Modelling, management and restoration of savannas in southern Africa

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Abstract

Context - Bush encroachment has been observed in southern African savannas for several decades. This form of land degradation reduces the abundance of (palatable) grass biomass on farms, which in turn can support less livestock sustainably. A reduction in livestock usually results in lower income or less food for farmers and can therefore threaten livelihoods. The vegetation dynamics of savannas are complex and multifactorially interconnected. Spatially explicit, process-oriented rangeland models are ideal tools to study these complex vegetation dynamics and the phenomenon of bush encroachment. These models can aid in optimizing management to reduce bush encroachment and give guidance to focus future research on the most relevant factors influencing vegetation processes and bush encroachment in savannas.

Objectives - This dissertation aims to identify and examine the key factors that can cause and influence the emergence and expansion of bush encroachment in southern African savannas. To this end, we incorporated potentially important factors and processes in a simulation model to study their impact on bush encroachment and to be able to test different environmental and management scenarios with a focus on realistic vegetation dynamics and livestock management.

Methods - To identify the potentially most important environmental and management factors that influence the vegetation dynamics of bush encroachment, we interviewed farmers and stakeholders, held workshops and had discussions with scientists and leading experts in the field. Through programming a landscape generator (PioLaG) and a process-oriented rangeland simulation model (Midessa), we gained the ability to set these influential factors and processes in relation to another and to observe and test their cause-and-effect relationship in terms of the impact on vegetation type distribution and livestock condition.

Results - The most important factors that determine the current state of savanna rangelands are heterogeneous precipitation patterns, soil moisture, vegetation competition and succession, fire events, seed availability, grazing and browsing, wood reduction by firewood removal or through arboricides, as well as other management factors such as livestock type and stocking density, type and characteristics of the grazing system, and farmer back-up plans for drought periods. Simulation results showed that introducing browsers and/or mixed feeders to a farm will greatly slow down bush encroachment. A grazer/browser mix thus seems to be a promising approach for a non-chemical management tool against bush encroachment. Careful and adaptive farming strategies including a sophisticated rotational grazing system, will improve vegetation conditions for livestock. Reducing the livestock density on a farm has also been found to slow down bush encroachment and delay the decline of livestock condition. From a modelling perspective, an interesting observation was that spatially heterogeneous distributed precipitation had a major impact on simulation results and led to a more realistic clustering of vegetation types. Ecologically, there were many fluctuations of vegetation types with this type of precipitation. Therefore, bare soil was often present under spatially heterogeneous rainfall, which is not beneficial for livestock as it contains no palatable biomass and thus leads to a faster decline of livestock condition.

Conclusions - Using the realistic rangeland model Midessa in combination with the landscape generator PioLaG and information gained from the farmer interviews proved to be a useful tool to understand the vegetation dynamics in southern African savannas, especially the phenomenon of bush encroachment. We could identify a multitude of various processes that interact on different spatial and temporal scales with varying importance depending on the environmental and historical circumstances at the place and time that was studied. By testing and comparing different environmental and farm management scenarios, we gained insights into the complex savanna system and found clues as to how bush encroachment can be counteracted and how the livelihoods of farmers in African savannas can be secured in the long term.

Keywords: bush encroachment, degradation, savanna rangeland simulation model, piosphere landscape generator, decision support system, process-oriented multi-scale modelling

Zusammenfassung

Hintergrund - Seit mehreren Dekaden lässt sich in den Savannen des südlichen Afrikas das voranschreitende Phänomen der Verbuschung beobachten. Diese Form der Landdegradation führt zu einer Verringerung der (essbaren) Grasbiomasse auf den Farmen und somit auch zu einer Verringerung der Viehzahlen die nachhaltig auf der Farm gehalten werden können. Ein Rückgang des Viehbestands führt in der Regel zu einem geringeren Einkommen oder zu weniger Nahrungsmitteln für die Landwirte und kann daher deren Existenzgrundlage bedrohen. Die Vegetationsdynamik von Savannen ist komplex und durch viele vernetzte Faktoren beeinflusst. Räumlich explizite, prozess-orientierte Weide-Simulationsmodelle sind ideale Instrumente, um diese komplexen Vegetationsdynamiken und das Phänomen der Verbuschung zu untersuchen. Weide-Simulationsmodelle können dazu beitragen, Bewirtschaftungsentscheidungen dahingehend zu optimieren, dass einer Verbuschung entgegengewirkt, oder sie sogar zurückgedrängt wird. Diese Modelle können außerdem als Orientierungshilfe dienen, um zukünftige Forschungen auf die wichtigsten Faktoren zu konzentrieren, die die Vegetationsprozesse und die Verbuschung in Savannen beeinflussen.

Ziele - Ziel dieser Dissertation war es, die Haupteinflussfaktoren, die das Auftreten und die Ausbreitung von Verbuschung in den Savannen des südlichen Afrikas verursachen und beeinflussen können, zu identifizieren und weitergehend zu untersuchen. Ein weiteres Ziel war es, diese Faktoren und Prozesse in ein Simulationsmodell zu integrieren, um ihre Auswirkungen auf das Savannensystem, mit einem Fokus auf realistische Vegetationsdynamik und Weidemanagement, genauer zu beleuchten und verschiedene Umwelt- und Bewirtschaftungsszenarien zu testen und zu vergleichen.

Methoden - Um die wichtigsten Umwelt- und Managementfaktoren zu ermitteln, die die Vegetations- und Verbuschungsdynamik beeinflussen, wurden, im Rahmen dieser Arbeit, Farmer und Stakeholder interviewt, Workshops veranstaltet und Gespräche mit Wissenschaftlern und führenden Experten auf diesem Gebiet geführt. Durch die Programmierung des Piosphären-Landschaftsgenerators (PioLaG) und des prozess-orientierten Weide-Simulationsmodells (Midessa) wurde die Möglichkeit geschaffen, relevante Einflussfaktoren und Prozesse miteinander zu verknüpfen und ihre Ursache-Wirkungs-Beziehungen im Hinblick auf die Auswirkungen auf die Vegetationsdynamik und den Zustand des Viehbestands zu untersuchen und zu testen.

Ergebnisse – Die wichtigsten Faktoren, die den Zustand von Savannen bestimmen, sind heterogene Niederschlagsmuster, Bodenfeuchtigkeit, Vegetationskonkurrenz und -sukzession, Feuerereignisse, Saatgutverfügbarkeit, Grasen und Verbiss, eine Reduktion der hölzernen Vegetation durch Brennholzentnahme oder durch Arborizide sowie andere Bewirtschaftungsfaktoren wie

Nutztierarten und deren Besatzdichte, Art und Umsetzung des Weidesystems sowie das Management während Trockenperioden. Die Simulationsergebnisse haben gezeigt, dass die Einführung von Selektierern (Wiederkäuer, die sich überwiegend durch rohfaserarme Nahrung, wie Knospen, Blättern oder Zweigen ernähren) und/oder intermediären Fresstypen in einem Betrieb die Verbuschung stark verlangsamen kann. Eine Mischung aus Selektierern und Gras- und Raufutterfressern scheint daher ein vielversprechender Ansatz für ein nicht-chemisches Instrument gegen Verbuschung zu sein. Nachhaltige und angepasste Bewirtschaftungsstrategien, einschließlich eines durchdachten Rotationsweidesystems, verbessern die Vegetationsbedingungen für das Vieh. Es hat sich auch gezeigt, dass eine Verringerung der Besatzdichte auf einer Farm Verbuschung verlangsamen kann und eine Verschlechterung des Zustands des Viehbestands verzögert. Aus Modellierungssicht konnte insbesondere festgestellt werden, dass räumlich heterogen verteilte Niederschläge einen großen Einfluss auf die Simulationsergebnisse hatten und zu einer realistischeren Verbreitung der Vegetationstypen führten. Allerdings schwankten bei dieser Art von Niederschlag die Vegetationstypen stark. Dies hatte zur Folge, dass der Boden oft kahl war. Da die Nutztiere dann keine essbare Biomasse finden können, verschlechtert sich der Zustand des Viehbestandes schnell.

Schlussfolgerungen - Die Verwendung des realistischen Weide-Simulationsmodells Midessa in Kombination mit dem Landschaftsgenerator PioLaG und den aus den Befragungen der Landwirte gewonnenen Informationen erwies sich als nützliches Instrument zum Verständnis der Vegetationsdynamik, insbesondere des Phänomens der Verbuschung, der Savannen des südlichen Afrikas. Wir konnten eine Vielzahl von Prozessen identifizieren, die auf unterschiedlichen räumlichen und zeitlichen Skalen interagieren und je nach den ökologischen und historischen Gegebenheiten an dem untersuchten Ort und zu der untersuchten Zeit von unterschiedlicher Bedeutung sind. Durch die Simulationen und den Vergleich verschiedener Umwelt- und Bewirtschaftungsszenarien konnten wir Einblicke in das komplexe Vegetationssystem von Savannen gewinnen und Anhaltspunkte finden, wie Verbuschung entgegengewirkt kann und somit die Lebensgrundlagen der Farmer in den afrikanischen Savannen langfristig gesichert werden können.

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Abbreviations

cf.	*confer*
i.a.	*inter alia*
i.e.	*id est*
LSU	large stock unit
MAP	mean annual precipitation
MIDESSA	dynamic, multi-functional rangeland model for the simulation of cross-scale vegetation dynamics in space and time for an integrative decision support system for sustainable rangeland management in southern African savannas
ODD	Overview, Design concepts and Details protocol
PioLaG	Piosphere Landscape Generator
SD	standard deviation

1 General introduction

1.1 Savannas

The savanna biome (Fig. 1) is an economically and socially important ecosystem that covers approximately 20 % of the world's land surface (Scholes and Walker 1993; Scholes and Archer 1997; Sankaran et al. 2005; Lehmann et al. 2011). Savannas are a characteristic landscape covered by grasses coexisting with woody vegetation (Scholes and Archer 1997). The landscape consists of a dynamic mosaic of patches in varying degrees of co-dominance between the grassy and woody components (Gillson 2004; Wiegand et al. 2006; Meyer et al. 2009). Many different factors determine the current state of the savanna patches, such as the heterogeneous precipitation patterns, soil moisture, fire, grazing and browsing, soil type and depth, vegetation competition, removal of wood (as fire wood or via arboricides to increase abundance of grasses), nutrient availability, and others (Scholes and Archer 1997). The woody vegetation occurs naturally scattered and in low abundance in a grass matrix in arid and semi-arid savannas. The woody vegetation generally increases linearly in abundance with mean annual precipitation (MAP) up to a MAP of 650 mm but only rarely reaches its maximum potential due to frequent disturbances (Sankaran et al. 2005). Different interacting factors such as overgrazing can decrease the competitiveness of the grass layer and are likely one of the causes that have led to increasing shrub-encroachment (O'Connor et al. 2014; Luvuno et al. 2018; Axelsson and Hanan 2018). This increased density of woody species, replacing nutritious fodder plants, can lead to an economic and ecological degradation of savannas and threaten the income and livelihood of farmers (Kong et al. 2014; Smit and Prins 2015; Ayalew and Mulualem 2018).

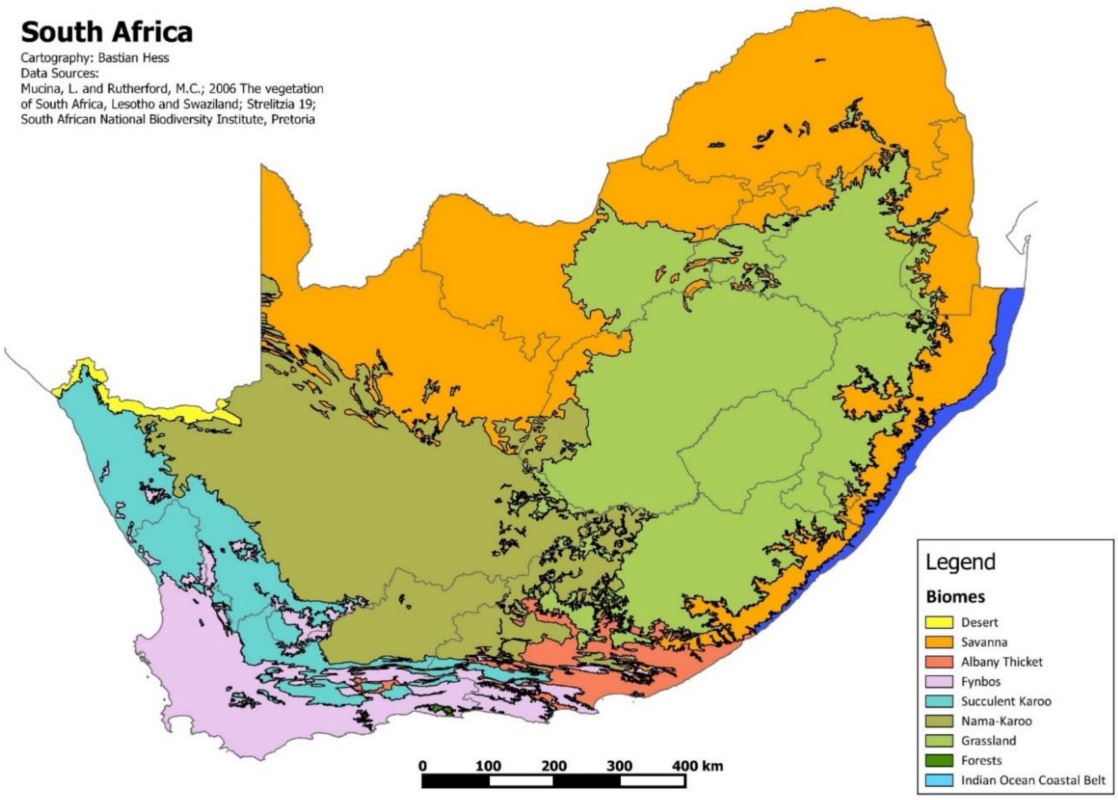

Fig. 1: Overview of the biomes of South Africa. Map based on data from Mucina L. & Rutherford M.C. (2006) The vegetation of South Africa, Lesotho and Swaziland, Strelitzia 19. South African National Biodiversity Institute, Pretoria.

