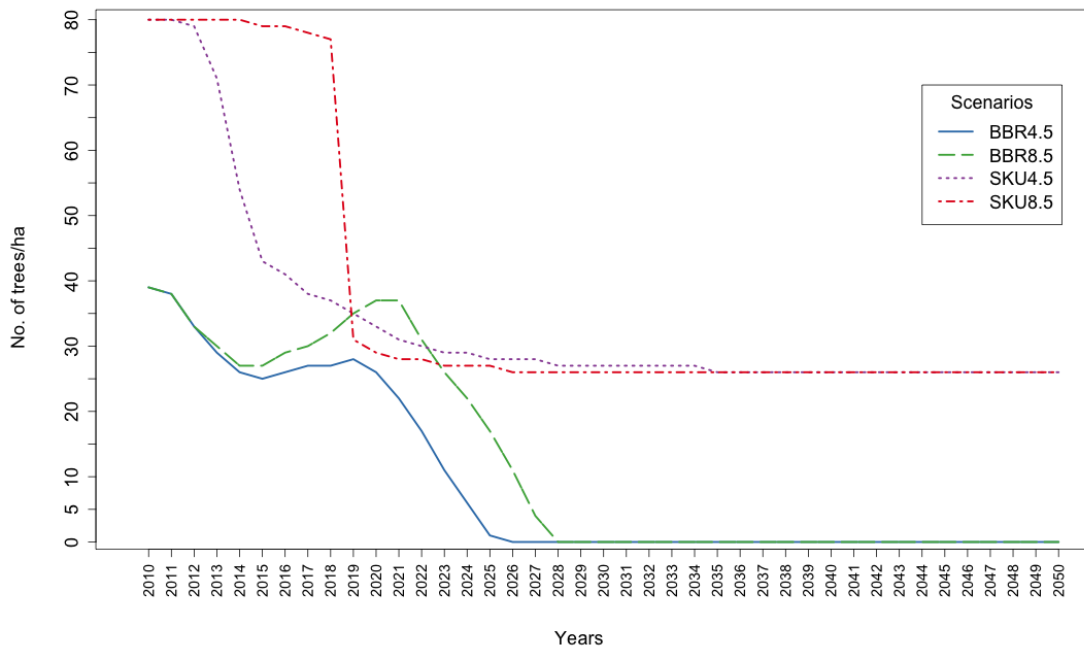


Figure 6.14: Number of adult trees in one hectare (sum of all species)

For the SkukuzaPlot we have very similar numbers of single trees from 2010 to 2050 with higher numbers in between. Here, the species *A.n.* seems to be more stable than outside the protected areas.

Combretum apiculatum shows the most significant differences between both sites. In the rural area, the number of trees is declining, whereas, inside the KNP, a fourfold increase of trees within the 40 years were observed. Surprisingly, the RCP 4.5 scenario produces higher numbers than the RCP 8.5 scenario.

Sclerocarya birrea plays a unique role in rural areas. Because it is forbidden by law to cut down an adult tree, we can observe a stable number of Marulas over a long time. Only when the firewood became scarce, this tree species was also harvested. There is still a stable number of trees in both climate scenarios but, as mentioned before, these are mainly juvenile trees (see also Figure 6.4).

6.5.3 Damages

Firewood collection in Bushbuckridge and damages by elephants in Skukuza are possible disturbances trees can experience. Even though in both scenarios, firewood collectors and elephants have a similar damage classes, there are different consequences between the two sites (see Figure 6.19).

In Bushbuckridge, there was an increase in the number of trees with the damages class "Extreme or Dead" between 2012 and 2024. In this period, there are also trees with damage class "Low". Because of the decline in AGB, the number of trees in general, and number of adult trees (see Figure 6.8 - 6.14), there is in total not enough easy-to-collect firewood. Since the firewood collector still has to reach his goal, he starts heavily damaging all trees as well as collecting less firewood.

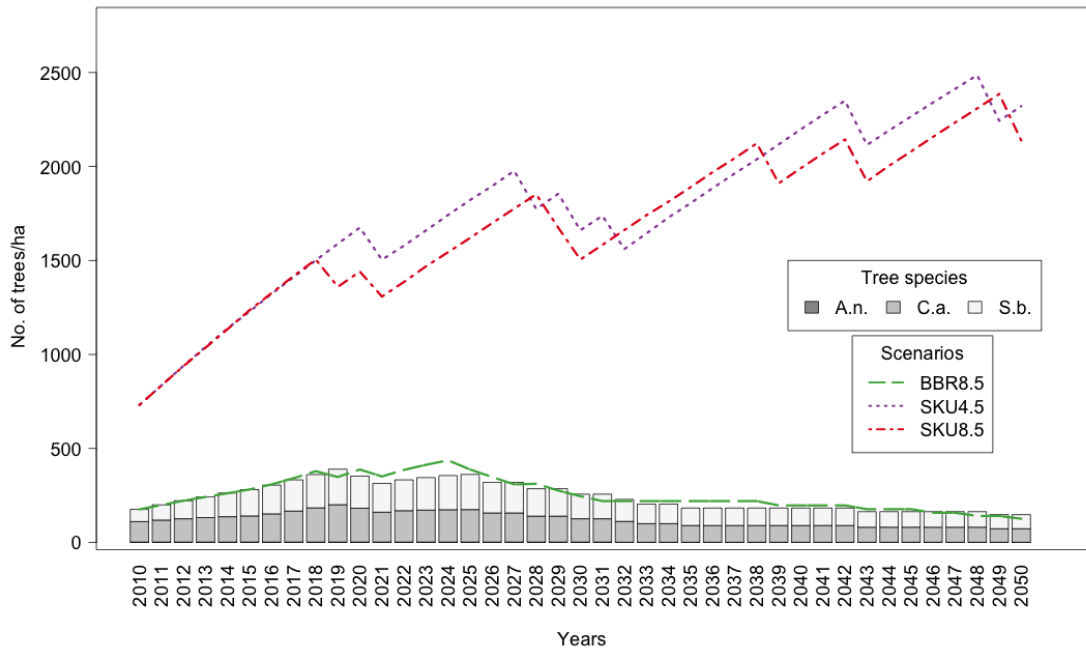


Figure 6.15: Species distribution in the Bushbuckridge (RCP4.5) scenario (A.n, C.a., S.b.)

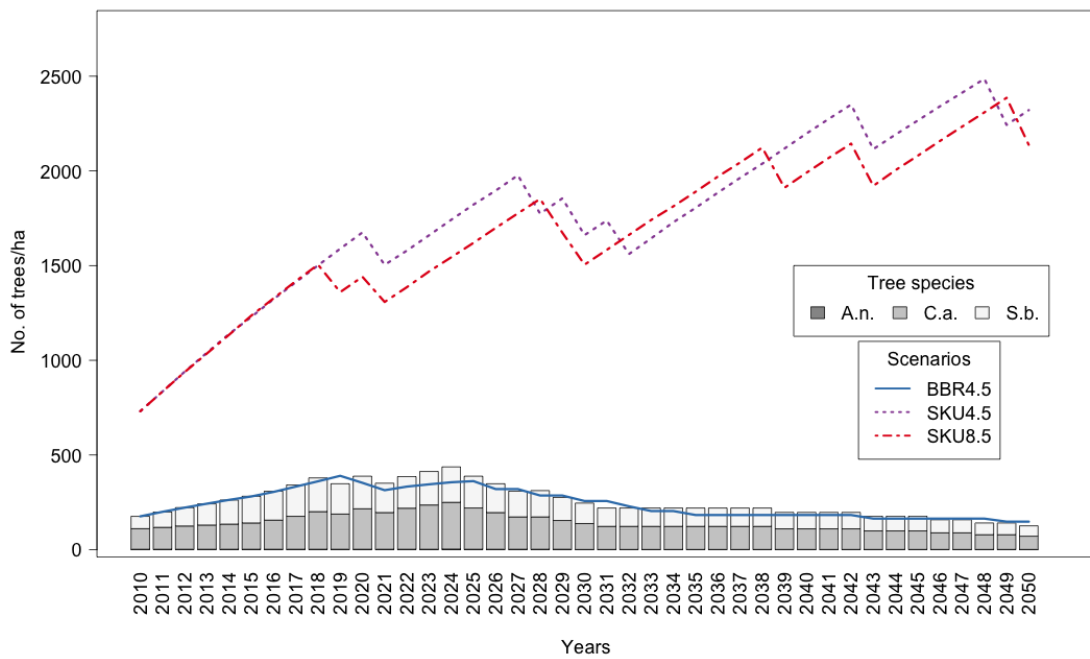


Figure 6.16: Species distribution in the Bushbuckridge (RCP8.5) scenario (A.n, C.a., S.b.)