In the following, I will shortly describe the key influencing factors that determine vegetation dynamics of savannas.

Precipitation

Rainfall is the most important driver of vegetation dynamics (Zucchini and Adamson 1984). In savannas, the MAP can be as little or even less than 100 mm in arid areas, up to 700 mm in semi-arid regions (precipitation is below the potential evapotranspiration, but not as dry as desert) and go even up to 1000 mm and above in mesic areas (Belsky 1990; Tainton 1999; Wiegand et al. 2006; Luvuno et al. 2018) (Fig. 2). The majority of the annual precipitation rains down during the summer months (October to April) and there is little to no rain in the winter months (Wiegand et al. 2004). The rainfall occurs usually spatially and temporally heterogeneous (Sharon 1981; Zucchini et al. 1992; Ward 2005; Botai et al. 2018).

The absence of rainfall is one of the biggest and serious concerns and economic as well as ecological threats for farmers (Zucchini and Adamson 1984; Tainton 1999; Tagesson et al. 2015). A drought with no or only little precipitation means only little grass biomass production and thus only limited natural fodder for the livestock. As a result, the existing grazing resources will be overused which can lead to a degradation of the veld and to decreased animal health/condition. A ‘drought year’ occurs when the MAP is less than the long-term MAP in that area minus one standard deviation (SD) (Meyer et al. 2007). In the semi-arid regions droughts are intense and recurrent (MacCracken and Luther 1985). Just as the highly variable rainfall, the droughts also show a random spatial and temporal distribution and can last in some areas for many years (Fig. 3) (MacCracken and Luther 1985).

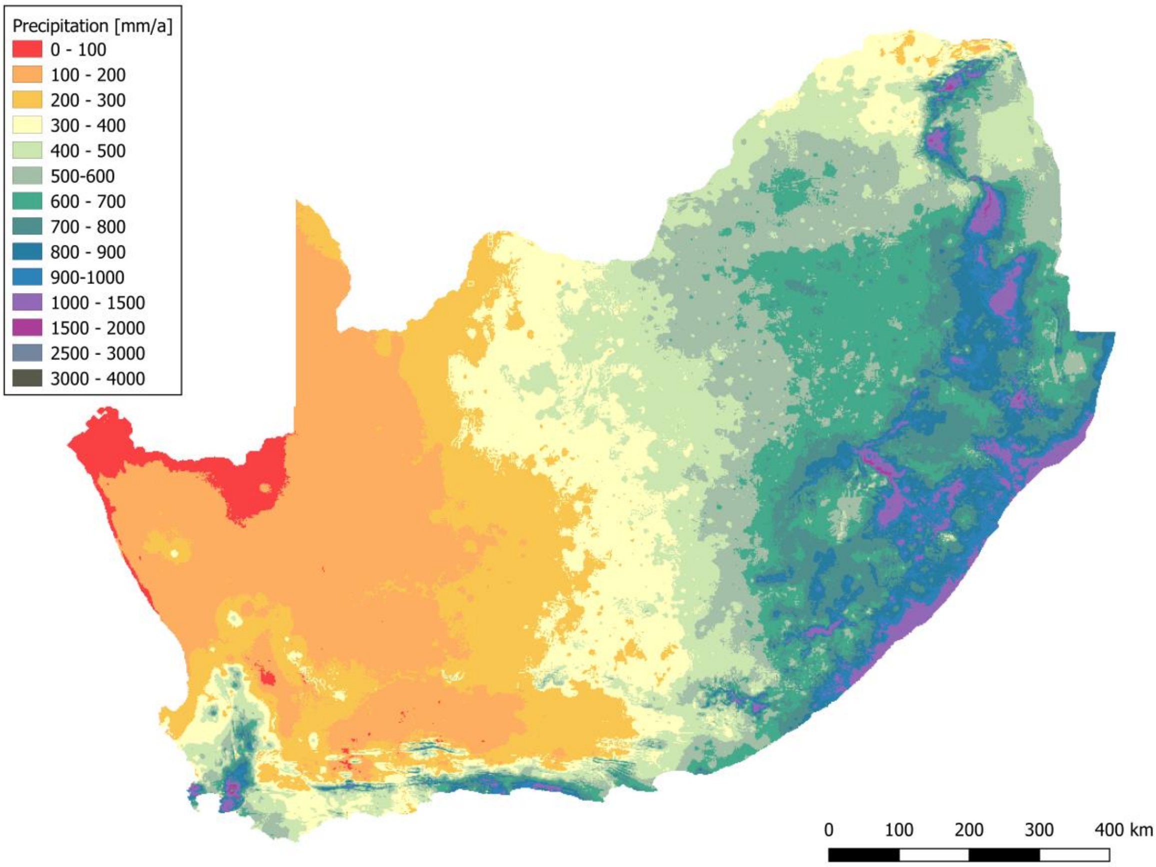

Fig. 2: Mean annual precipitation in South Africa, Lesotho and Eswatini. Modified after Schulze and Lynch (2007).

Fig. 3: Example of a very small, patchy rainfall event in the Mier area.

Soil properties

Soil type is one of the key factors when determining plant-accessible water in the soil. There are diverse soil types with different properties in southern African savannas including shallow rocky soils, clayey soils, and plinthic soils (Mucina and Rutherford 2006). In some regions deep soils can be found and allow the vertical root-partitioning between deep rooting woody vegetation and shallow rooting grass vegetation being the basis for Walter's two-layer hypothesis (Walter 1971; Walker et al. 1981; Meyer et al. 2009). Whereas other regions are dominated by shallow soils. These shallow soils do not allow such a retreat into the different rooting zones where the respective vegetation type is the superior competitor. The hindrance of this retreat leads to increased competition and dry stress (Wiegand et al. 2005; Ward et al. 2013). **Soil moisture** is considered the most limiting factor for the growth and propagation of grasses and woody species (Kambatuku et al. 2013; Liu et al. 2020). Soil moisture is strongly determined by **soil texture**. Especially the **clay content** is a good indicator of soil texture and considered the major soil property influencing bush encroachment dynamics (Grellier et al. 2014). Due to their smaller pores, fine textured soils allow less water infiltration into the deeper soil layers (where tree roots reach) compared to other soil textures thus limiting potential soil moisture (Kgosikoma et al. 2012). Moreover, the soil moisture content as well as the evapotranspiration are important factors for determining **drought** (Zucchini and Adamson 1984). High temperatures often lead to a strong evapotranspiration of the already scarce rainfall. This results in dried out soils that do not absorb water well. This is especially problematic in sloped areas as it causes runoff, which will decrease the amount of water that gets into deeper soil layers, and it will cause **erosion**. *Gully erosion* can be caused, when the superficial runoff water penetrates the hard upper soil layer, for example in places where termite mounds form a barrier to the natural flow path of the water. The water will flow around these mounds and take soil particles with it so that over time, the soil around the mound is eroded further and further and the hard upper layer is broken through. The water then continues to flow underground while continuously removing subsoil thus increasing the underground tunnels. This soil erosion mechanism is called *piping*. The large underground tunnels can collapse over time and form large gullies in which more soil is detached and transported. This causes significant soil losses and is a major form of land degradation causing ecological and economic problems (Poesen et al. 2003; Scholes 2009; Grellier et al. 2012).

Temperature

The mean annual temperature for South Africa is 17.5 °C with an average monthly minimum of 11 °C and maximum of 22 °C (World Bank Group 2021) (Fig. 4). Extreme daily minimum and maximum temperatures can drop below 0 °C (in July) and exceed 32 °C (in February), respectively (Mucina and Rutherford 2006). There is an increasing trend in temperature due to climate change with annual trends of an estimated increase of up to 1.9 °C in maximum temperature and up to 1.2 °C in minimum temperature (Gebrechorkos et al. 2019). As minimum temperatures in savannas are very variable, the average number of frost day can be as much as >120 days per year while other areas are mainly frost free (Mucina and Rutherford 2006). This is important because frost can have a severe effect on developing saplings (Childes and Walker 1987).

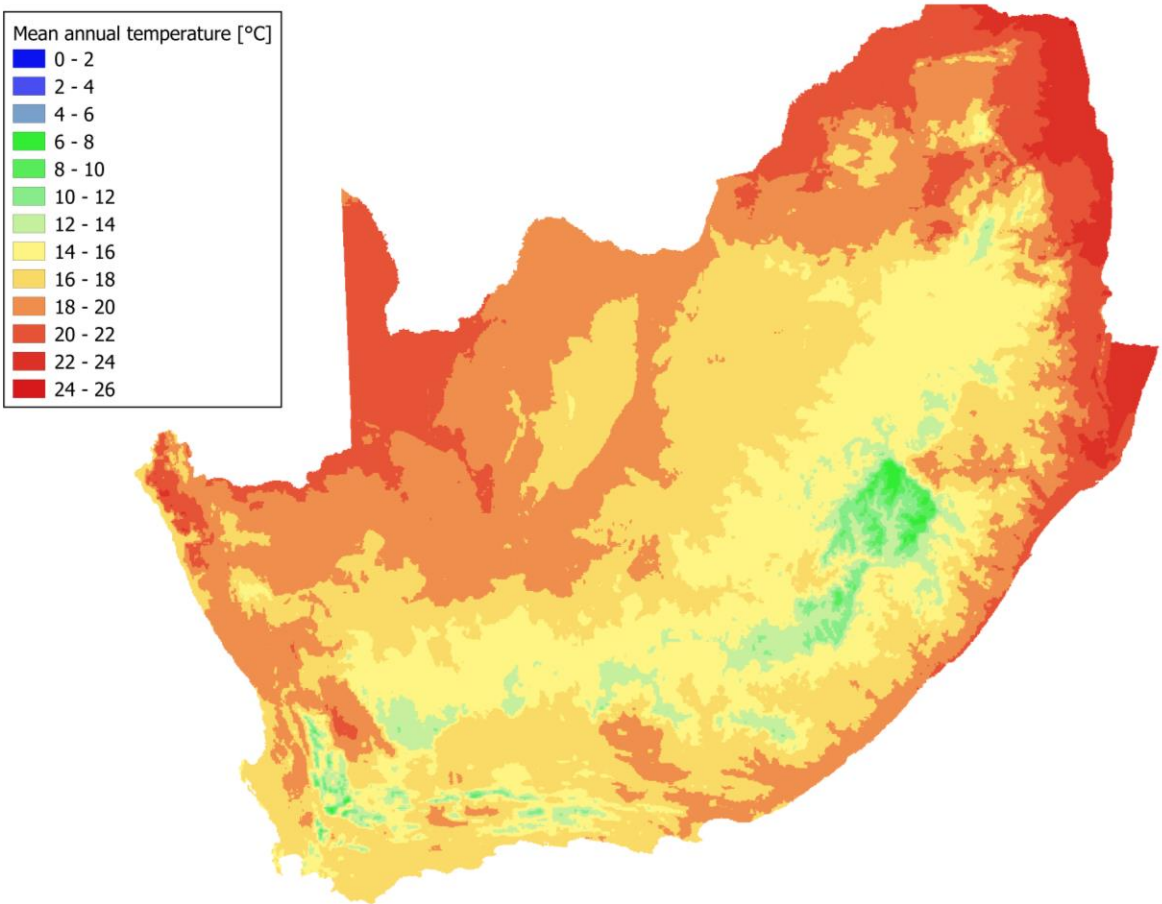

Fig. 4: Mean annual temperature (1950 - 2007) in South Africa, Lesotho and Eswatini. Modified after Schulze and Lynch (2019).

Fire

Fire occurs naturally in savannas and can have a major impact on vegetation dynamics and species composition. It can be caused by lightning, by focused sunlight through broken glass pieces but also through discarded cigarettes. These fire ignition events need sufficient vegetation biomass to turn into a big, intense fire and to spread in the landscape. Factors such as a high wind speed, high air temperature, low relative humidity, etc. will increase the spread rate of the fire (Tainton 1999). When fuel biomass is sufficient, the fires can become hot enough to kill trees (Fig. 5). The higher the precipitation, the bigger the role of fire as a regulator of woody vegetation in savannas. The woody content in a savanna as well as the overall biomass (fire fuel) increases with precipitation. Fire starts to have a serious effect on vegetation composition in areas with a MAP of about 288 mm and more, and with a woody vegetation cover of less than 40% of the landscape. This is because critical amounts of biomass as fire fuel have to be reached to create an intense fire with wood killing potential (Archibald et al. 2009). In unstable savannas i.e. with an MAP of more than 650 mm, fire or other disturbance are essential to prevent the complete displacement of grasses by woody vegetation (Sankaran et al. 2005). Natural fires used to be common and were thereby able to delimit the abundance of woody species. With increasing human impact on savannas through farming i.e. higher grazing pressure, and active farm- and fire management, the frequency of fires decreased. Farmers usually try to avoid fires, the spreading of fires and the associated risks in order to have a better control over the vegetation biomass, which is the main fodder for their livestock. Once all available fodder in the shape of grass biomass is destroyed by fire, the farmers and their livestock are left to the fate that by chance a good rainfall event will occur soon again and the grasses can regrow. Substitute feedings are possible but costly. Farmers avoid big fires by keeping grass biomass volume low and by establishing so-called firebreaks. Firebreaks are lines with no or very little grass to stop fires from spreading. Fires can however also be used as a management tool to target bush encroachment and increase heterogeneity and floral- faunal-, and structural diversity (Tainton 1999; Geldenhuys et al. 2004; Lohmann et al. 2014; Case and Staver 2017; Zhou et al. 2021).

Fig. 5: Effects of a prescribed burning in the Ithala Game Reserve: Fire destroyed the grass biomass and the resulting heat was hot enough to kill many, but not all, of the trees.

Vegetation

The herbaceous and woody layer of savanna vegetation is rich in grass-, forb-, shrub-, and tree species. However, for certain research aims and modelling purposes, it can help to reduce complexity in plant communities and generalize on the level of basic plant functional types or groups (in the following referred to as "vegetation types"). Each vegetation type consists of plant species that possess similar traits and show similar functional responses to the environment or act in ecologically similar ways.

The actual plant community, a portfolio of different species within each vegetation type in a specific area can be an indicator for veld condition as described by O´Connor et al. (2001) and Wiegand et al. (2004). **Veld** is the natural vegetation consisting of different plant growth forms, not necessarily climax species, that is grazed/browsed by animals (De V. Booysen 1967; Trollope et al. 1990). Typical vegetation types of southern African arid and semi-arid savannas are annual grasses, palatable and unpalatable perennials grasses, forbs, as well as woody vegetation in form of bushes and trees:

When dominant, **annual grasses** can be an indicator of disturbances and can be found for example around watering points where a lot of trampling occurs (van Rooyen et al. 1994; Jeltsch et al. 1997b; Dreber et al. 2011). Typical representatives for annual grasses in arid and semi-arid savannas are e.g. *Aristida adscensionis, Aristida congesta, and Schmidtia kalahariensis* (Smit et al. 1999; Thomas and Twyman 2004; Dalgleish et al. 2012; Harmse et al. 2016).

Perennial grasses can be divided into palatable and unpalatable species. The categorization also depends on the location and can differ between different areas. A grass species considered palatable and nutritious in dry areas can be considered poor fodder or even unpalatable in another area with more precipitation, due to better alternatives i.e. more nutritious grass species. Among the different grass species in southern Africa are also several (12 %) introduced invasive species that have the potential to outcompete indigenous grasses and change ecosystem processes (Milton 2004). Examples for perennial grasses in arid and semi-arid savannas are: *Aristida diffusa, Aristidia meridionalis, Aristida stipitata, Pogonarthria squarrosa, Schmidtia pappophoroides, Stipagrostis amabilis, Stipagrostis hochstetteriana, Stipagrostis uniplumis* (Tainton 1999; Thomas and Twyman 2004; Dreber et al. 2011; Dalgleish et al. 2012; Harmse et al. 2016).

The highly diverse **forb** plant group is receiving increasing attention and have become the focus of studies in recent years (Siebert and Dreber 2019). This non-graminoid herbaceous savanna component with a high functional richness provides important ecosystem services such as: nutritious fodder for game and livestock, protein and vitamin rich food for human consumption and medicinal use, habitat for many arthropod species, indicator for habitat degradation and climate change (Siebert and Dreber 2019). Examples for forb species are: *Amaranthus praetermissus*, *Gisekia africana*, *Helichrysum candolleanum*, *Indigastrum argyroides*, *Lotononis platycarpa*, *Microcharis disjuncta*, and *Trianthema parvifolia* (Tainton 1999; Dreber et al. 2011; Siebert and Dreber 2019; van Coller et al. 2021).

Woody vegetation can occur as scattered growing trees and shrubs that can provide ecosystem services, increase biodiversity, become fertile islands and benefit livestock and game with *i.a.* shade, shelter and fodder (Dean et al. 1999; Tews et al. 2004). These trees, Acacias being a common representative, also provide fuelwood for many households and some parts of trees can be used for medicinal purposes (Swemmer and Ward 2019). However, woody vegetation can also form dense layers that decrease the amount of grasses on a veld and restrict access of livestock to grass patches and thus lower the carrying capacity on a camp.

Another problematic property of woody vegetation is its potential for spatial spread and outcompeting other vegetation resulting under certain conditions in the phenomenon of **bush encroachment** (Fig. 6, Fig. 7) (Teague and Smit 1992; Ward 2005; Swemmer and Ward 2019). Examples for woody species in arid and semi-arid savannas are: *Acacia mellifera* (Syn. *Senegalia mellifera)*, *Acacia erioloba* (Syn. *Vachellia erioloba)*, *Boscia albitrunca*, Cadaba aphylla, Calicorema capitata, *Grewia flava*, *Phaeoptilum spinosum*, and *Rhigozum trichotomum* (Tainton 1999; Thomas and Twyman 2004; Dreber et al. 2011; Hesselbarth et al. 2018; Dreber et al. 2019).

Savanna dynamics and land degradation

As mentioned above, savannas are not stable systems in equilibrium instead they consist of a dynamic mosaic of patches in different vegetation stages (Gillson and Hoffman 2007; Moustakas et al. 2009). However, the dynamics and distribution between grasses and woody vegetation can drift to an extreme where woody vegetation gains the upper hand and dominates all other vegetation. This disequilibrium of the grass:woody vegetation ratio can also spread over an area and manifest itself in the long term (Scholes and Archer 1997; Sankaran et al. 2005). Without strong anthropogenic intervention (or a combination of special climatic events and management actions), this condition can be irreversible (Roques et al. 2001; Kellner 2009; S. et al. 2013; Joubert et al. 2014). This phenomenon of long-term veld degradation is called bush encroachment, also known as shrub or woody plant encroachment and can be observed in savannas around the world. It has been a problem since the late nineteenth century and is currently increasing in arid and semi-arid savannas (Roques et al. 2001; O’Connor et al. 2014; Mureva and Ward 2016). The increased abundance of woody vegetation does have some positive effects depending on scale, species and environment (Smit 2004; Eldridge and Soliveres 2014). Bush encroachment can e.g. be beneficial for browsers, mixed-feeders, and game (for cover), can increase the soil organic carbon content in the top-soil layer (Li et al. 2016) and thus aid in the reduction of climate change inducing greenhouse gases and it can have positive effects also on other ecosystem services (Eldridge and Soliveres 2014; Birch et al. 2016).

But from a farming perspective, the effects of bush encroachment are mainly negative (Stanton et al. 2018). Bush encroachment reduces the carrying capacity and thus the amount of livestock that can be put on the veld sustainably (Trollope et al. 1990). Thereby bush encroachment has a negative effect on livestock farming and food security, reduces floral and faunal species richness and total abundance, and has negative effects on biodiversity, groundwater recharge rates, tourism, and other ecosystem functions (Birch et al. 2016). The species mainly responsible for bush encroachment in the (semi-) arid southern African savannas are *Acacia mellifera* (Syn. *Senegalia mellifera)*, *A. hebeclada* (Syn. *Vachellia hebeclada)*, *A.* (Syn. *V.) karroo*, *A.* (Syn. *V.) nilotica*, *A.* (Syn. *V.) tortilis*, *Dichrostachys cinerea*, *Grewia flava*, *Rhigozum trichotomum*, and *Tarchonanthus camphoratus* (Meyer et al. 2007; O'Connor et al. 2014). The exact cause of this form of land degradation are not yet fully understood and it is likely a combination of different factors and processes also depending on the region (Hoffmann et al. 1999; Patrick Graz 2008; Venter et al. 2018).

There are **two main theories** explaining the coexistence between grasses and woody vegetation and the phenomenon of bush encroachment: The "two-layer hypothesis" and the bottleneck theory. Walter (1954, 1971) developed the '**two-layer hypothesis'** which attributes the horizontal separation of the roots of different vegetation types (niche partitioning) to the coexistence of grasses and woody vegetation. Trees, who are the superior competitors in the lower depth root level can exist in a dense grass matrix while grasses cannot survive in a dense woody vegetation matrix (Teague and Smit 1992; Tainton 1999). The balanced grass:woody vegetation ratio can be destabilized and turn toward bush encroachment when e.g. through overgrazing, more rainfall water percolates to the lower soil levels, which gives a competitive advantage to deep rooting woody vegetation. This two-layer theory however cannot be the only explanation for bush encroachment as bush encroachment also occurs in areas with shallow sandy soils that do not allow root niche separation and also moist savannas and their disturbances cannot be reflected realistically (Wiegand et al. 2005; Ward et al. 2013). It is therefore helpful to look at the different life stages of the vegetation and check which factors, **extreme events** and climatic conditions act strongly on the different life stages and thus create **demographic bottlenecks** by stopping or reducing reproduction, seed dispersal, germination, establishment and growth (Higgins et al. 2000; Sankaran et al. 2004; Bond and Keeley 2005; Lohmann et al. 2017). The major disturbances assumed to have an effect on bush encroachment in savannas are overgrazing, trampling, suppression of the natural occurring regular fire events, long-term low and irregular precipitation events in connection with properties like soil type and soil moisture (Suttie et al. 2005; Wiegand et al. 2005; Ward 2005; Wiegand et al. 2006; Kellner 2009; Kgosikoma et al. 2012; Swemmer et al. 2018; Swemmer and Ward 2019). These disturbances affect the grass:woody vegetation ratio. Overgrazing, for example, removes a lot of grass biomass and the resulting unused resources (especially water) benefit the remaining vegetation such as woody vegetation (Richter et al. 2001; February et al. 2013). Trees are also able to survive droughts more easily than grasses due to their longevity and larger reserves. Especially in arid savannas with shallow soils, the highly variable (temporal and spatial) rainfall is the main driver of tree-grass competition. Reoccurring rainfall events on one particular patch will allow the germination and establishment of e.g. Acacia species and thus the woody dominance on this patch (Wiegand et al. 2005). **Small fires** based on low grass biomass (overgrazing/low rainfall) are easily survived by trees while regular large, **hot fires** are mostly deadly for small trees. Complete **suppression of natural fires** allows saplings and young trees to grow undisturbed until they are above the flame zone and fire has little harm to them (Geldenhuys et al. 2004; Smit et al. 2010, 2016; Case and Staver 2017). When, in a more humid savannas, a **drought** occurs with insufficient moisture for woody saplings to grow, they may however be able to sustain their current state and remain in this dormant state as 'gullivers' (suppressed juveniles) (Higgins et al. 2000) under the grass layer (or outcompeted by grass tufts), waiting for better conditions. In this state they can even survive repeated fires (Higgins et al. 2000). This is especially relevant in more humid savannas (with a MAP above 820 mm) where fires occur regularly. In an above average rainfall season, which occurs maybe only every 6-7 years depending on region (World Bank Group 2021), the woody species will then have the chance to establish and dominate the perennial grasses and thus become the dominant vegetation type on the patch (Higgins et al. 2000). Other authors (February et al. 2013) argue that it is actually a sequence of dryer years that will promote juvenile tree growth as then the competition by grass is lower (due to lower grass biomass and thus less total water demand). Beside these classical disturbances, there are also recent trends that promote woody vegetation, e.g. **higher temperatures** and **increasing atmospheric CO2 levels** (Russell and Ward 2014). **Controlling and reverting bush encroachment** is a challenging task and there are several different approaches, for example the use of arboricides (Fig. 6), manual tree cutting, stem burning (Tainton 1999; Suttie et al. 2005; Lukomska et al. 2014; Reed et al. 2015; Harmse et al. 2016; Hare et al. 2020). There are also more long-term approaches of introducing (more) browsers and adapting the veld and livestock management in a way that will slow down bush encroachment or potentially even put it to a halt (Tainton 1999; Biggs et al. 2009; Kellner 2009; Kgosikoma and Mogotsi 2013; Stolter et al. 2018; Swemmer and Ward 2019).