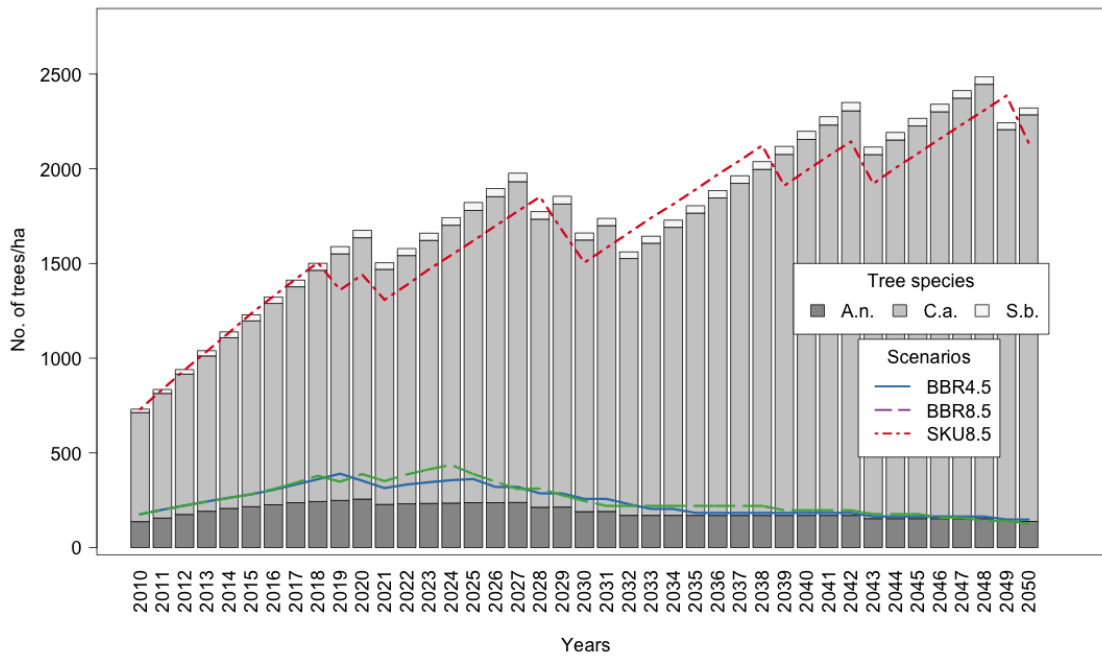


Figure 6.17: Species distribution in the Skukuza (RCP4.5) scenario (A.n, C.a., S.b.)

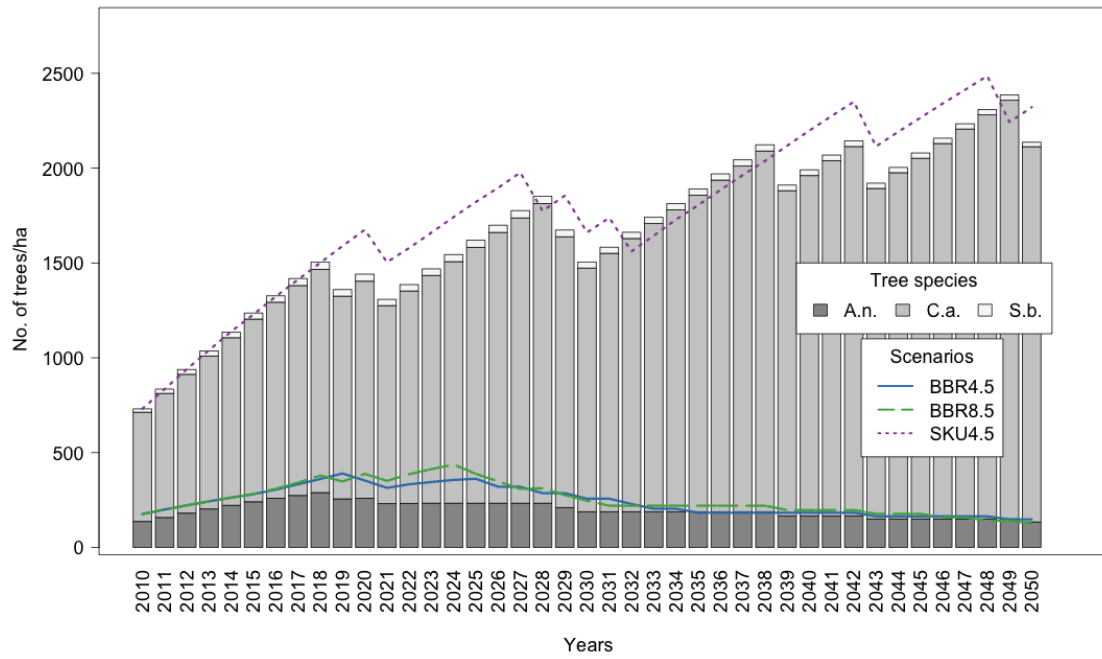
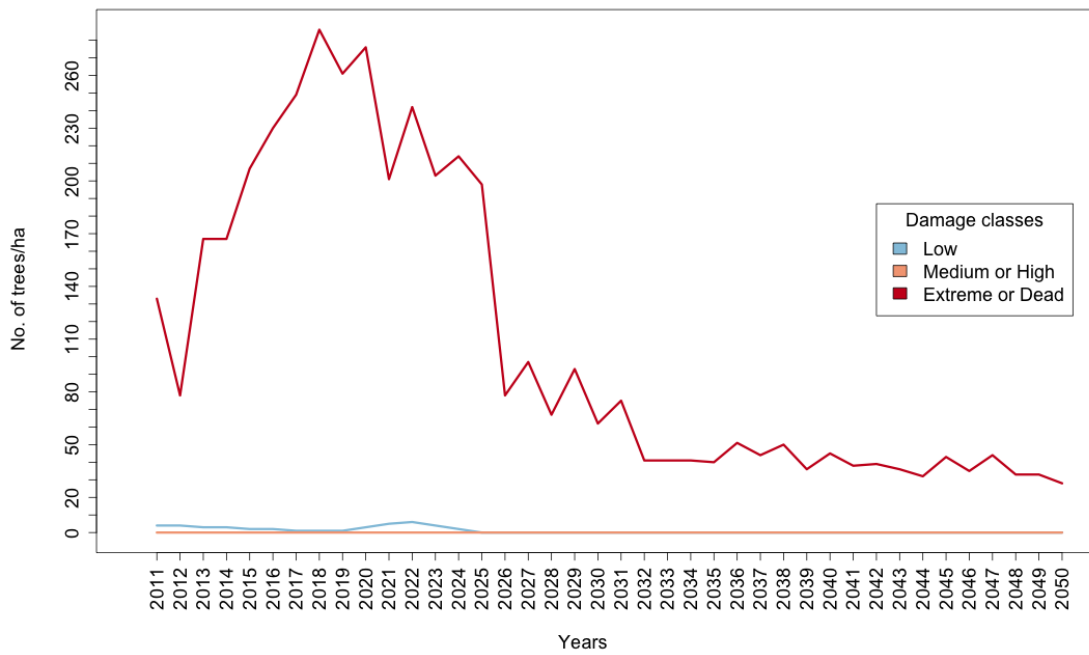
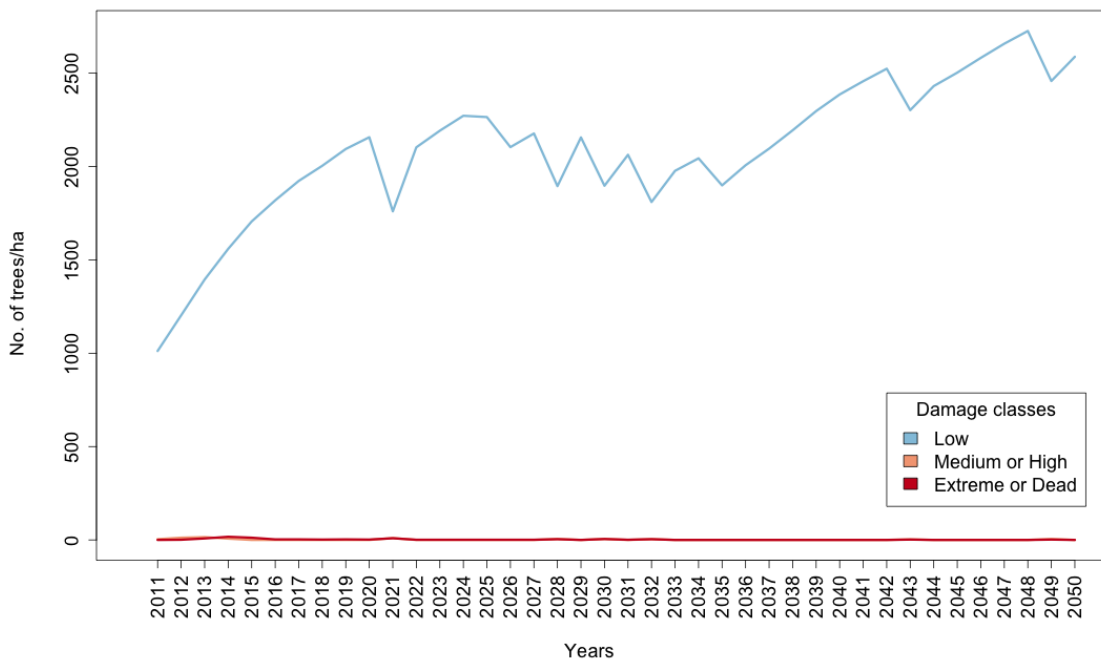


Figure 6.18: Species distribution in the Skukuza (RCP8.5) scenario (A.n, C.a., S.b.)