Fig. 6: Top: Bush encroachment in the Molopo area: Many Acacia trees and bushes in a matrix of bare soil with almost no grasses. Bottom: The same area treated with arboricides via airplane: The trees are dead and decaying, and the (palatable) grasses are recovering and cover most of the ground.

Fig. 7: Bush encroachment in the dry Mier area with *Rhigozum trichotomum* on the right side. The left side was treated manually with arboricides to allow palatable grasses (*Stipagrostis ciliate*, *S. obtuse*, and *S. anomala*) to recover.

Climate change

Global climate change is also affecting the savannas in southern Africa. Different climatic factors are influenced to different degrees. These factors are temperature, intra- and inter-annual precipitation, and atmospheric CO2 levels. Future climate projections are subject to uncertainty, but most projections agree that there will be increased temperatures, higher variability of rainfall but in general a drier climate with more extreme events, and an increase in atmospheric CO2 (Lohmann et al. 2012; Hoffman et al. 2019; IPCC 2021). These climatic trends are already visible in southern Africa (Gebrechorkos et al. 2019). These climatic changes are likely to have serious, and severely limiting impacts on the ecology and farming in southern Africa (Chapin et al. 2000; Heisler-White et al. 2008; Moncrieff et al. 2014; Gaur and Squires 2017; Tietjen et al. 2017; Synodinos et al. 2018).

Temperature increases in South Africa were already visible since the 1960 over all seasons. Not only have the daily maximum and minimum temperature increased severely, but also the extreme temperatures increased and are predicted to increase even more (IPCC 2021; World Bank Group 2021). An increase in temperature will likely have direct and indirect limiting effects on the available water in the soil (which is one of the most influential variables for vegetation dynamics) by affecting evapotranspiration and vegetation growth (Tietjen et al. 2017).

Precipitation trends show an increasing **intra- as well as inter-annual variability** (IPCC 2021; World Bank Group 2021). This is in general bad for long-time planning of stocking rates, livestock rotation patterns, buying supplemental fodder and other management decisions. However, more extreme rainfall events and with that a decrease of days with rainfall, means also longer dry periods in between the rainfall events. Another effect of extreme rainfall is that, when the top soil is dried out, not as much of the water can penetrate into deeper soil layers but runs off superficially or evaporates. This effect together with the predicted slight decrease (depending on region and climate scenario) of mean precipitation in arid areas will lead to increased drought stress in plants (Dore 2005; Tietjen et al. 2017; Berry and Kulmatiski 2017).

Increasing **atmospheric CO_2 levels** are suspected to lead to an increase of bush encroachment while lower CO_2 levels could delay bush encroachment (Diaz and Cabido 1997; Ward 2005; Kgope et al. 2009). This is due to the fact that many trees and shrubs use the C3 carbon fixation as metabolic pathway for photosynthesis. Thus, increasing CO_2 levels will allow a more water efficient photosynthesis for C3 plants (Morgan et al. 2004; Conradi 2018).

1.2 Farming and challenges in southern Africa

Farming is a challenging business and a farmer needs to not only care for the livestock but also has to consider the vegetation and the vegetation dynamics in response to varying long and short term environmental factors. He or she needs to be aware of the heterogeneity of the landscape, the long-term trends that the system is facing, and the history of the veld. The farmers sometimes have to deal with unpredictable extreme events like fires and droughts and adapt their management decisions accordingly. The farmer has a variety of setscrews to influence the rangeland system. The main management decisions are the type of livestock, the stocking rate, the spatial distribution / type of rotation system (Fig. 8), the positioning of watering points and other farm infrastructure, the removal of woody vegetation in case of bush encroachment, supply with supplemental fodder and the improvement of the grass quality by introducing more nutritious grass species. The available money (and time) limits the management decisions so that e.g. supplemental fodder cannot be bought in the needed amount during a drought or measures against bush encroachment have to be delayed until more funds are available (Kong et al. 2014). Farming in South African savannas is connected with many risks and uncertainties, and requires a lot of knowledge and information for good decision-making.

Fig. 8: Rotational grazing: Livestock (cattle) has grazed on the left side of the fence (vertical brown centre line). The grasses on the right side of the fence are not grazed at the moment and have time to regrow.

Game

Wildlife occurs naturally in most areas of South Africa and a great diversity of wildlife species can be found in nature conservation areas. After an all-time low in the 1930s due to droughts, epidemics, and human-wildlife conflicts, the animal numbers have started rising again until today (Tainton 1999; von Solms and van der Merwe 2020). Game, especially antelopes are also kept on game ranches for commercial meat production and large wild herbivores are kept for hunting purposes (Tainton 1999). In parts, game has been excluded from some livestock-farm areas by fences. However, some animals (e.g. Bushbuck and Warthog) can crawl under the fence while other species (e.g. Eland and Kudu) can jump over common fences so that under normal precautions, wild game is never fully excluded from a farm. Amongst the wild game there are (high-selective and low-selective) grassers, browsers and mixed feeders (Bothma et al. 2005). The effect of wild game can thus be similar to livestock (grazing palatable grasses) but can also have a decimating effect on bush encroachment in case of browsers. This means that the type/mix and abundance of wild game has to be considered when calculating the livestock stocking density on a farm because there will be a certain amount of wild game present on the farm that will put additional grazing/browsing pressure on the vegetation (Tainton 2000). During the time of wild game herds roaming around freely, there was usually a low overall stocking rate but very high spatially concentrated grazing/browsing pressure. This situation was due to the large herd sizes and spatially concentrated feeding (fear of predators) for a short time in one place until grazing resources were exhausted and the herd moved on; similar to livestock herding in communal rangelands in the past (Kgosikoma et al. 2013). This led to a more homogeneous grazing of all the different kinds of grasses, instead of the very selective grazing of only the highly nutritious grasses as is the case in long-term low(er)-stocked grazing with e.g. cattle (Vallentine 2001). Also due to the low precipitation in the arid areas, the growth of wild game populations there was usually limited by droughts. Because the wild game constantly moved to new areas when the vegetation resources were exhausted, a continuous overgrazing in one place and the resulting degradation of the vegetation was avoided. A modern imitation of this system is for instance the multi-paddock rotational grazing system (Tainton 2000; Hoffman 2003; Teague and Barnes 2017). In multi-paddock grazing, livestock is rotated through a number of camps thus limiting the time that the animals can graze on one camp and ensuring that the vegetation on each camp has time to rest and regrow after grazing. With this, multi-paddock grazing allows farmers to adaptively manage southern African rangelands and thus can improve vegetation and soil conditions as well as increase animal production (Teague et al. 2013).

1.3 Savanna rangeland models as a decision support tool

To be able to cope with all the challenges on their farm, farmers need tools to help them make informed decisions. This can start from nature observations, gathering knowledge of the farm, the specific vegetation and their response to the different influencing factors, getting the local weather forecast and can be as complex and comprehensive as rangeland simulation models that allow the farmer to not only see an example of the future development from the current starting conditions under constant influences, but instead can include many dynamic inputs such as climate change and can consider different management decisions so that the farmer can test different alternatives to see their potential effect in the future. This allows farmers to get a feeling for the short- and long-term effects of their decisions and actions. Especially with very complex phenomena, such as bush encroachment, that have a multitude of different influencing factors whose interaction effects are hard to grasp, a rangeland simulation model becomes a very valuable tool to explore many different options, cause-and-effect relationships and optimal management strategies.

There are various (mixed) types of savanna models, for an overview of several models see Belsky (1990), Sankaran et al. (2004), Tietjen and Jeltsch (2007) and Warth et al. (2020). **Statistical models** are generally data driven and predict the outcome of vegetation dynamics irrespective of the underlying natural processes (Lehmann et al. 2011; Wesuls et al. 2013). There are large-scale models that analyse the trends of biome shifts and future tree cover under climate change using e.g. **generalized additive models (GAMs)** (Heubes et al. 2011) but due to limited details these models do not consider individual farmer management decisions as response to veld and livestock condition. Another model type are the **terrestrial biosphere models (TBMs)** which simulate vegetation dynamics based on the interaction between the land-surface and atmospheric conditions (Whitley et al. 2016). These types of model have some shortcomings as they often misrepresent e.g. the effects of fire and root-water access (Whitley et al. 2016). This, and their static nature make them not ideal for predicting the development and vegetation dynamics of savannas especially into the future under different climatic scenarios. **Dynamic vegetation models (DVM)** consider the vegetation physiology and dynamics in interaction with climatic factors from leaf to landscape and globe scale and thus increase predictive strength for future developments (Prentice et al. 2007; Sitch et al. 2008; Baudena et al. 2015; Moncrieff et al. 2016). Then there are **process-oriented simulation models** (Jeltsch et al. 1997a; Weber et al. 1998; Wiegand et al. 2006; Moustakas et al. 2009; Sané et al. 2016) that recreate in detail and often spatially explicit and grid-based the processes and interactions between different drivers of vegetation dynamics in space and time with separate functions (for example: Duraiappah and Perkins 1999). This approach allows to focus on the important drivers for a specific research question and allows an easy extension and interlinking of the models for future questions (Rötter et al. 2021). These models can be **agent based models** with agents representing collective or individual actors in the studied system (e.g. vegetation type groups, single plants, or livestock) that will be affected by the different biological and physical processes. A drawback can be that because of the high level of detail, simulations require high computing and memory capacities and take a long time to run or that only small spatial extents can be simulated at once.

1.4 Aims of the study

The aims of this study were:

- To identify the relevant processes and factors to understand the vegetation dynamics in South African savannas
- To develop a model to create realistic, user-defined, site-specific input landscape maps with information on vegetation distribution and farm infrastructure
- To create a rule- and grid-based spatially explicit rangeland model based on the Molopo simulation model (Hanß 2013)
- To model the savanna vegetation dynamics in a process-oriented way to be able to further deepen knowledge about savanna dynamics and processes by running various simulation scenarios with different environmental conditions and management actions
- To identify crucial processes and factors that are most influential in modelling South African vegetation dynamics and that need to be further explored and modelled (in greater detail)

This study took place within the IDESSA project (An integrative decision-support system for sustainable rangeland management in southern African savannas) in the scope of the BMBF-SPACES program (Science Partnerships for the Assessment of Complex Earth System processes) investigating landscape changes in the southern African region (Wiegand et al. 2017).

Structure of the chapters

In the **second chapter** I am describing the results from farmer interviews and workshops that we did within the IDESSA project. I analysed and qualitatively evaluated the answers and compiled them in this chapter. We talked with eleven farmers, as well as several scientists and stakeholders about their experience of managing veld and livestock, and about their observations and research with the vegetation dynamics and the complex interactions in savannas.

In the **third chapter** the piosphere landscape generator PioLaG is introduced. I will explain the structure and functioning of this model and show exemplary the variety of landscapes that can be created. This landscape generator allows users to create realistic, individualized landscapes that can for example be used for rangeland simulation models.

In the **fourth chapter** I will be giving a detailed model description of the Midessa rangeland simulation model. I will present and discuss results from various simulation scenarios and analyse the effect of input parameters with a sensitivity analysis. The model can be used to simulate the complex interactions of environmental factors and management decisions on the vegetation dynamics in savannas.

2 Farmer interviews and input from workshops

2.1 Introduction

To be able to create a model as realistic as possible, it is important to get to know the system that is to be modelled as well as all its actors and stakeholders. Following the principle of triangulation (i.e. by using all available information sources including literature, stakeholder reports, aerial images, own expressions in the field, etc.) we wanted to capture different dimensions and gain a good understanding from different perspectives of the dynamics in a savanna rangeland system (Treumann 1998). This is why we conducted individual, semi-structured interviews with eleven Kalahari farmers in March 2014. The farmers were located in the north-northwestern part of South Africa in the Mier, Molopo and Kimberly areas and were working with different land use and management systems (commercial and communal farmlands, and game reserves). The farms were located in different savanna types: The arid savanna in the Mier area (Northern Cape province) with less than 300 mm of MAP, the semi-arid savanna in the Molopo area (North-West province) with an MAP of 300-500 mm, and the semi-arid savanna in the Kimberly area (Northern Cape province) with an MAP of around 400 mm. We collected also some anecdotal information from two farmers and a game reserve/wildlife park ranger from the mesic savannas and bush-encroached grasslands in the Louwsburg area (KwaZulu-Natal province) with a MAP of more than 700 mm. In addition, we organized and conducted a series of workshops, one with rangeland experts (July 2016, Kimberley, South Africa; 25 participants) and two with commercial farmers (February 2017, Ganyesa and Askham, South Africa; 29 and 28 participants, respectively) (Hess et al. 2020).

2.2 Aim

The goal of the interviews, participatory observations and workshops was to gain an understanding of the common practices of South African farmers in livestock and pasture management. In addition, we were interested in which factors are most important for management decisions, which details farmers pay particular attention to, how they respond to the various changes and extremes in the system, and how they deal with uncertainties and risks that are present in a rangeland system. We were especially interested in the management goals, control variables, and set screws of rangeland management that farmers typically use. Moreover, we wanted to find out which processes and factors are particularly important for vegetation dynamics in southern African savannas and to gain other interesting and useful information that might aid in creating a more realistic and more user-friendly simulation model.

2.3 Methods

We conducted focused interviews with both closed and open-ended questions. Open-ended questions were included whenever we wanted to avoid limited responses and rather allow for detailed discussions about topics important for the particular farm and management system of the interviewed farmer. The interviews were semi-structured and consisted of questions centred on the farm properties, livestock types and abundances, as well as other management decisions. There was extra time reserved to have an open discussion and “story-time” for open questions, interesting facts, and other anecdotal information from the farmer which often revolved around his specialties and local characteristics.

List of the questions and topics as conversation starter:

- What is the average rainfall and temperature on the farm(s)?
- What is the size of the farm(s)?
- How long has the farmer been managing the farm?
- What is the herd composition?
- What is the stocking rate on the farm?
- Does the stocking rate fluctuate (e.g. is adapted during drought)?
- What is the land tenure type? Commercial or communal?
- What is being used: camp rotation system or open grazing system?
- In case of a camp rotation system:
    - Does it depend on environmental conditions or is it fix?
    - How many camps are used for rotation?
    - How long do the animals stay in one camp?
- How are the animals distributed on the farm/camp?
- Is grazing possible everywhere on the farm?
- Are there backup plans for a drought?
- What happens during good years (i.e. years with high precipitation and sufficient biomass/fodder) vs. bad years (drought, insufficient fodder for livestock)?
- Is there active fire management?
- Are camps shrub-encroached/has there been shrub-encroachment in the past?
- Are there measures against shrub-encroachment?
- How do the farmers adapt their management to the different environmental conditions?

The farmers were chosen based on farm location in the focal study area and on their reliability from past collaborations with our project partner in South Africa, namely Prof. Klaus Kellner, who arranged the meetings. For reasons of research ethics and data protection agreements, a precise listing of the farmers is omitted here. During the series of expert workshops, we handed out questionnaires about factors and processes that should be considered in the model.

2.4 Results

2.4.1 Precipitation

As the most restricting environmental variable for vegetation growth, the precipitation was closely monitored by all interviewed farmers. The **MAP** at the farm locations ranged between 125 mm to 450 mm with an average of 273 mm across all farm locations (Fig. 9). Several farmers owned more than one farm and noted that precipitation varies on the different farms. They especially pointed out the high spatial heterogeneity of precipitation in the region with thundershowers creating a patchy rain of as low as 500 m radius.

2.4.2 Land tenure type

The land-use type on the farms was either commercial, communal, game farm or a nature reserve. The goal of the **commercial farmers** was to make money. Some of the interviewed farmers had a major focus on maximizing profits, while other farmer concentrated on the long-term sustainability and stability of their farm system. The commercial farmers made economic considerations about the pros and cons of management options and were generally more willing to invest in their land.

The goals of the **communal farmers** were to provide themselves with food, and to provide a side income by selling individual animals. In all cases, the herd sizes of the communal farmers were significantly smaller than those of the commercial farmers. Since the majority of the grazing land of the communal farmers was community owned and also used by other farmers, there was very little motivation to invest in the land (e.g. by setting up camps with fences, or conducting control measures against bush encroachment).

The **game farm manager interviewed** cared for the growth, flourishing and reproduction of game used for ecotourism or hunting purposes. This posed some different management challenges than, for example, traditional cattle management; the different game animals were grazers, browsers or mixed feeders and therefore have different demands on the veld. Since a game farm can be economically very profitable (Lindsey et al. 2009), it is also very likely that the game farmers invest in improving the farm for example by fighting bush encroachment, increasing the vegetation structure of the farm, and by sowing beneficial grasses.

The farmers used a number of different grazing systems. All commercial cattle farmers that we interviewed used a **rotational grazing system** with several camps, where cattle graze in each camp for a certain time (can be a few days, some weeks or even several months) while the other camps are at rest and the vegetation has time to recover. After the grazing time on a camp the cattle are moved to the next camp. There were different numbers of camps and rotation strategies amongst the farmers. Several farmers used **3 or 4 camp rotation systems** on their farms. In these systems they let one camp rest for the whole growing season up to the winter. They found that the resting period is very important and that it should be at least one season. Another cattle farmer used **4 and 6-camp systems** with two camps resting for one year and two camps being grazed for 8 to 12 months. The exact timing depends on factors such as growing season, mating season, biomass production, etc. Often farmers have mentioned an adaptive system in response to environmental variables (mainly precipitation and its effect on biomass production). They regularly observed the condition of the veld and then decided when animals needed to be moved to the next camp. Camps are often different in size, fodder availability (nutritional value and biomass amount) and number/placement of watering points, which are all important factors to consider when deciding how long the camps shall be grazed and how long they need to rest. One farmer used an **8-camp system** for his cattle. Rotation is fast in this system. On each camp, he allowed a short grazing period followed by a long resting period. Usually, the cattle were 9 days in a camp and then there were 63+ days where the camp was not grazed. For the heifers on his farm, he used a **16-camp system**.

One commercial sheep farmer used a **semi-rotational system**, where camps are available but there is no clear rotation, instead the animals are brought to the camp that received recently the most rain. Another commercial sheep farmer used an open system and only has some small camps close to his house where he puts his sheep to protect them from jackals.

On the game farm, an **open grazing system** was used. There were no or rather only few fences (small camps for breeding) within the farm, making it one huge open camp for the game. The game benefits from this freedom of movement (Lindsey et al. 2009) and the different species can choose their preferred habitat, avoid predators and non-beneficial areas.

The communal farmers used an **open grazing system** with no camps. They kept either all of their animals, or at least the small lambs and kids (baby goats), overnight in a small fenced camp to avoid them being killed by jackals or stolen by humans. The farmers reported that the communal farms used to be divided into fenced areas. These camp partitions and infrastructure no longer exist. Nobody cared about the fences back then, so they were broken and often also stolen. All the communal farmers interviewed would appreciate more fences and also more watering points. The watering points were also very scarce and many animals, in addition to the humans that live in the communal area, used the few watering points to drink. Partly there were also animals from neighbouring areas, which will then often be driven away.

Duration of farm ownership

Some farmers had been for a very long time on their farm and inherited it from their parents and grandparents, while other farmers had been on the farm only for several years. The earliest ownership of the farm amongst the interviewees was in 1964 while the latest was in 2008. On average the farmers owned their farm for 50 years.

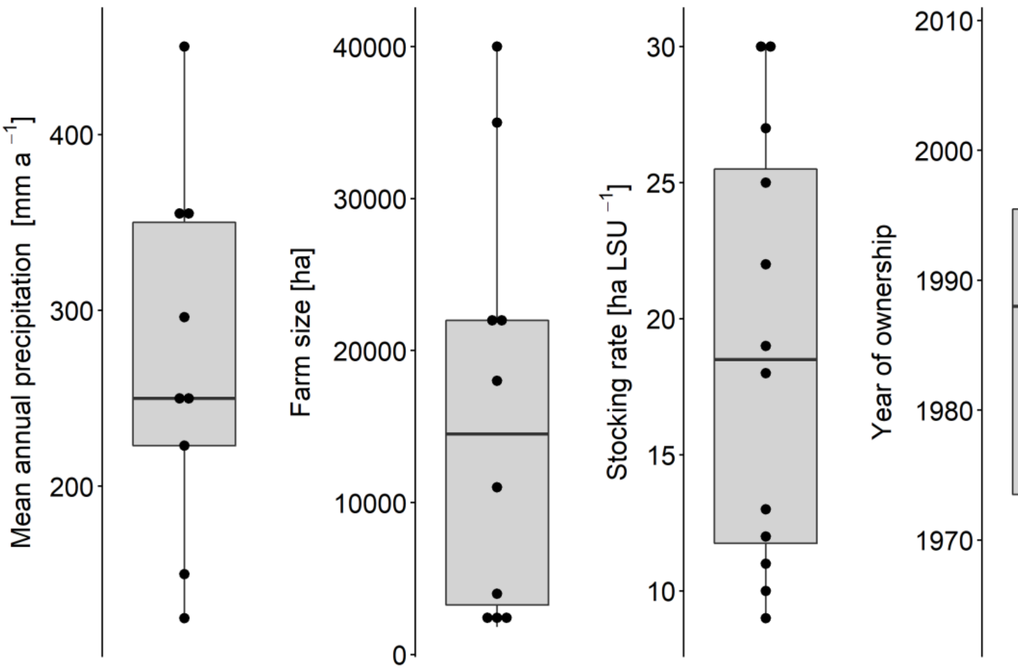

Fig. 9: Mean annual precipitation on the farms, farm size, stocking rate on the farm and year of farm ownership of the farmers interviewed.

2.4.3 Farm size

The farmers we interviewed could be grouped into those running small, medium and large farms. Some farmers had several farms. Farms in dryer areas needed to be larger to sustain the same amount of livestock compared to areas with more rainfall. Amongst the interviewees were four farmers with farms of up to 5000 hectares, four farmers with farms between 5000 and 25,000 hectares and two farmers/communities with a farm area of more than 25,000 hectares (Fig. 9).

2.4.4 Livestock

Most farmers had livestock and game (intended or unintended) on their farms. The most common (intended) animal type owned by farmers was cattle (10 farmers), followed by sheep (5), other livestock (5), wild game (5) and goats (4) (Fig. 10, Tab. 1). Other livestock included horses, donkeys and ostriches.

Animal compositions and abundances were for example:

- Cattle (950), sheep (40), game (400+)
- Cattle (142), goats (71), horses (3), donkeys (2)
- Sheep (300), cattle (29), springbok (75), oryx (34)
- Goats (137), donkeys (6)

Most farmers kept a small amount of sheep for own consumption in addition to their main livestock (Fig. 10, Tab. 1).

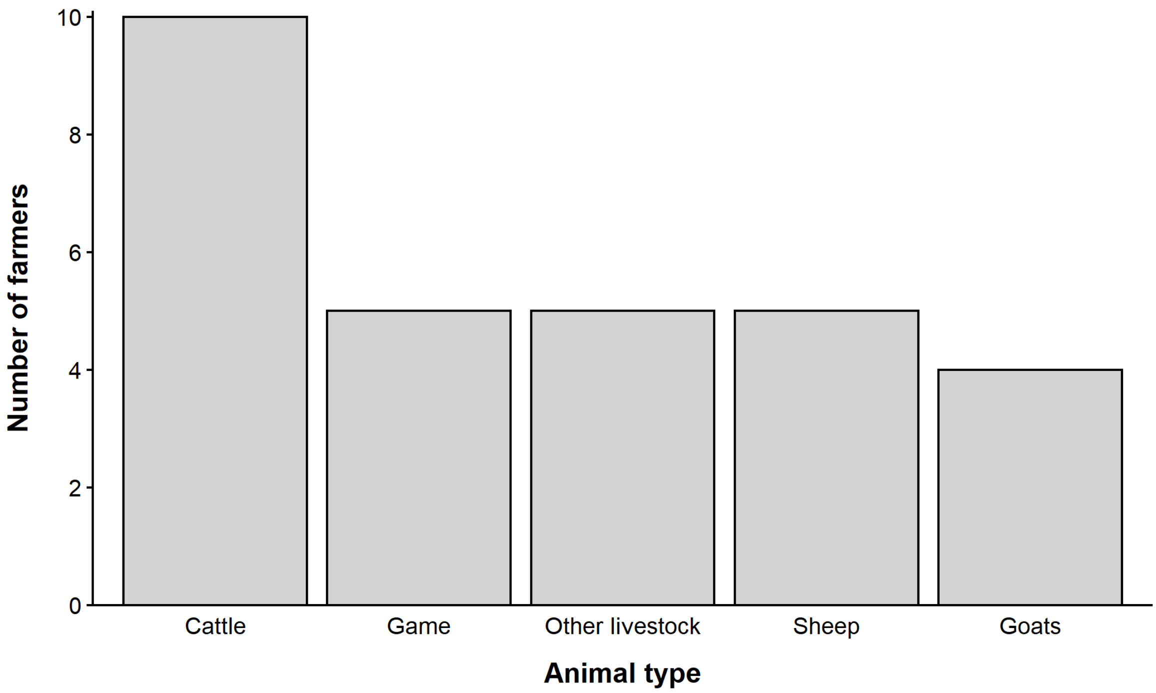

Fig. 10: Animal types owned by the interviewed farmers.

Tab. 1: Land tenure types of the interviewed farmers and their animal types.