(a) Bushbuckridge (RCP4.5)



(b) Skukuza (RCP4.5)

Figure 6.19: Damages taken by trees: (a) Bushbuckridge RCP 4.5 and (b) Skukuza RCP 4.5 (sum of A.n., C.a., S.b.)

In Skukuza, the elephants mostly damage the trees with maximum damage class Low (<30 %). But because of the declining number of adult trees (see Figure 6.14), each tree with the damage class “Extreme or Dead” is changing the age class distribution to more juvenile trees and fewer adult trees.

6.6 Discussion

The study aimed to compare the current and future distribution of savanna trees for two different land-use forms and under two different climate scenarios by applying a massive agent-based simulation model. Concerning our research questions, we were able to gather the following answers.

Q1 How do the different tree species evolve in these differing land-use and under various RCP climate scenarios?

Our research suggests extreme differences between the two land-use types. In the rural area, there will be a substantial loss of trees under ongoing firewood collection and land-use change (Díaz et al. 2013; Mograbi et al. 2016, 2019; Twine and Holdo 2016). Even if our results are hyperbolized, the decreasing number of adult trees will destabilize the system. However, we were also able to show that there are still enough individual trees to potentially stabilize the site. For that to happen, the ongoing firewood collection must be regulated.

Inside the Kruger National Park, the AGB seems to stay more or less unchanged but with a significant trend toward more and thinner trees (Stevens et al. 2016). This is mainly driven by an increasing number of juvenile trees of *Combretum apiculatum*. This finding correspond to a potential shift in the species composition and bush-encroachment (Mograbi et al. 2019).

To compare the land-use forms, we modeled the main disturbers of the trees. FirewoodCollector modeled with GOAP showed adaptive behavior in starting to collect less firewood as a result of changing conditions at the site after some time of overharvesting. Nevertheless, the total number of extreme damages to the trees, like coppicing and felling of trees, is extremely high (Holdo 2006; Mograbi et al. 2016).

Elephant damages are most damaging in the class “Low”, which means damages up to 30 % (Gaylard 2015). These damages seem to regulate the biomass in total. However, all push-over and ringbarked adult trees will change the tree distribution because of a lack of upcoming new adult trees (Emanuel et al. 2005; Moncrieff et al. 2008).

Our research suggests no significant differences between both climate scenarios. The time frame would need to be extended significantly in order to detect long-term changes.

Q2 Are mature trees becoming rare?

In all four scenarios, we observed a loss of adult trees. Even if savanna trees have a high potential of recovering after damages, fewer adult trees mean fewer seeds eventually. Therefore, every single tree that disappears from the landscape might have a destabilizing effect on the tree-grass savanna system. For assessing the impact of elephant damages on mature trees, the questions when did that happen and what did

the elephants, is explicitly highly relevant. Seeing elephants as agents that re-build the savanna all the time (Gaylard 2015) can help to understand the future distribution of mature trees.

The situation looks much more dramatic in the rural areas where the demand for firewood will no longer be covered sustainably by the ecosystem. When the preferred stem diameter, i.e., 4 - 10 cm, becomes scarce, the FirewoodCollector also started to cut down larger trees (Twine and Holdo 2016). Both disturber, covered by this study, can create specific spatial patterns without adult trees (Mograbi et al. 2016). A few healthy mature trees can stabilize the savanna system. But the generation, e.g. of *Sclerocarya birrea*, is highly episodic (Scholes and Walker 1993) and will need many years to reestablish a normal age class distribution again.

We are aware that this study has several limitations. Future development will be to include more complexity in all three agent types. Trees will extant by more detailed seed production and dispersal, with that elephants will interact as seed distributors. For a more realistic human behavior, we will include more goals and actions to cover the changing living conditions in rural areas better. Nevertheless, the whole part of coming technical innovation is still missing.

6.7 Conclusion

The attempt to model future tree distribution in the savanna landscape by applying ABM was able to give some insight into the different systems. There are big differences in tree composition in the rural area and inside the KNP.

The BushbuckridgePlot has a stable AGB for a long time but when overharvesting starts, the collected diameter decreases accordingly. Even when there is different firewood quality, the collection pressure equalizes it. Additionally, all adults are under high pressure and at the hands to ongoing collection, they will likely disappear with fatal consequences. However, when the system can recover for some years, it might be able to return to a stable state. Protecting adult trees seems to be very important.

In the SkukuzaPlot, the system is much more resilient during periods of high elephant damages. In total, the system tends to more individuals with smaller stem diameter. Adult *Sclerocarya birrea* disappears because of elephant damages during droughts. To protect single adult Marula trees seems to be a good way to stabilize the system. At the same time *Combretum apiculatum* is doing very well. This is driven by a high number of juveniles and could be a signal for bush encroachment.

The study findings highlight the complexity of savanna system. Even by modeling a simplified tree-interaction system, we were able to form an understanding of the three different tree species under the chosen scenarios. Also, changes in tree density need decades the models could stand as an early warning for potential loss of tree species, loss of big trees, as well as point out zones with high potential for conflict as a result of loss of resources.

Acknowledgment

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6.8 Appendix A

ODD Protocol (Grimm et al. 2006, 2010)

Basic principles

In this study, two different disturbance systems were designed to predict the future distribution of three selected savanna tree species (*Acacia nigrescens*, *Combretum apiculatum*, *Sclerocarya birrea*) in the South African Lowveld. We compared a firewood collection site with a similar site that is under elephant pressure inside the Kruger National Park. With different tree species, adaptive human behavior, and more random elephant behavior, we achieved a better understanding related to looking only for the AGB on a site. Additionally, we compared RCP 4.5 and RCP 8.5 IPCC scenarios (Figure 6.20). We designed all agents as individual entities that sense the environment, their surroundings, as well as other agents with whom they are able to interact.

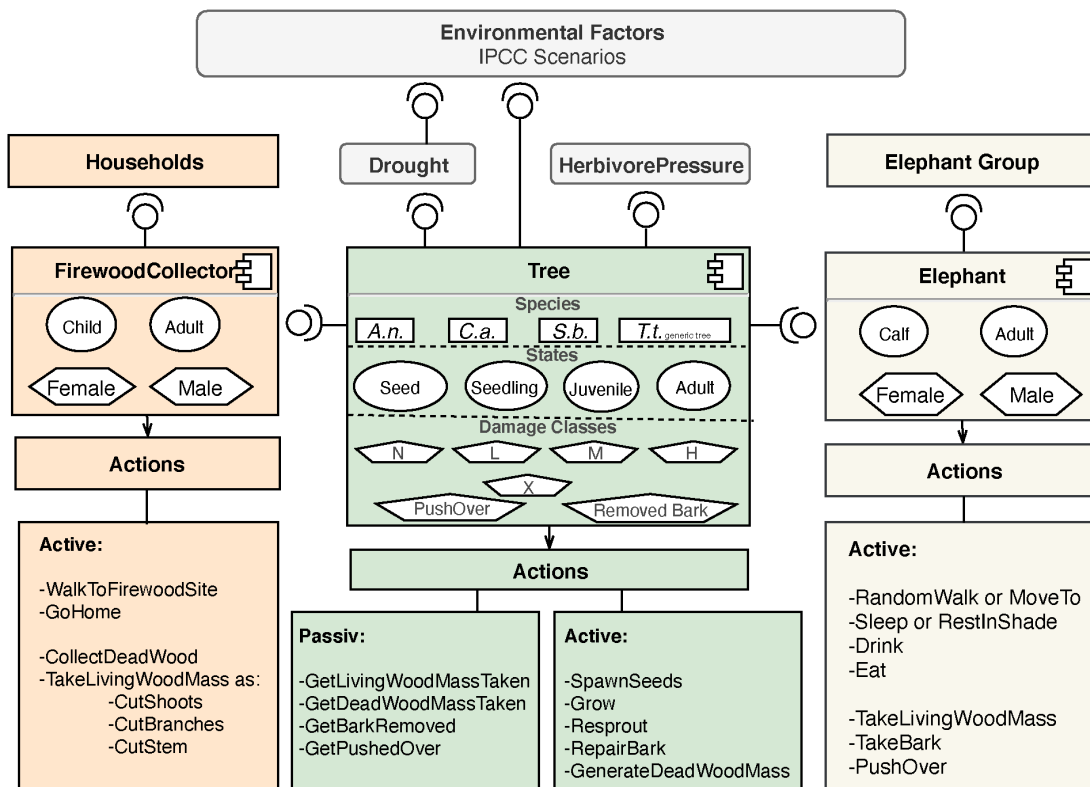


Figure 6.20: Conceptual model

Emergence

Tree: Three tree species and one generic tree are initialized according to literature. They react according to species, state, damage, drought, with different growth to the

different environmental conditions, and disturbances by elephants or firewood collectors.

Elephant: Moves in the KNP after hunger and thirst. In the study site, mainly the interactions with trees are of interest. These actions vary in the annual cycle and during droughts (Figure 6.21).

Firewood collector: Collects firewood according to the needs of the household and tries to collect firewood with as little effort as possible. He can distinguish between the tree species, states, as well as dead wood, shoots, branches, and stem.

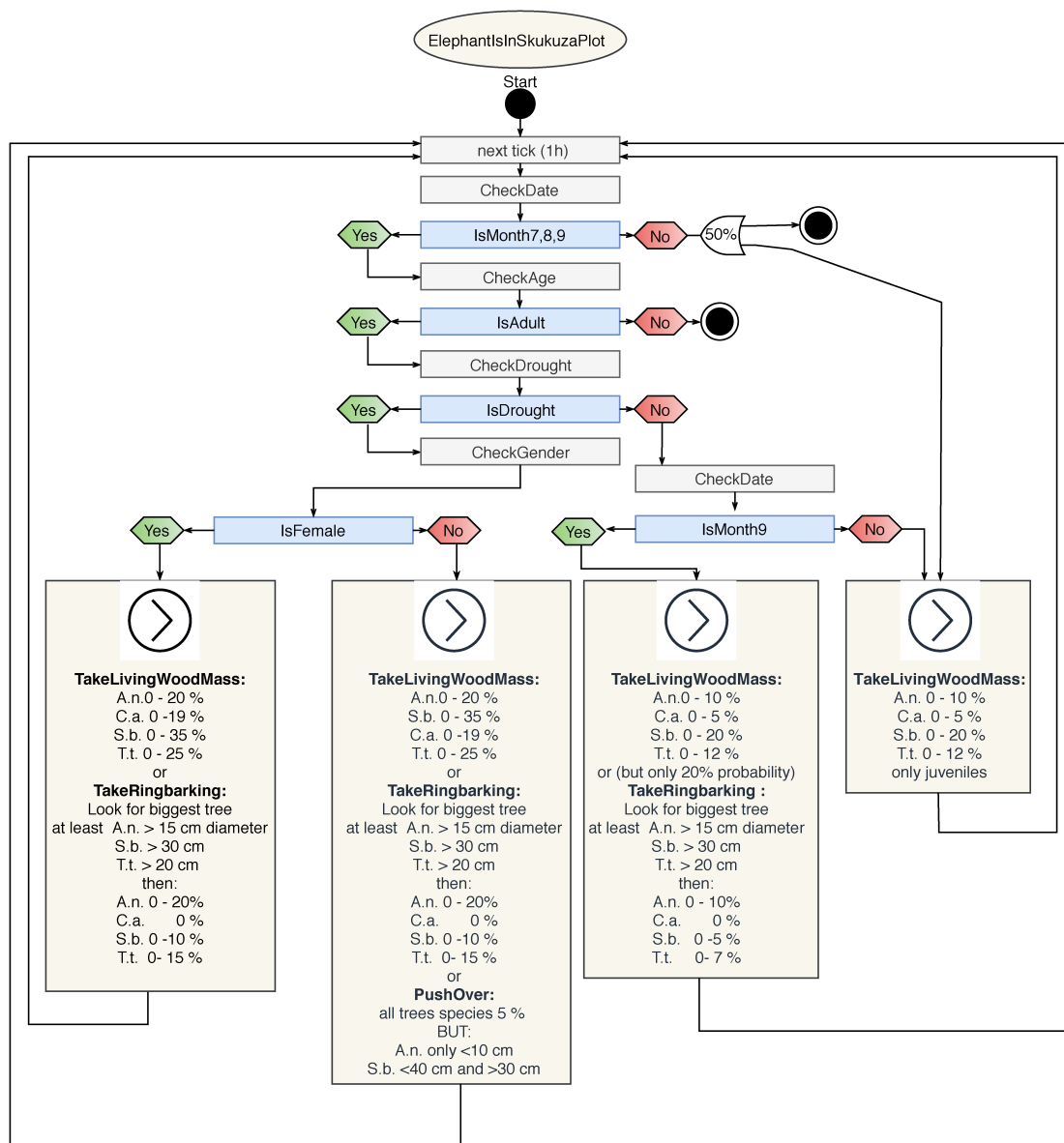


Figure 6.21: Elephant hourly tick routine, inside the SkukuzaPlot

Adaptation

Tree: Depending on the species, they can grow, sprout, and (after reaching a specific size) produce seeds.

Elephant: Movements depend on existing biomass and water holes. The agent type elephant is reproducing better observed behavior patterns. For example, differences in the month with and without grass biomass, droughts and differences in species utilization. Only leading cows and bulls are allowed to plan actions. In order to show the behavior of the herd, selected actions are then executed five times.

Firewood collector: The collection is cost-optimized. Agents attempt to minimize the total effort of movement and wood collection. If the effort is too high, the collection is aborted prematurely. The firewood collectors are modeled with GOAP (goal-oriented action planning). They must collect an amount of firewood with preferences and different costs of collecting them.

Objectives

Tree: Trees have to grow to become adult trees and to spawn seeds.

Elephant: Elephants have to drink water and eat biomass. When they are inside the plot, they can interact with trees (Figure 6.21).

FirewoodCollector: The behavior could be described as a sequence of decisions. GOAP derives from the field of AI (Artificial Intelligence) and integrates adaptive decision-making into multi-agent models. An action might hold a “cost” value, indicating the effort that is necessary for the action to be executed.

The planning algorithm calculates a way of minimal costs to reach the goal. That decision-making architecture allows the agents to adapt their behavior in correspondence to a changing environment.

Each agent keeps an internal state which is represented by a set of properties (attributes). These properties are often described as Boolean predicates that evaluate to true or false. These properties can change over time, influenced by the agent’s inner or outer sensations. A “goal” can be described as a desired state to be reached. When an agent has to collect firewood, e.g., the “HasEnoughFirewood” predicate results in false (“HasEnoughFirewood=false”). The agent might follow his individual goal to change his internal state to “HasEnoughFirewood=true”.

Fitness

Tree: Grow, become adult, and produce seeds.

Elephant: Search for food and water.

Firewood collector: Collect the required amount of firewood.

Learning

Firewood collector: Our experiment showed that the firewood collectors first increased the distance to walk. When firewood is scarce, they collect less firewood. This emergent behavior is a result of the exhausting circumstances.

Prediction

Tree: The tree can grow and has the ability to resprout after cutting but has a passive role apart from that. The tree agent type is corresponding to the RCP 8.5 scenario with a higher seedling survival rate and a growth rate boost of plus 30 %.

Elephant: The amount of interaction of elephants with trees vary according to tree species and increase with drought.

FirewoodCollector: They first collect deadwood and shoots, if the distance or the effort is too high, collection is stopped.

Sensing

All agents can access the environmental layers and their surrounding agents. Firewood collectors and elephants are sensing/know the entire site but look for the nearest tree with the attributes to fulfill the next action. For elephants, there is a random possibility of the fired actions (Figure 6.6).

All agents are located in a geo-referenced system.

Tree: Trees' growth behavior is linked to the climate data coming from the IPCC scenarios and seeds are able to germinate only when there is enough space. Additionally, seeds have to sense precipitation, germinating with the first rainfall. Afterwards, they check if there is any precipitation within the first 12 days after germination to start growing and become a seedling or to die.

Elephant: They can sense the environment and recognize the tree species with all other tree attributes.

FirewoodCollector: They can sense the way between home and firewood sites and they can recognize the tree species and the amount of dead and living wood mass.

Interaction

Tree: Trees get the elephant interactions and the firewood collector interactions.

Elephant: "TakeLivingWoodmass", "TakeRingbarking", "PushOver".

Firewood collector: "TakeDeadwood", "TakeShoots", "TakeLivingwoodMass".

All actions are based on the damages for savanna trees by elephants and firewood collection. The simulation time is 2010 to 2050; tick length is generally one day, except for elephants where there are hourly tick routines.

Stochasticity

Probability equations determinate the likelihood of tree growth and seed production as well as elephant interactions with trees. The firewood collectors plan their actions with GOAP. All probabilities are described in section 6.3.2.1 and summarized in Appendix 6.9.

Collectives

Tree: Trees are individuals and stand only for themselves.

Elephant: Elephants are members of elephant groups; males can be without a group. Therefore, the leading cow and the bull interact with the trees. This behavior is afterwards repeated five times with other trees.

Firewood collector: One firewood collector represents a household of six members; all households are part of Agincourt/SA.

Observation

For model testing, the Graphical User Interface (GUI) facilitated the elephant movement; tree growth and collection behavior were observed with R Version 1.1.463 and the open-source visualization tool Kepler.gl (www.kepler.gl).

Tree: AGB in total per species, species composition, age class (state) composition, damage classes, reason to die, number of juveniles becoming adults and vice versa.

Elephant: Pathway tracking.

Firewood collector: Amount of collected firewood per collection and in total, number and reason of the abort.

6.9 Appendix B

In this Appendix there are additional information of the three agent types.

Agenten type: Tree

Trees are only growing when they have leaves. For this study all trees have leaves from October 1st to March 31st. For the daily tick routine, the total growing in one year is divided in the DaysWithLeavesOn.