Land tenure type	Farm number	Animal type
commercial farm	1	Livestock: cattle, goats, horses, donkeys Game: no information
	3	Livestock: cattle, sheep Game: mainly blue wildebeest, duiker, eland, kudu, oryx, red hartebeest, springbok, steenbok, warthog
	4	Livestock: cattle Game: blue wildebeest, kudu, oryx, steenbok, spring bock
	5	Livestock: mainly cattle, some ostriches Game: no information
	7	Livestock: sheep, cattle Game: no information
	9	Livestock: cattle, sheep Game: many (>1000) springboks
commercial / game farm	2	Livestock: cattle Game: black wildebeest, blue wildebeest, blesbok, cape buffalo, cape eland, duiker, gemsbok, giraffe, impala, kudu, njala, red hartebeest, roan antelope, sable antelope, springbok, steenbok, warthog, waterbuck, zebra
(semi-) commercial farm	6	Livestock: mainly sheep, some cattle Game: springbok, gemsbok, oryx
communal farm	8	Livestock: mainly goats, few donkeys Game: no information
	10	Livestock: goats, cattle, sheep, horses, donkeys Game: almost none
	11	Livestock: goats, cattle, donkeys, horses Game: no information

All farmers agreed that the stocking rate [hectare per livestock unit] will strongly depend on the veld condition, especially on the type of grasses (nutritional value), biomass amount available, and the region. The better the grass in terms of nutritional value and biomass production, the higher grazing pressures are sustainably possible. The farmers used different stocking rates on their farms. The stocking rates mentioned ranged from 9 to 30 ha/LSU with an average of 18.8 ha/LSU (Fig. 9). All farmers that used a rotation system kept the stocking rate on their farms below the grazing capacity of their veld. Game can not only be found on game farms but it occurs on most farms. According to some farmers, it is very important to also consider the wildlife that roams on the farm, when calculating the grazing capacity of the veld and setting the stocking rate for a farm. Some farmers did not mention the consideration of wild game at all, while other farmers were very aware of it and hunted wild game for food or captured it for selling and to avoid overgrazing. One cattle farmer reported for example that he captured and sold about 400 game animals in the year 2013. In another case a farmer counted more than 1000 springboks on his farm that caused a lot of overgrazing. He captured several hundreds of them and removed them from the farm which led to a recovery of the veld. The farmer mentioned that after overgrazing, it can take 20 years for a camp to fully recover, depending on the rainfall. Communal farmers did often not consider stocking rates or, because the land is shared, had no knowledge about the total amount of animals grazing and/or browsing in the area. Sometimes there were community rules that (shall) limit the amount of livestock held by one farming household.

2.4.5 Adaption to drought

In general, there were two adaptions to drought. One strategy was to reduce the stocking rate so that the little biomass that is on the veld will be sufficient for the number of animals. The other was to feed additional fodder to the livestock. The fodder could be bought or grown, harvested and stored beforehand by the farmer himself. It was mentioned that also a mix and slight adaptations of these main strategies are possible. Out of the eleven farmers nine would provide additional fodder in times of drought and two would rather not invest in additional fodder. The animal number will be decreased as a response to drought by six farmers, while five will try to keep the animal numbers on the farm constant.

Supplemental fodder used was:

- Lucerne/alfalfa
- Self-grown, harvested and stored hay
- Maize meal
- Old raisins
- Chicken litter

Most farmers said that they will supply additional fodder and reduce the animal numbers by selling the live animals, or by slaughtering them and selling the meat (Fig. 11). A commercial cattle farmer who was breeding cattle sold the young heifers during dry seasons. He said that he has no other backup plan for droughts other than selling. He actively fluctuated the number of cattle a lot to respond to the conditions of the environment (e.g. high rainfall and biomass production). One farmer mentioned anecdotally that when it has rained a lot and a lot of plant biomass is available on the veld, the birth rate of lambs increases naturally. While another farmer said that when there is a lot of rain and the veld looks good, he sends the ram to the sheep twice a year and so the sheep have offspring twice a year. However, if it is dry and a bad season is on the horizon, he lets the ram go to the sheep only once. For cattle, this farmer mostly considered the prize he can get for an animal. If it is too low (as is often the case during a drought), he will rather keep and feed than sell them. One farmer told us that he will feed chicken litter to his cattle. Additionally, he mixes a tannin inhibitor *browse plus* into the fodder, which shall allow the cows to browse and be able to digest shrubs. He will try to keep the same number of cattle and only sell some calves if necessary. One reason mentioned to not buy additional fodder was that this supplemental food is very expensive; especially in the drought periods when there is a very high demand. One commercial farmer said that he buys Lucerne and maize for the dry season. But when there is an extreme drought he will slaughter 40 % of his cattle directly and then only feed the remaining animals to keep the costs down. A communal farmer said that the well-adapted goat breeds will be able to cope with drought. They will eat gannabos (*Salsola aphylla*) and get some additional fodder. The strong animals will be kept and the weak ones will be sold. Another communal farmer who aims to keep the goat population stable, said that even during an extreme drought, less than 15 % of the goat kids die. Several farmers, who aim to always keep the same number of cattle on their farm, emphasized that it is very important not to overgraze in good times. Instead it may be better and more sustainable to keep the stocking rates permanently a bit lower and to not stock up in good years so that the veld can rest and regenerate and is not continuously under heavy use.

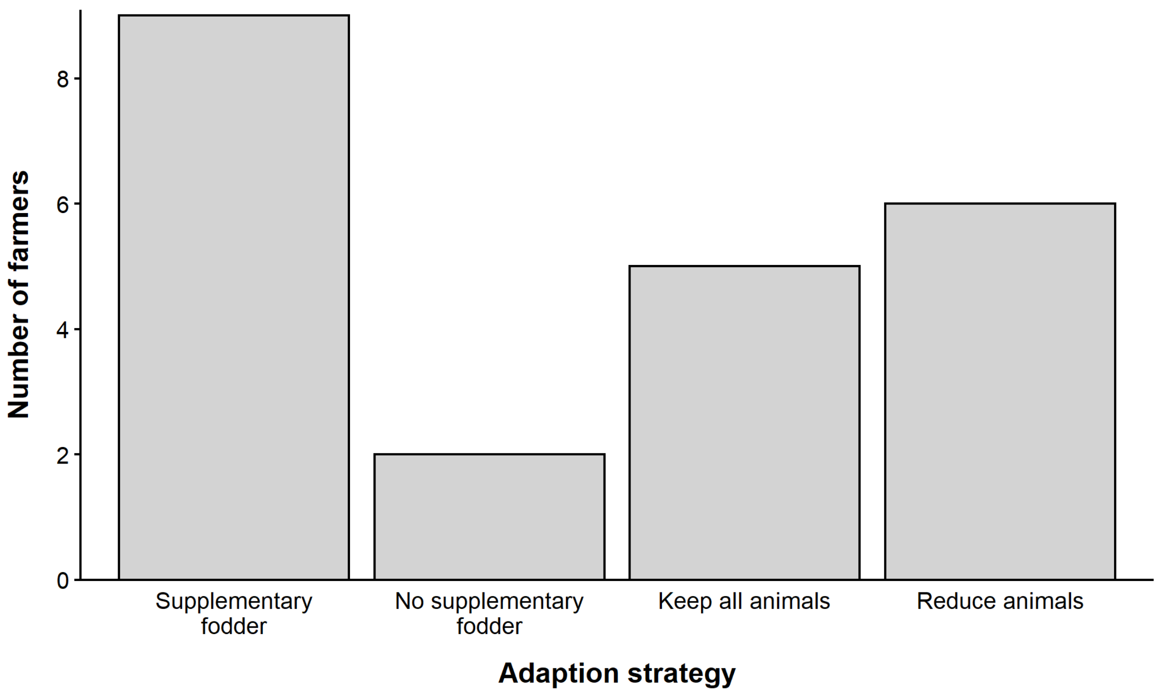

Fig. 11: Adaption strategies of the interviewed farmers to droughts: Supplementary fodder was or was not harvested/ purchased and fed to the animals. The animal numbers on the veld were kept constant or reduced throughout the drought.

2.4.6 Fire management

Fire can play an important role in suppressing bush-encroachment by burning the shrubs and trees severely during an intense hot fire, potentially killing the woody vegetation (Lohmann et al. 2014; Smit et al. 2016). Such fires can be natural events or intentional bush control measures (Geldenhuys et al. 2004). Fires can start to have an impact on savannas with a MAP above 288 mm (Archibald et al. 2009). Some of the interviewed farmers from the Mier area never or rarely experienced fires on their farms, while others had fire incidences regularly, every three years (Molopo area) or even 2-3 times a year (Kimberly area). At high stocking densities, the biomass on the veld might be so low that an intense, potentially deadly fire cannot establish. Another problem mentioned was that a fire destroys all available fodder on a veld and it can take several years for the veld to recover. One farmer said for example that if it rains directly after the fire, the grassy vegetation will regrow quite fast and good, but if it doesn't rain sufficiently for several years, the farmer will have a bad veld for a long time, and the effects of the fire can still be seen after eight years. In combination with the uncertainty of good rainfall, this recovery problem is a big risk that farmers would like to avoid. They do this by creating fire breaks, i.e. stripes with no or little vegetation, either with herbicides, by mowing or through concentrated grazing. Creating fire barriers can slow down or completely stop a spreading fire. Several farmers mentioned that factors such as wind and available fuel (amount of biomass and moisture content) play a very important role in the spread and intensity of a fire. Very strong winds can make it impossible to control a fire because under these conditions fire may be able to cross the fire break. Glowing amber may fly several tenth of meters through the air. Whether the fire risk to a farm is high also depends on the surrounding farms and the biomass on them. Half of the interviewed farmers established fire breaks, while the other half did not.

One farmer in the dry Mier area said for example that he never had a fire on his farm (he has been on the farm since 1972). This is also why he does not establish firebreaks. He also says that woody vegetation (in his case mainly threethorn *Rhigozum trichotomum*) burns well, but that the roots then sprout again after a short time, so fire cannot be used for effectively controlling threethorn encroachment in his area. A farmer from the Mier area reported that in the year 2000 during the rainy season, when a lot of grass was available, he lost 2000 ha of biomass to a fire and in a later year again 500 ha and 600 ha burned down on different camps. One farmer said that because he always fights and has been fighting fires (and with that stopping it from killing shrubs), he now has to kill the bushes manually with fire (he uses selective stem burning to fight bush encroachment). On the communal farms there was no active fire management in terms of fire breaks, since the biomass of grass is already quite low, nor was fire used to fight bush encroachment.

2.4.7 Bush encroachment on the farm

All farmers reported **problems with bush encroachment** and had bush encroached and non-bush encroached areas on their farm. For almost all commercial farmers, this was mentioned as an economic problem. Bush encroachment can drastically reduce the number of livestock that can be stocked on the farm. One farmer mentioned sites with a grazing capacity of 10-12 ha/LSU in non-encroached areas that were drastically altered to a grazing capacity of 48-53 ha/LSU when the sites were bush encroached. Goat farmers were not so strongly affected by bush encroachment because the goats also browse the shrubs and small twigs of trees; thus their motivation to fight bush-encroachment was low. On game farms the bushes can have a positive effect on the game through edge effects (intersection of different habitat types that cover the needs for food and shelter) and increased vegetation cover. Also the (economic) impact of bush encroachment depends on the composition of grazers, browsers and mixed-feeders in the game portfolio on the farm. The bush encroachment was especially strong on communal farms. All interviewed farmers mentioned a more or less strong **increase of bush encroachment** on their farms over the last years and decades. One farmer remembered that he used to drive around on the farm everywhere with an all-terrain vehicle (ATV) when he was a teenager; but over the last 25 years the bush cover increased so much that it is not easily possible anymore to drive everywhere with an ATV. This experience from the past made him aware of the problem and let him search for the right, sustainable and adaptive grazing strategies so that at least the rapid spread of the woody vegetation is slowed down.

2.4.8 Fighting bush encroachment with arboricides

Arboricides where either applied as a non-selective chemical treatment or as selective treatment, targeting unwanted species. One of the benefits of non-selective treatment is that it can be applied via airplane. This is economically advisable at bush encroachment severities of 1500 tree equivalents and more per hectare (Harmse et al. 2016). A tree equivalent (TE) is defined as a 1.5 m tall tree or shrub (Tainton 1999). Amongst the interviewed farmers, measures against bush encroachment were taken in most rotation systems (commercial cattle farming) as well as in the open grazing/browsing systems (commercial game farms and game reserve). In the communal (open grazing) farms there were no active measures again shrub encroachment in place. Selective chemical treatment was applied in case of lower bush encroachment severity or when, for example fodder and shade trees needed to be saved. This treatment was done with products such as *Molopo CC* granules, *Bushwacker GG, Grazer,* or *Limpopo*. Dosage depended on the shrub/tree density in the area (e.g. 2.5 - 3kg/ha, or 2-3 granules for a tree). These granules were put close to the stems of unwanted species. Farmers used them especially against *Acacia (Senegalia) mellifera*, *A. luederitzii*, *A. hebeclada*, *A. tortilis, Dichrostachys cinerea* and *Terminalia sericea*. The height classes of the trees were not considered. Species not treated with chemicals were *Grewia flava*, *Acacia (Vachellia) erioloba* and *Boscia albitrunca*. When the herbicide pellets are distributed in the veld for selective bush control, it still needs a certain amount of rain for the chemicals to get into the soil and start working. Manual application of herbicides was usually done every year for some different parts of the farm (one farmer applied it on 800 ha in a year). At other farms, it was manually applied every 2-3 years, or only when there is money left that can be invested in the veld. After a treatment against bush encroachment, follow-up treatments needed to be done, for example, in years 2 and 4 or 5-6 after the initial treatment, depending on chemical, the method used, and farmer experience. But a re-application of the chemicals was sometimes not done at all. Financial constraints were one reason for omitting the reapplication.