Age types by stem diameter in cm

Table 6.6: Age types classification by stem diameter

	A.n.	C.a.	S.b.	T.t.
Seedling	<1	<1	<1	<1
Juvenile	1-8	1-10	1-20	1-13
Adult	>8	>10	>20	>13
Max.	20	20	50	30

Growth rates - juveniles

The max. growth rates (max) per species based on undisturbed average diameter and time span to become an adult tree.

$$A.n. \text{ (stem diameter 1 – 14cm)} \quad x_{inew} = x_i + (-0.068 * x_i + 0.9) \quad (6.1)$$

$$C.a. \text{ (stem diameter 1 – 13cm)} \quad x_{inew} = x_i + (-0.068 * x_i + 1.2) \quad (6.2)$$

$$S.b. \text{ (stem diameter 1 – 19cm)} \quad x_{inew} = x_i + (-0.068 * x_i + 1.9) \quad (6.3)$$

$$T.t. \text{ (stem diameter 1 – 16cm)} \quad x_{inew} = x_i + (-0.068 * x_i + 1.33) \quad (6.4)$$

Growth rates - adults

- **Definition reduceFactor:** The growth rate is reduced by damages. By damage type N the growth rate is maximum; damage type L reduce the growth rate randomly between 0 and 10 %; damage type M reduce the growth rate randomly between 10 and 30 %; damage type H reduce the growth rate randomly between 30 and 60 %. By damage type X the tree falls back into the juvenile state or dies.
- **Definition growthRate:** Because *Combretum apiculatum* grows much slower than *Accacia nigescens* and *Sclerocarya birrea* we integrated a growthRate value. The value is for all species=1, beside Accacia where it is 0.5.
- **Definition MaxStemDiameter (xmax):** The maximum stem diameter differs within the species. For A.n. it is 20 cm; for C.a. it is 20 cm; for S.b. it is 50 cm, and for T.t. it is 30 cm.

$$x_{inew} = (x_i + (1 - \frac{x_i}{x_{max}}) * growthRate / DaysWithLeaves) * reduceFactor \quad (6.5)$$

- **Germination, establishment and needs to become a seedling** Adults spawn 50 seeds per year. Seeds can germinate with the first rain but need space to establish (see Table 6.7). The tick routine for "Tree" in the seedling state, see Figure 6.22.

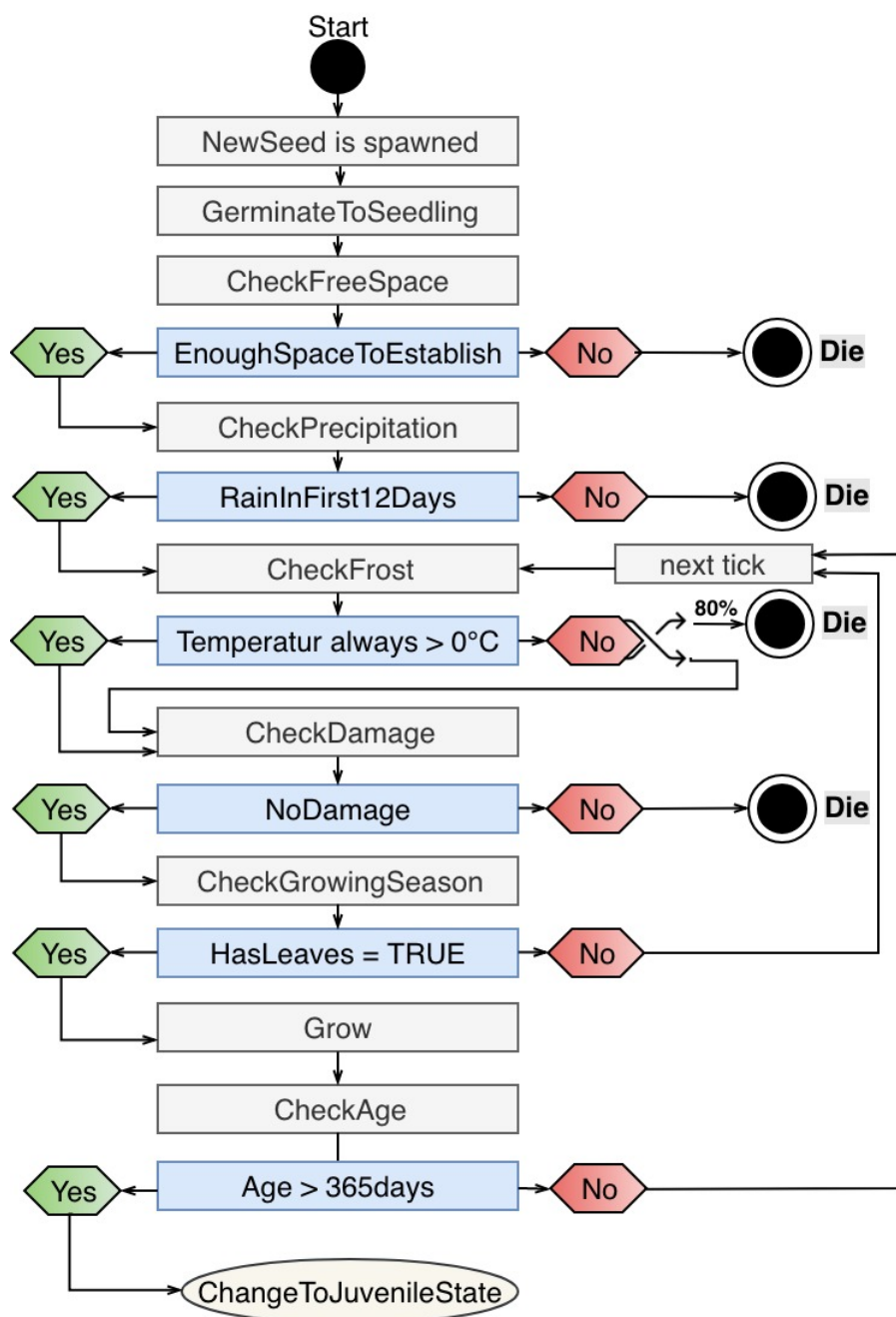


Figure 6.22: Daily tick routine for Tree in seedling state

Table 6.7: Need for space for establishment

Radius (cm) of no establishment when neighbored by	seedling	juvenile	adult
A.n.	4	32	80
C.a.	4	40	80
S.b.	4	80	500
T.t.	4	52	220

Calculation from stem diameter to woody biomass

We calculated the AGB for each species after (Nickless et al. 2011) with *Dried woody biomass in kg = regression coefficient wo for species + regression coefficient w1 ln (stem diameter in cm)*. Dried woody biomass is only 60 % of the AGB so that we modified the formulas by that. For the species the taken formulas are:

$$A.n. (AGB) = \frac{-3.55 + 3.06 * \ln(\text{stem diameter})}{0.6} \quad (6.6)$$

$$C.a. (AGB) = \frac{-3.27 + 2.8 * \ln(\text{stem diameter})}{0.6} \quad (6.7)$$

$$S.b. (AGB) = \frac{-3.35 + 2.62 * \ln(\text{stem diameter})}{0.6} \quad (6.8)$$

$$T.t. (AGB) = \frac{-3.39 + 2.827 * \ln(\text{stem diameter})}{0.6} \quad (6.9)$$

Agenten type: FirewoodCollector

The agent type FirewoodCollector is modeled with goal-oriented action planning (GOAP). To calculate the best sequence of actions there must be a list of actions and costs (Table 6.8).

Table 6.8: Actions and cost for firewood collection

action	cost
CutBranchAn	50
CutBranchCa	50
CutBranchSb	90
CutBranchTt	50
CutShoot	30
CollectDeadWood	10
CarryWoodHome	0
AbortAndGoHome	0
EvaluateAndPackWoodForTransport	0

Agenten type: Elephant

During the dry season and especially in September up to 94 % of the elephant diet is woody biomass (Jacobs and Biggs 2002a). We included the different utilization of trees by elephant from (Campbell 1996; Cook et al. 2005; Gillson 2015; Jacobs and Biggs 2002a; Moncrieff et al. 2008; Shannon et al. 2008).

Table 6.9: Ranking of Elephant interactions

Elephant interactions	
Food preferences	Fresh grass>fresh leaves>twig, bark, roots
Ringbarking (by food/water stress)	A.n.>S.b.>>>C.a.
Push-over (by food/water stress)	Juvenile A.n.>S.b.
No damage	Stem diameter <2cm

Chapter 7

Discussion

This thesis is focused on studying current and potential tree distribution of selected savanna tree species in the South African Lowveld by applying agent-based modeling. To look at tree distributions, it is not enough to examine snapshots of age, size, and spatial tree data. Just as the current distribution is a result of past biotic and abiotic factors, the future distribution will be a result of current and subsequent interactions between species and their environment. Tree populations in savannas are generally driven by disturbances and, therefore, in an ongoing ecological process of re-composition.

In general, there is a strong positive correlation between tree distribution and soil properties, as well as between precipitation and tree distribution in savannas (Sankaran et al. 2005). Still, it is not entirely understood how the patchiness of savannas is created (Archibald et al. 2005; Guo et al. 2018; Meyer et al. 2009, 2007; Moustakas et al. 2009). Additionally, planting experiments (Griffith et al. 2018) shows an even more complex relationship. It seems that each species and each state of these species has different needs (Morrison et al. 2019).

Furthermore, even if trees in smaller areas are measured precisely in the field, the outcome between year, sites, and methods are not homogeneous (Mograbi et al. 2016; Nickless et al. 2011; Odipo et al. 2016; Shannon et al. 2011; Vanak et al. 2012). For example, available data from the Skukuza site of this study is not homogeneous in terms of aboveground biomass. Nickless et al. (2011) measured 20 – 30 t/ha AGB and 260 single tall trees (> 5 m), whereas Odipo et al. (2016) measured 3.1 – 94.3 t/ha AGB and 40 – 50 trees (> 1 m) for the same area. Having these snapshots is, however, indispensable for modeling. They are essential to creating a starting point in human-modified as well as in elephant-dominated, savanna landscapes.

To cover the current and potential distribution of individuals and attributes such as age class differences, survival rates, recruitment pattern, germination success, damages, and mortality risk but also their responses to climate and land-use changes, a multi-scale model approach is needed. Only in ABM, it is possible to include detailed descriptions of heterogeneous individual (agent) behavior, to generate emergent properties, and to handle moving and active agents. Thereby, an agent-based model approach contributes to a better understanding of trees within the savanna ecosystem and makes predictions of future developments possible.

As described in Chapter 4, the initial main goal was to identify representative tree species for the South African Lowveld. Data from nine different sampled savanna sites, including 11 functional traits for five different tree species (Wigley et al. 2016), were examined. The analysis laid out in Chapter 4 revealed three main survival strategies. For each strategy, one representative tree species was chosen.

Acacia nigrescens represents a species investing in the root system to optimize nitrogen-uptake, which is one of the limited elements (Cramer et al. 2010; Holdo and Mack 2014; Hooper and Johnson 1999).

Combretum apiculatum employs a defense strategy. To avoid browsers and damages by natural disturbance, a high concentration of carbon is stored inside leaves, twigs, and other wooden parts (Archibald et al. 2005; Guo et al. 2018; Meyer et al. 2009, 2007; Moustakas et al. 2009). This makes for very high firewood quality.

Sclerocarya birrea stands for a third strategy. The large leaf area in combination with an early green-up in the early vegetation year yields, after a first investment, a high and early photosynthetic rate (Archibald et al. 2005; Guo et al. 2018; Meyer et al. 2009, 2007; Moustakas et al. 2009). This leads to browsers, like elephants, resting in the shade and browsing the first fresh green. Rest and subsequent digestion, in turn, result in better soil conditions for the tree (Fornara and Du Toit 2007). Outside of the protected area, the healthy and delicious fruits are one of the main reasons for protecting the adult trees of *Sclerocarya birrea*.

The modeling purposes of this thesis are to explain the current tree distribution for a deeper understanding of the system, simulate different trajectories of land-use and climate, and predict the future tree distribution in a changing world. Much work is already being done for **tree inventory** (Asner et al. 2016; Helm et al. 2009; Odipo et al. 2016; Scholes et al. 2001; Twine and Holdo 2016), **firewood collection impact** (Matsika et al. 2013b,a; Mograbi et al. 2016, 2015, 2019; Twine and Holdo 2016), **elephant impact** (Gaylard 2015; Helm et al. 2009; Levick and Asner 2013; Shannon et al. 2011; Vanak et al. 2012), and **model application** (Moncrieff et al. 2016; Scheiter and Higgins 2012; Scheiter et al. 2019; Twine and Holdo 2016).

However, the approach described in this thesis is unique in that it compares two similar sites in the Lowveld under different land-use conditions in a micro-simulation for the first time. To develop an ABM, a conceptual model needs to be designed first. A list of concepts belonging to trees in the complex savanna ecosystem must be prioritized by quality to answer the main questions. Modeling is also always a reduction of information.

One aspect of the Anthropocene is that the different land-use conditions are of high importance for the tree distribution (Knitter et al. 2019). Owing to the need for predictions of trees in human-impacted landscapes, this activity must be incorporated into the ABM. Chapter 5 demonstrates that the development of a method to integrate human adaptive behavior during firewood collection is feasible. The transition from small spatial and temporal decisions to an aggregate measure of the impact on landscape is one of the main achievements of this study.

Furthermore, a near-nature landscape must also be considered. Within a protected area, the environment seems to be optimal for tree distribution, and here, elephants as agents of changes in the complex system are shown to be the main concern (Asner and

Levick 2012; Asner et al. 2016; Eckhardt et al. 2000; Helm et al. 2009; Holdo 2006; Jacobs and Biggs 2002a; Levick and Asner 2013; Nellemann et al. 2002; Odipo et al. 2016; Owen-Smith and Chafota 2012; Riginos 2015; Rugemalila et al. 2016; Shannon et al. 2008; Skarpe et al. 2014).

Another aspect is the more indirect anthropogenic influence of global change. This is included in the different scenarios of the modeling approach (Aleman et al. 2016; Blanco et al. 2014; Canelles et al. 2019; Engelbrecht et al. 2015; Keane et al. 2015).

To summarize, the developed ABM from Chapter 6 was applied to geo-referenced trees in two different study sites and with two different climate change input datasets for a timeframe from 2010 – 2050 on a daily time step. Because of the massive amount of data, applying a comprehensive method of data reduction and creating a summarized visualization was also part of this study.

7.1 Answering the Research Questions

The key achievements of this thesis summarized in Section 7 aimed to contribute to answering the three main research questions underpinning the entire text.

RQ 1 Which conceptual components are best to model with the multi-variant savanna system as accurately as possible to get answers about current and potential tree distribution?

The main components for ABM are agents and an environment build by different layers (Hüning et al. 2016). However, the concepts to be included in the model must first be defined. Throughout the modeling workflow, the research question is the leading process. The initial question in Chapter 4 was what distinguishes the tree species in savanna landscapes from each other. Trees are driven mainly by tree-grass competition and disturbances like fire, browsers, or droughts. Nevertheless, even after more than 100 years of research, the complexity of these interactions is still not completely understood (Calabrese et al. 2010; Colgan et al. 2012; Moustakas et al. 2013; Osborne et al. 2018; Scholes and Walker 1993; Scholtz et al. 2014; Shackleton 2001; Witkowski and Garner 2000).

Due to this limited knowledge, the idea for this thesis was to resort to existing data to develop an agent-based model. The advantage of starting with an existing data set was that the data collection had no relation to this study. All data items were statistically validated and analyzed for the original research (Wigley et al. 2016). By applying the mathematical partial order (PO) theory to the data set, new insights emerged even from analyzed research with the same research focus. On the other hand, it should be noted that a different data set might have led to a different outcome and, consequently, to a different model for answering the main research question of this thesis.

However, by applying PO with a Hasse diagram (HD) visualization, the main components must reveal the different survival strategies of the selected tree species. The central disturbances are human-driven firewood collection in the rural area and elephant damages inside the KNP. These three components are the agent types in the

model: “Tree”, “FirewoodCollector”, and “Elephant”. The primary agent type “Tree” has four subtypes (A.n., C.a., S.b., T.t.). An autonomous block of code contains each agent’s geo-referenced coordinates as well as a set of attributes. Therefore, each agent can sense, reason, and interact with all other agents and the environment. Different layers make up the environment. Various climate scenarios are simulated mainly by a temperature and precipitation time-series layer along with a drought layer to organize the specific thresholds during droughts. In summary, the main achievement of this phase of conceptualization was the formal definition of agents and the environment based on existing data (see Chapter 4).

The next step was to determine the right number of agents and the range of the environment as well as the granularity and duration of the simulation (Linkov et al. 2014). However, these decisions were to be made in the modeling process. The development process of an ABM is typically too agile to be feasibly realizable in a strict step-by-step evolution. This applies to model creation, simulation, and analysis. The dynamic nature of development might be a reason why there is no literature on how to build an ABM. A second focus was the integration of adaptable human behavior under changing conditions within the agent type “FirewoodCollector”. This resulted in the following RQ 2.

RQ 2 Is it possible to include adaptable human behavior in an agent-based model to simulate different preferences and efforts in collecting various kinds of firewood?

One advantage of ABM is that each agent has its own identity built by attributes, thresholds, and rules. During each time step, every single agent steps through its decision tree within the sense-reason-act method to decide what has to happen next (Dalski et al. 2017). For example, on a hot day and when an elephant agent’s water saturation drops below a certain threshold, the agent must move to the next water body to drink. In order to make that assessment, the environment is sensed at each time step to determine the next set of actions.

Human behavior is very often more goal-oriented. Mograbi et al. (2015) observed that firewood demand is not a linear system, and people can respond to their socio-economic and natural resource environment. These responses include, for example, switching preferred species, more frequent trips or more time spent per trip, traveling farther, using vehicles, organizing firewood markets, and collecting in the neighborhood. All these strategies are single decisions on a local scale, but in total, have a strong influence on a regional scale.