The practice of stem burning was used on a cattle farm in the North-West Province. Here a fire is set at the stem of selected trees to kill them. This method is labour intensive and thus quite expensive nowadays and not practiced much anymore. One farmer preferred this method because he distrusted the chemicals and thought that they will persist and stay active in the ground longer than advertised and have a negative effect on beneficial, wanted species (also mentioned by Dreber et al. (2019)).

For a game farm, trees and shrubs are welcome structural components because game likes edges (transitions between trees/bushes and grass areas) because they offer both protection and fodder (Tews et al. 2004). So it is ideal to have a lot of these edges. One way of achieving this is by spraying an arboricide via airplane in a checker board pattern fashion. This was done by one of the interviewed farmers and it creates an impressive pattern, easily visible on satellite images (Fig. 12). But on this farm the follow up treatments and measures in areas with less BE or with many beneficial tree species that should be kept, were also done manually by hand. Some farmers remarked that they reseed nutritious grasses in some parts of the farm as an additional measure to increase the quality of the veld. A few communal farmers expressed the wish that the government or scientists should start a project against bush encroachment and take the initiative in combating shrubs on their communal farm. For these communal areas, *extension officers* are an important link between recommendations from experts for example about good and/or new management methods and the individual farmers, some of whom do not have good internet access. One farmer mentioned anecdotally that there used to be a lot more seed boring beetles in the Acacia's seed pots destroying the seeds. However, these seed predators have been significantly reduced by the increased use of herbicides and are now no longer present in such large quantities. This has significantly weakened one of the antagonists of shrub encroachment.

Fig. 12: Farm where a chemical application was done via airplane in a checker board pattern (Google images © 2021 CNES / Airbus, Landsat / Copernicus, Maxar Technologies, map data © 2021 AfriGIS (Pty) Ltd).

2.5 Deductions for the model

The interviews provided an insight into the different types and strategies of farm management. According to the interviewees, the distinction between commercial and communal farming is most important to be considered in the model. This distinction should be mainly expressed through a rotation system vs. an open grazing system and the presence or absence of the motivation to sustainably improve the condition and infrastructure of the farm. Also, the farm infrastructure in terms of arrangement of camps (if used) and watering points was often mentioned. Another central parameter was the stocking rate on a farm which is set by the farmer. It is usually set depending on the type and abundance of vegetation. A common problem was the increasing amount of woody species in the vegetation composition on the farms. To fight shrub encroachment and alter the vegetation types, a set of management options are available such as chemical control, active fire management, adaption of stocking rates, especially during drought periods to avoid overgrazing. To improve the model even further, it would be beneficial to interview more farmers to get a broader view of the frequency of the different management practices and decisions as not every farmer manages the farm the same way. Also further interviews with more in-depth questions about the parameters and variables that will be identified as very sensitive in the model will be very beneficial for future adaptions and extensions of the model.

In summary, the interviews identified important factors and processes that must be present in a rangeland simulation model and that we considered during the creation of the landscape generator and the simulation model.

3 PioLaG: A piosphere landscape generator for savanna rangeland modelling

As it became clear from the interviews, there are very different concepts and management principles among farmers. To set up and parametrize a simulation model, it is not sufficient to simply use aerial images because the current management situation is often unknown and would need to be determined by e.g. questionnaires. But also then, historical management actions and fine scale environmental heterogeneities and effects of the past may remain unknown. These circumstances make it urgently necessary to use landscape input data created under controlled conditions for running different scenarios in rangeland models. By this we can exclude external effects on the landscape patterning. A major benefit is also that a farmer or other stakeholder can precisely create a landscape according to his/her wishes and experience. For creating such user-defined, exemplary yet realistic landscapes, we developed the piosphere landscape generator 'PioLaG'.

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3.1 Abstract

Context

Piospheres describe herbivore utilization gradients around watering points, as commonly found in grass-dominated ecosystems. Spatially explicit, dynamic models are ideal tools to study the ecological and economic problems associated with the resulting land degradation. However, there is a need for appropriate landscape input maps to these models that depict plausible initial vegetation patterns under a range of scenarios.

Objectives

Our goal was to develop a spatially-explicit piosphere landscape generator (PioLaG) for semi-arid savanna rangelands with a focus on realistic vegetation zones and spatial patterns of basic plant functional types around livestock watering points.

Methods

We applied a hybrid modelling approach combining aspects of both process- and pattern-based modelling. Exemplary parameterization of PioLaG was based on literature data and expert interviews in reference to Kalahari savannas. PioLaG outputs were compared with piosphere formations identified on aerial images.

Results

PioLaG allowed to create rangeland landscapes with piospheres that can be positioned within flexible arrangements of grazing units (camps). The livestock utilization gradients showed distinct vegetation patterns around watering points, which varied according to the pre-set initial rangeland condition, grazing regime and management type. The spatial characteristics and zoning of woody and herbaceous vegetation were comparable to real piosphere patterns.

Conclusions

PioLaG can provide important input data for spatial rangeland models that simulate site-specific savanna dynamics. The created landscapes can also be used as a direct decision support for land managers in attempts to maintain or restore landscape functionality and key ecosystem services such as forage production.

3.2 Introduction

In arid and semi-arid rangelands worldwide, livestock utilization gradients around watering points are commonly used to investigate the ecological effects of grazing on the biotic and abiotic environment (e.g. Adler and Hall 2005; Peper et al. 2011; Wesuls et al. 2013). These so-called 'piospheres' (Lange 1969) are ideal model systems to understand the interplay between grazing, vegetation, and the abiotic environment and can be used to guide range management with respect to landscape functionality and rangeland productivity (Thrash and Derry 1999). Thus, piospheres should be incorporated into more detailed rangeland simulation models that aim at understanding vegetation dynamics under different land-use and climate scenarios.

A piosphere can be understood as a spatially concentrated form of land degradation. It derives from a radial symmetry of ecological impacts around watering points (or similar animal concentration points like stables or kraals). The livestock density per unit area - and thus effects of grazing, trampling, and faeces accumulation - is highest in direct vicinity to the watering point and decreases with distance from it until effects start to vanish in the rangeland matrix (Andrew 1988), which may appear in a few hundred meters or several kilometres distance. A characteristic vegetation zoning develops, which commonly includes a largely vegetation-free 'sacrifice zone' at the watering point, a zone of denser woody vegetation with reduced grass cover ('bush thickening'), and beyond this a transition into the typical vegetation composition and structure with usually increasing occurrences of perennial palatable forage grasses (Tolsma et al. 1987; Jeltsch et al. 1997b; James et al. 1999; Thrash and Derry 1999). Along this gradient, the spatial distribution of plant species and plant functional types show specific response patterns in their frequency and cover according to the plants' niche breadths, i.e. the ability to cope with different intensities of livestock disturbance and related changes in biotic interactions and the abiotic environment (van Rooyen et al. 1991; Heshmatti et al. 2002; Todd 2006; Wesuls et al. 2013).

Though the degradation of vegetation and soil around watering points may represent a permanent state with a low inherent capacity to regenerate (e.g. Jeltsch et al. 1997; Croft et al. 2007), piospheres are not static in time and space. Their overall shape, spatial extent, and the zone-specific vegetation formation may vary considerably with factors such as age of watering point and land-use history, precipitation pattern and season, grazing system and stocking rate, type of livestock, size of management units (camps or paddocks), or due to environmental gradients (Perkins and Thomas 1993; Jeltsch et al. 1997b; James et al. 1999; Derry 2004; Washington-Allen et al. 2004; Smet and Ward 2005). Hence, piospheres can show considerable spatial and temporal variation in both the quantity and quality of forage resources. This can have ecological and economic consequences that are highly relevant for animal production systems (Tainton 1999; Todd 2006).

Therefore, models of rangeland vegetation dynamics at local (e.g. camp) to landscape (e.g. farm) scales should preferably include the ecology and management of livestock in relation to watering points (Duraiappah and Perkins 1999). While it is possible to initialize spatial simulation models with field data or remotely sensed maps, the ability to generate a range of plausible scenarios is a powerful means for systematically understanding ecological processes (Pe'er et al. 2013). In this regard, complementary to simulation models of grazing gradients, landscape generators can be effective tools.

Landscape generators tend to be less complex than ecological simulation models concerned with the spatiotemporal dynamics of natural systems. Landscape generators are widely used in ecology to systematically create landscapes ranging from near-natural landscapes to artificial extremes for a better understanding of scale-dependent interactions and processes that shape landscape patterns (Gardner et al. 1987; With and King 1997; van Strien et al. 2016). There are basically two approaches to create such patterns by means of landscape generators: process-based and pattern-based (Pe'er et al. 2013). Process-based landscape generators take into account interactions between the different agents in a landscape and their interaction with the environment both in space and time. Agents are collective or individual objects in the observed system (such as livestock or vegetation) that underlie biological and physical processes. Pattern-based models generate realistic landscapes focusing on spatial characteristics of the landscape irrespective of the underlying processes acting in nature (Pe'er et al. 2013). While there exist many different approaches to model piospheres (Thrash and Derry 1999; Derry 2004; Adler and Hall 2005; Frank et al. 2012; Wesuls et al. 2013) for strengths and weaknesses of some), these focus primarily on the emergence of patterns without providing contextualized landscapes as input for simulation models.

In the present study, we report on the development of a piosphere landscape generator (PioLaG) based on a hybrid modelling approach that combines aspects of both process- and pattern-based modelling. PioLaG was originally designed as a complementary component of a spatially-explicit rangeland simulation model for southern African savannas (www.idessa.org) in order to provide vegetation input maps in a user-defined farm setting with realistic, yet modifiable piosphere formations and landscape representations. To our knowledge there is currently no such landscape generator available. Here we introduce and describe the model underlying PioLaG and illustrate model performance with respect to the formation of vegetation patterns around watering points. Results are discussed with respect to the general functionality of PioLaG, its behaviour under varying pre-settings defining the environment and management regime, and how well real-world patterns are resembled. Complementary to the model description, we also outline steps in model validation by means of real piosphere formations identified on aerial images covering portions of our reference savanna system (Supplementary material B.1).

3.3 Methods

The ODD (Overview, Design concepts, Details) protocol standardizes the description of individual-based simulation models (Grimm et al. 2006, 2010). In absence of such a protocol for landscape generators, we follow the ODD protocol as closely as possible.

3.4 Overview

3.4.1 Purpose

The overall aim was to generate piosphere patterns under a range of environmental and management conditions. In order to serve vegetation modelling and decision support in rangeland management, generated landscapes should feature the number and spatial arrangement of management units (hereafter referred to as 'camps'), the number and position of livestock watering points therein, as well as the spatial distribution and abundance of different vegetation components defining the overall rangeland condition. PioLaG was conceptualized in reference to Kalahari thornbush-type savannas typically found in northern semi-arid South Africa and bordering Botswana (Mucina and Rutherford 2006). Here, increased livestock activity and grazing pressure around watering points and kraals, and the concomitant reduction in perennial grass cover and suppression of fire is seen as a primary cause of present bush thickening (encroachment of indigenous species) over extensive areas (Perkins and Thomas 1993; Reed et al. 2015; Harmse et al. 2016). Though the application ability of PioLaG should not be restricted to this region, its parameterization was based on the ecology of this savanna type and typical forms of local land use and range management. The underlying model was kept as simple as possible in operating with dominant plant functional types, rule-based biological, pedological, and meteorological information, as well as local and expert knowledge.