There are always one or more goals to fulfill, which requires planning. That is particularly valid if environmental factors like weather conditions change or a reprioritization of current tasks occurs during tick execution. Each planning step is centered around one or more goals that must be reached in the future. Here, goal-oriented action planning (GOAP) was a suitable way to model adaptable human behavior. The main goal for the firewood collectors was to bring home a required amount of firewood. To reach that goal, the costs of several actions had to be calculated to find the cost-optimized way to reach the goal (see Chapter 5). The behavior realized here

is still very limited, since the focus of this work was on trees. To understand firewood harvesting and find regularities to sustain the activities, a much more complex system would have to be developed.

Next steps might include giving the “FirewoodCollector” more variables (for example, money, firewood to buy, different energy sources, more complex household structures) and flexibility (for example, daily actions with time and cost factors) to get a more realistic behavior. Applications of technical innovation, such as renewable energy or other new technologies, might also be factored into the model.

However, it should be noted that there is always the risk of overfitting a model (Gotts et al. 2019). On the one hand, defining too many parameters might complicate a correct calibration of the model; on the other hand, computational power is limited. The performance grows exponentially with the number of possible actions (Hart et al. 1968). Within the constraints of the present study, the research question can be answered with: “Yes, at least in a basic way”. Gotts et al. (2019) have shown that human behavior and decision-making in models need additional knowledge about psychology and social sciences. Nonetheless, an enhanced, complex, and adaptable GOAP model will also need technical solutions in the fields of AI and computer sciences.

The applications made possible by this approach are broad. For instance, it might be particularly interesting to examine which combination of behavior, alternative energy sources, money, tools like wheelbarrows, and other factors can lead to more sustainable harvesting of resources and which specific areas make for high potential for conflict. Another question not studied is how large an area must be for the effects of random and planned behavior to differ. In summary, it can also be stated if there is not enough wood for sustainable harvesting, there is no model or planning algorithm to solve this dilemma.

The main focus of this thesis was on answering different aspects of the following question.

RQ 3 How do different tree species evolve in different land-use and under two extreme IPCC climate scenarios?

This research question is answered mainly in Chapter 6. Here, the findings of Chapter 6 are discussed in a broader context to include all aspects of this thesis. One of the key strengths of ABM is that every single agent runs through the simulation independently and can be tracked. In order to handle the data volume, the daily tick output (14,600 timesteps result in 14,600 data outputs for 500,000 single trees) was summarized for one vegetation year (October to September) at a time. At the same time, all trees of one species are summarized either by species, within species, or by age groups. Each Tree, Elephant, and FirewoodCollector has its ID and can also be viewed individually for further investigation.

The generic tree (T.t.) is a tree agent with generic attribute values within an average range. These trees fill up the landscape to get a realistic stock of trees for firewood collectors and elephants to interact with. All 500,000 trees are of interest regarding the total amount of AGB, the development of the number of trees, and any overall trends. The main interest was on the three selected tree species regarding AGB, the

number of trees, age class distribution, and damage class distribution. The first focus of Chapter 6 and RQ 3 was the comparison between the human-modified rural area “BushbuckridgePlot” and the near-nature site “SkukuzaPlot” inside the conservation area of the KNP.

Particular attention must be paid to the fact that of the two sites, each had different initial conditions. The rural area had, on average, a total amount of AGB by 10 t/ha with 4,508 individual trees per hectare, including 48 adult and 844 juvenile trees (Mograbi et al. 2015). With only 2 % of the total amount being accounted for by the three species studied, there are only 10 A.n., 165 C.a., and 111 S.b. per hectare compared to 4,222 generic trees (Twine and Holdo 2016).

Within the KNP, the total amount of initial AGB was 23 t/ha (Nickless et al. 2011; Odipo et al. 2016). That resulted in 6,554 individual trees, including 80 adult and 997 juvenile trees (Odipo et al. 2016; Shannon et al. 2008), to be initialized. Here, 67 % of all trees were of the studied species. Hence, for the initialization of both models, a variety of data objects had to be considered.

Nevertheless, even at simulation onset in 2010, AGB in the rural area was noticeably reduced. The findings described in Chapter 6 still show a dramatic decrease in the total amount of biomass with a high number of trees. However, while the first years (see Figure 6.8) are stable, there is a trend towards a higher number of thinner trees and fewer adult trees (see Figure 6.11). Although with a different model set (for example, more collectible trees, a bigger site, or fewer firewood collectors), this trend leads to problems in the future. A sustainable tree distribution requires a stable AGB along with a healthy age distribution structure.

Inside the park, the modeled system is driven by elephants. These interactions represent only one part of the complexity of a healthy savanna system, which leads to very different results regarding the presence or absence of elephants (especially in the first simulation years). In a way, this represents the truth of elephant damaging. It is less a question of how many elephants are within the park and more about where they are and what they are doing (Gaylard 2015). As a result, more woody areas are partly opened by elephants. These creatures are important landscape architects (Asner and Levick 2012; Levick and Asner 2013; Scholtz et al. 2014). In a changing world with fewer healthy mature trees, elephants must be managed so that some (mainly adult) trees are protected against high damages to assure that there is a seed bank to produce new generations.

The results of Chapter 6 summarized for the selected tree species are:

- ***Acacia nigrescens***, with its investment in the root system, is not represented sufficiently at the Bushbuckridge site. Inside the Skukuza site, the population seemed to have been stable over the next 40 years.
- ***Combretum apiculatum***, with the high content of carbon as a defense strategy against browsers, showed different result for the two sites: a decreasing population in Bushbuckridge because of the high quality of firewood, and an increasing number of mainly juvenile trees inside the park.

- *Sclerocarya birrea* is a very special tree because of its investment in healthy and palatable leaves and fruits. In the rural areas, especially the healthy fruits and the popular Marula beer derived from them are essential (Shackleton 2002). Therefore, there is a cultural agreement to protect these trees. Regardless, the model output showed that if the demand for firewood can no longer be met in any other way, these trees will also be felled. Here, discussions with experts on whether this is because of the model design or because there are first signs for a behavior change are needed.

Inside the KNP, the S.b. is very attractive to elephants. Leaves, twigs, branches, bark, and roots are very often taken by elephants. Therefore, it is difficult to find an undamaged Marula tree inside the KNP. Nevertheless, an elephant push-over of an adult tree is only possible if the tree is already weakened.

On the landscape scale, two general trends have emerged:

- **Significant trend towards more and thinner trees**
After a decline of AGB in the rural area, firewood collectors damaged trees more heavily and more frequently. That leads to trees with a small stem diameter, which in turn leads to more damages. However, providing more patches for firewood collection would result in a completely different picture. Even when AGB has dramatically decreased, there are still many very thin trees left. A temporary halt to firewood collection might be enough for the site to recover. This trend can also be seen within the KNP. Here, elephants damage adult trees more quickly than young trees can grow. Therefore, very few trees manage to reach the adult state. Hence, the **loss of mature trees** is also observable.
- **An increase of young *Combretum apiculatum* inside the KNP**
Inside conservation areas, some trends can destabilize the ecosystem. An increasing number of young C.a. is mostly driving the total amount of AGB (see Figure 6.12). This tree species, with its defense strategy, is optimally equipped against damages by browsers. Additionally, *Combretum apiculatum* can easily resprout after disturbances, is usually multi-stemmed, and grows in larger groups (Grant and Thomas 2006). An increasing number of these trees results in dense vegetation, or so-called bush encroachment (O'Connor and Page 2014; Stevens et al. 2017; Umer et al. 2010). A high rate of bush encroachment means large areas with dense vegetation, less grass, and, therefore, less desirable vegetation for animals. The benefits of ABM are evident here by highlighting findings at the individual and species level with consequences on the landscape level.

The second focus of Chapter 6 in answering RQ 3 is on the comparison of current and potential tree distributions in a moderate versus an extreme climate scenario. The findings did not reveal any significant differences in the results. One explanation could be that the examined tree species are slow responders to climate change. All of them are well adapted to droughts, disturbances, and extreme events. Nevertheless, changing precipitation patterns will affect tree species differently. Marula (S.b.), as an early-flushing tree, needs rain to establish fresh leaves. By shifting the rain patterns, these trees must drop down their leaves and re-flush again after the first rain.

Another reason can be found in the climate scenario data sets. In this study, the main differences in precipitation and temperature became noticeable only in later years. However, a correlation between the development of the AGB and the years of droughts is observable (Druce et al. 2008; Liedloff and Cook 2007). Within the model, there is a fixed threshold of 65 % of the average precipitation, which changes the seedling and juvenile mortality and the growth rate (see Table 6.5). It should be noted that there are other definitions for droughts. Other values would have led to different results in this model. However, as mentioned before, even the moderate climate scenario shows significant changes.

In addition to the research questions addressed in this thesis, there will be many further essential research priorities in the future. For example, the inclusion of fire in the modeled environment would allow for reductions in biomass, seedling, and juveniles more dynamically. Besides, topics like invasive species, elephant management, and further integration of indigenous knowledge about sustainable wood harvesting will be integrated.

7.2 Consequences of the Findings

In general, models are useful simplifications to explain, to understand, and to make predictions. Because of those simplifications, each model must deal with uncertainties and limitations. Uncertainties and the resulting limited validation lead to a wide-open prediction corridor. On the other hand, adaptive management of complex systems like savannas needs indicators to decide if tendencies could lead to irreversible consequences, at an early state. Only simulation models can predict future impacts of present indicators, even when there are uncertainties. It must also be considered that there will be some delay between decision and management actions because of the time it takes to make things happen (Scholes and Kruger 2011).

This thesis was developed in the context of stakeholder involvement for the Bushbuckridge Municipality and the SANParks management. On the one hand, this implies more system knowledge, data, and insights, and with that more acceptance. On the other hand, this leads to different viewpoints and requirements of these diverse stakeholder groups.

Overall, the model results indicate that the savanna system is becoming more vulnerable. Additionally, the climate projection for the region is highlighting more extreme events, generally drier landscapes, more heat-wave events, more intense thunderstorms, and a temperature increase twice the global rate (Archer et al. 2018). Bush encroachment, as well as a loss of mature trees, will lead to more significant effects.

Bush encroachment or simply more shrub will lead to areas that are not reachable for browsers (Bunting et al. 2016). If these areas are not opened up again, a critical food source will remain unavailable for many grazers and browsers. Especially in drought years, food is much more critical than the amount of water for most animals (I. Smit (SANParks Scientific Service), *pers comm.*).

Each **loss of an adult tree** in an ecosystem with only some scattered trees has a significant impact on the system beyond the potential of species loss because of the

lack of new trees. In a healthy and complex system, each part has secure connections to many other parts. For example, the loss of mature Marula (S.b.) trees implies the loss of food for, among others, elephants, baboons, squirrels, impalas, insects, and the loss of shade, shelter, and nesting possibilities, e.g., the Southern Ground-Hornbill (*Bucorvus leadbeateri*), an endangered species. These cascading effects lead from the loss of a mature tree to a vulnerable ecosystem and eventually to reduced resilience of the entire savanna system (Kutsch et al. 2001; Van de Leemput et al. 2018).

These results might open new management options, like an expansion of buffer and exclusion zones or protection of single mature trees, for **SANParks management**. Further requirements for the simulation will be more scenarios with different elephant management strategies (SANparks 2018), together with an integrated fire layer. Another aspect will be invertebrate outbreaks in combination with extreme weather events.

For the **Bushbuckridge Local Municipality Stakeholders**, the most important topic is to define adaptation and mitigation strategies for climate change, conflict zones, and species shifts (Mukuyu 2018). In particular, land degradation in rural areas can lead to the loss of at least parts of this unique landscape. Additionally, the increase of extreme weather events has a broad range of potential changes, especially for rural areas.

Nevertheless, the results of this study need to be verified for several aspects. One focus is to minimize the uncertainties to provide better predictor sets in terms of accuracy and resolution. For the current tree distribution, it would be an option to include LiDAR data, and with that correctly measured tree data for the initialization.

The stable number of elephants inside the KNP is only one of the management options. So far, the numbers are increasing (Henley and Cook 2019). In forthcoming simulations, the number of elephants must be much higher to observe the impact on tree distributions.

The data on firewood collection are sampled in the municipality by questionnaires (Statistics South Africa 2016). Currently, there seems to be a new trend, mainly driven by monetary input, to substitute firewood as the primary energy resource, which must be included in the model. In a way, this is typical worldwide for positive developments out of the poorest conditions (Rosling et al. 2018). As mentioned before, money and more energy options will be included in the next model for Bushbuckridge.

In summary, forecasting the tree distribution of tomorrow can show risks to biodiversity at the species and community level. The model output quantified how different land-use and climate risk will change the distribution of selected tree species.

Chapter 8

Conclusion

This thesis presents an agent-based tree modeling approach that combines academic knowledge and tree distribution data from the South African Lowveld. The future of trees in savannas is of high importance, and modeling these ecosystems requires precise spatial knowledge about species and their age distribution on the landscape level.

The results show that the tree model is well adaptable to different tree species and land-use areas. The transferability of the approach to other tree species results from the conceptual design of the generic tree agent. Based on the generic tree agent, each tree species and its age states have different rules to cover needs, growth characteristics, and survival strategies. The same tree agents are used for modeling interactions between firewood collectors and trees in the rural areas near the Kruger National Park and interactions between elephants and trees inside the park.

As a result of modeling more than 500,000 single trees in the two land-use areas of the South African savanna and forecasting to 2050, this thesis predicts significant changes in future tree distribution. Not only will the age distribution change towards younger and thinner, and fewer adult trees. A species shift towards *Combretum apiculatum* is detectable within the three tree species as well. The loss of mature trees in a system of scattered trees, as well as a significant trend towards bush encroachment, will harm the resilience of this unique bi-stable ecosystem.

Therefore, this thesis contributes to an increase of knowledge in species composition and age distribution on a varying spatial and temporal scale. By creating a model with geo-referenced tree agents in two land-use types and under two climate scenarios, a realistic representation of the time frame from 2010 to 2020 was achieved, which can count as a form of validation. Modeling individual trees provided more insight than aggregating biomass.

This thesis, thereby, increased an innovative modeling tool set that allows the analysis of interactions between social, ecological, and economic systems. Moreover, it provides a methodological option for the conceptualization of an agent-based model. By applying methods of partial order theory, the essential concepts become apparent. This could be useful in identifying main agent types (as was done in this study) or essential parts of the environment. At the same time, it can cluster data, potentially leading to a reduction of complexity within the conceptual model. Simultaneously, AI

methods to model adaptable human behavior was integrated and applied to ABM in a new way.

These two proposed concepts seem especially useful for forecasting tree distribution in savanna ecosystems in the presence of changes in land-use, climate, the population, technical innovation, and economic drivers. However, in a changing world, the conditions for natural recruitment and re-growth of mature trees have become critical. Therefore, practitioners should consider continuing and strengthening efforts to protect single trees within the landscape and create buffer zones with undisturbed patches of vegetation, including keystone species. The results also show that acting rapidly would have a major positive impact. In the field of social-ecological modeling, one aim is to support local decision-makers in coping with the challenges of environmental and societal changes.

In addition to the research questions addressed in this thesis, further research will be conducted. Future work will, on the one hand, enhance the model complexity and, on the other hand, prepare models for policy and decision-making to translate different scenarios into beneficial actions for nature and human well-being. To this end, ABM allows the option of replacing and supplementing all parts of the model as needed.

Additionally, the interaction of other animals with trees needs to be investigated. Mainly, other browsers but also pollinators and key seed dispersal agents must be focused on in future research. A fire layer and a more complex human adaptable behavior should also be incorporated. Similarly, the various environmental processes, together with more detailed climate data, must be enhanced.

Local communities have a long tradition of conservation and sustainable resource use. They also have an invaluable amount of indigenous knowledge (see e.g., Figures 1.4), which regrettably, is not fully included in this thesis. To support decision-makers and stakeholders in the region, not only the research outcome has to be discussed. In a next step, this source of knowledge has to be incorporated as well. In general, there is and must be the awareness of species loss, invasive plants, bush encroachment, over-harvesting, as well as a loss of indigenous knowledge. For this purpose, it is crucial to work with local communities as well as the SANParks (South African National Parks) management. Long-term projects can increase not only knowledge but also trust, responsibility, and the amount of time spent on site. The results of this thesis is directly transferred into stakeholder workshops (see Figure 8.1) in the modeled region. Here, the output for different “if-then”-scenarios must be fast and concretely supportive, like a traffic light system for different options.

Lastly, it should be noted that agent-based model comparisons can investigate interactions between trees, climate change, management decisions, and social-economic aspects of land-use. It is important to stress that all modeled outcomes of current and potential tree distribution presented in this thesis apply primarily to the savanna type Granite Lowveld. In the next steps, its underlying methodology will be adapted to other African landscapes.



Figure 8.1: Stakeholder Meeting, March 2020, Wits Rural Facility, SA.

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Declaration of Authorship / Eidesstattliche Erklärung

Hiermit erkläre ich an Eides statt, dass ich die vorliegende Dissertation, abgesehen von der Beratung durch meine Betreuer, nach Inhalt und Form selbständig verfasst habe und keine weiteren Quellen und Hilfsmittel als die hier angegebenen verwendet habe. Diese Arbeit hat weder ganz noch in Teilen bereits an anderer Stelle im Rahmen eines Prüfungsverfahrens vorgelegen. Als kumulative Dissertation sind Kapitel 4 und 5 wie zu Beginn der Kapitel vermerkt in den genannten Zeitschriften veröffentlicht, sowie Kapitel 6 wie zu Beginn des Kapitels vermerkt in der genannten Zeitschrift submittiert. Ich erkläre, dass die vorliegende Arbeit unter Einhaltung der Regeln guter wissenschaftlicher Praxis der Deutschen Forschungsgemeinschaft entstanden ist. Weiterhin versichere ich hiermit, dass mir bisher kein akademischer Grad entzogen wurde.

Norderstedt, den 05.05.2020

(Ulfia A. Lenfers)