3.4.2 Entities, state variables, and scales

PioLaG is spatially explicit and has no temporal progression. The modelled landscapes are grid-based, with cells 30 m × 30 m in size being the basic entity of the model. This cell size was chosen as a middle ground between a very detailed resolution (e.g. 0.5 m x 0.5 m) which requires extremely high computational power, and on the other hand a spatial scale that is too coarse to depict patterns and dynamics of different vegetation components or plant functional types, that are relevant for management purposes. Moreover, piosphere zones would become more difficult to differentiate (e.g. at 250 m x 250 m). Each cell is assigned several state variables, the most important ones being dominant vegetation type, piosphere zone, and herbivore-use intensity. For simplicity and broad applicability, the model only considers basic plant functional types and 'bare ground' (altogether referred to as 'dominant vegetation type', or short 'vegetation type') (Fig. 13). There are six dominant vegetation types: bare soil, annual grasses, unpalatable and palatable perennial grasses, as well as young and mature woody vegetation. Dominant woody vegetation corresponds to bush thickening and subsumes both trees and shrubs. A piosphere zone is the distinct, roughly circular, area of a given vegetation type. Jointly, the zones form the piosphere. The herbivore-use intensity quantifies the impact of livestock on the rangeland depending on the distance to watering point and the stocking ratio (see below). While cell properties define the conditions at the local scale, several cells can define spatially confined conditions of larger spatial extent, i.e. at the multi-cell scale (e.g. clumps of woody vegetation in a grass-dominated matrix). The extent of a landscape is not pre-determined and should be chosen to encompass at least one piosphere. Here we use 400 × 400 cells. Parameters related to climate, soil, and the overall grazing regime are to be set for the landscape scale.

3.4.3 Process overview and scheduling

The PioLaG landscape generator considers the complex structure of effects from different factors, state variables, and parameters that interact with each other through different processes (Fig. 13). The temporal sequence of the related computational steps (Fig. 14) is rather secondary, except for initialization and farm setup. In the following, the single steps are briefly described. Information about their implementation and related calculations are detailed in section 'Submodels' below. The model was implemented in NetLogo 5.3.1., an agent-based programmable modelling environment (Wilensky 1999).

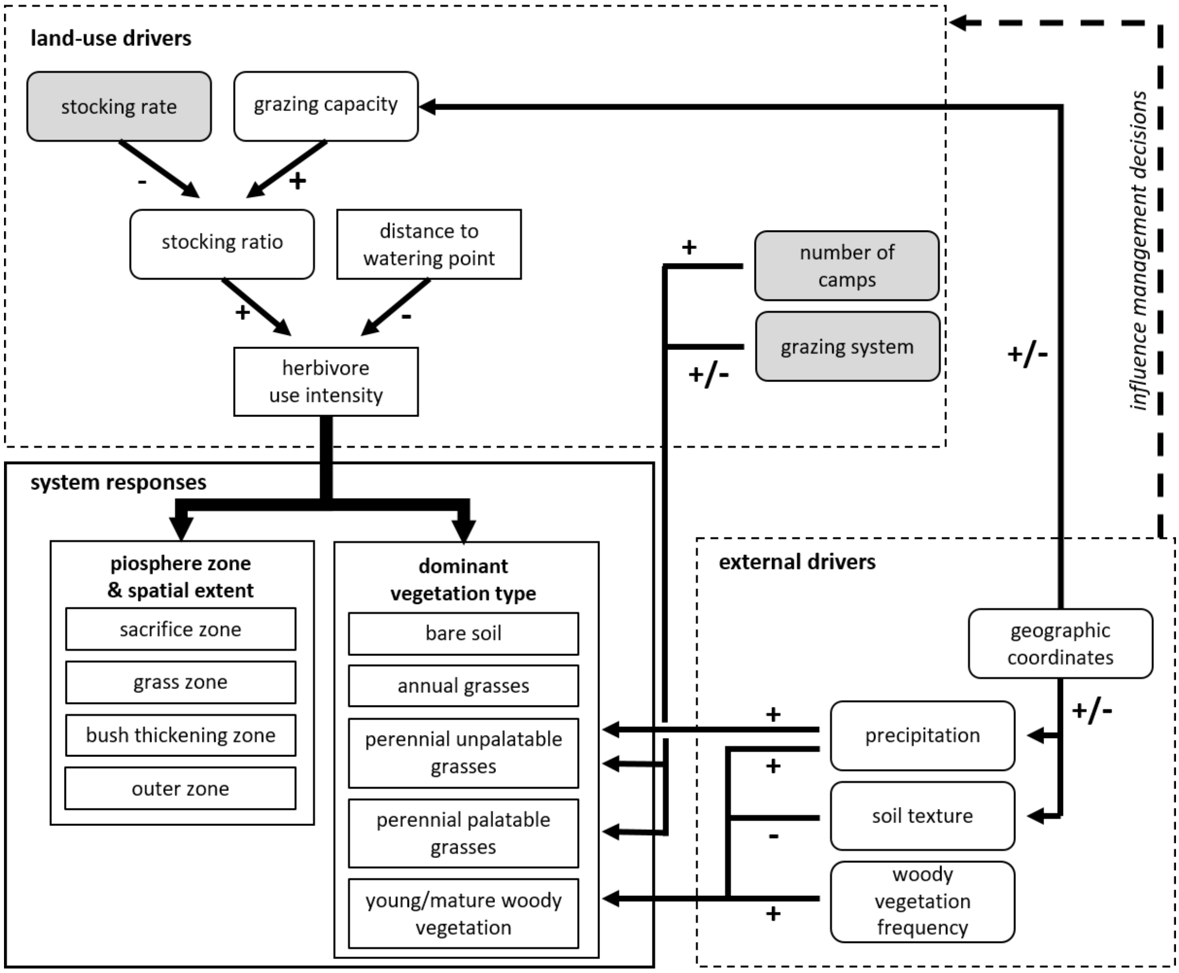


Fig. 13: Causal diagram of the PioLaG model showing global parameters (rounded boxes), local cell state variables (square boxes), and their positive (+) or negative (-) causal relationships. The target output variables are shown in the lower left. Primarily external drivers (right part) influence rangeland decision making (dashed arrow), i.e. they determine the internal land-use drivers (upper part). External and internal drivers jointly determine the system responses, i.e. the vegetation response to herbivory at a cell level (bottom left).

A simulation begins with the setting of global parameters, especially regarding precipitation and soil texture, and the initialization of cell variables. In addition, farm size, exact positions of watering points, and camp layout (arrangement of camps and fences) are set. Next, stocking ratio and herbivore-use intensity (HUI) are calculated for each camp. Each watering point is assigned the highest HUI of all camps associated with a specific watering point. This is because the highest HUI will be used as the upper boundary for calculating the relative probability of the different vegetation types and with that of the piosphere zone widths (Tab. 3). Upper bounds for the frequency of 'woody vegetation' cells are calculated depending on MAP and soil texture. Next, the user-defined initial abundance (cell frequency) of (young/mature) woody vegetation is implemented and considered in the calculation of the final overall abundance of woody vegetation. After these preparatory steps, the actual landscape generation begins. The extent of each piosphere zone is classified based on the herbivore-use intensity values of the cells (Tab. 3). Subsequently, the different vegetation types are distributed on the landscape randomly, based on piosphere zone-specific probabilities. This constitutes the final map of vegetation types. If rotational grazing is used, however, its positive effect on vegetation regeneration is additionally considered via an increase of cells dominated by perennial grasses. Finally, vegetation map, used parameters, and variables are saved for further analysis and use.

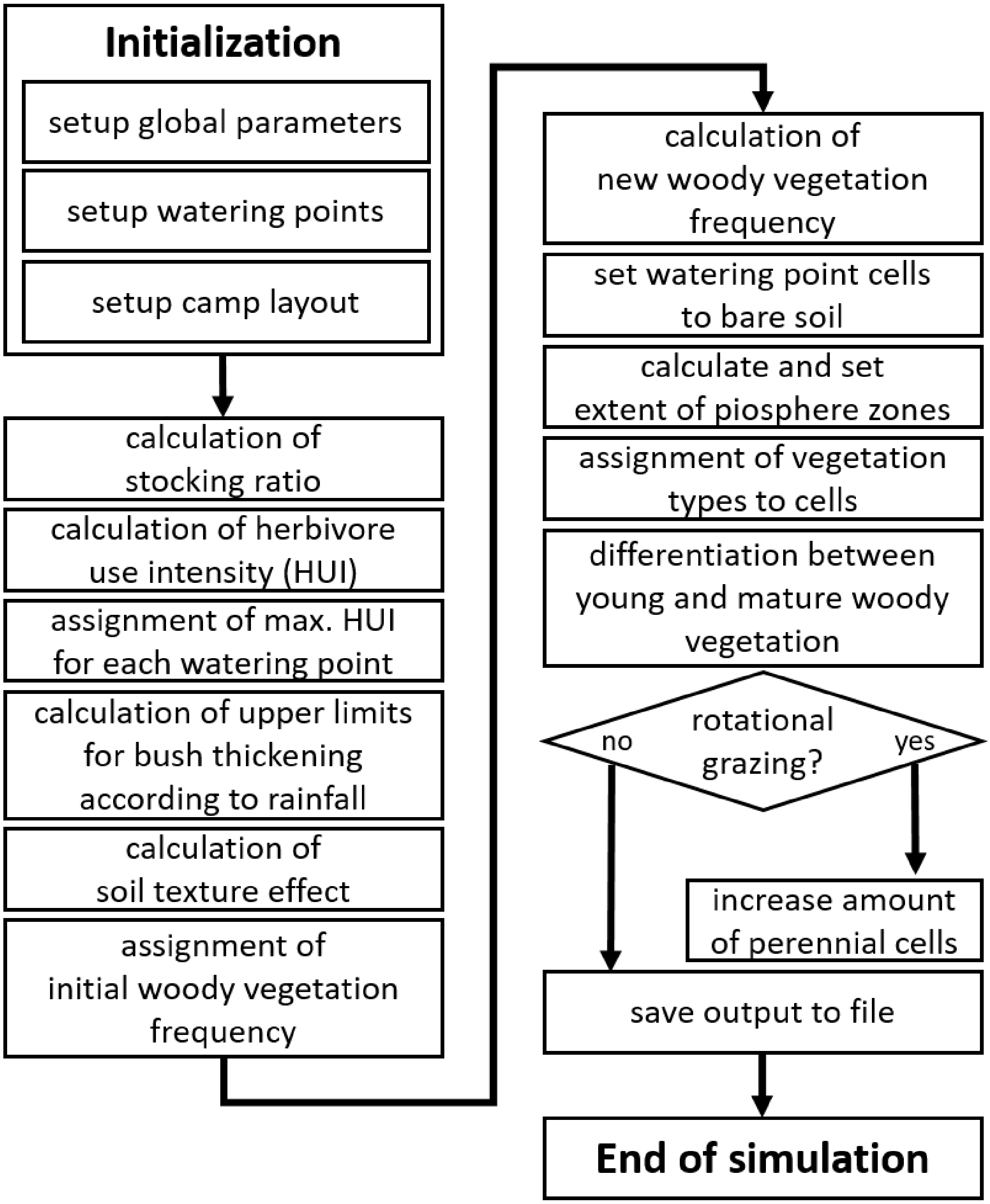


Fig. 14: Flowchart depicting the process overview and scheduling within the PioLaG model.

3.5 Design concepts

3.5.1 Basic principles

PioLaG is a spatially-explicit, hybrid landscape generator, combining properties of process-based modelling (e.g. the effect of precipitation and soil texture on woody vegetation abundance and increased herbivory effects close to watering points) and pattern-based modelling (e.g. zonation of vegetation and clustering of similar vegetation types) (cf. Pe'er et al. 2013). The basic principles underlying this model are the vegetation response to internal and external drivers. The main internal driver is the distance-dependent herbivore-use intensity around livestock watering points. External drivers include precipitation and soil texture, which determine the general environment and are unaffected by local vegetation properties (Fig. 13). At this, the piosphere formation or zoning is based on the assumption of different plant-specific abilities to cope with a certain level of livestock-induced disturbance, as well as differences in attractiveness to livestock (palatability). Vegetation patterning is further influenced by processes like favourable conditions for grass establishment depending on precipitation and scarcity of woody vegetation.

3.5.2 Emergence and interaction

By being spatially-explicit, PioLaG takes into account the fact that spatial patterns (at landscape scale) emerge from ecological processes that usually take place at other spatial scales (e.g. local interactions among vegetation, livestock, and watering points and interactions with global/external drivers) (Levin 1992). The main emergent properties and key outputs of the model are the herbivore-use intensity for each cell and the spatial distribution of dominant vegetation types. Herbivore-use intensity and spatial vegetation distribution shape the circular vegetation zoning around each watering point. At the landscape scale - intended to cover a whole farm or communal rangeland - specific piospheres emerge that can display patterns ranging from quite homogeneous to highly heterogeneous savanna vegetation. By assigning a dominant vegetation type to each cell, the outcome of competition between different vegetation types like tree-grass interactions is modelled indirectly. PioLaG also considers how the user-defined livestock-, farm infrastructure-, and management settings interact with environmental conditions, available resources, and natural processes.

3.5.3 Stochasticity

Vegetation types are randomly assigned to cells, based on piosphere zone-specific probabilities (Tab. 3). These probabilities depend on herbivore-use intensity, MAP, and soil clay content. Thereafter, the resulting spatial distribution of vegetation types is slightly rearranged to achieve clustering of woody vegetation. In case of a rotational grazing system, the ratio of perennial grasses to other vegetation types is increased depending on the duration (and resting) of grazing and on precipitation.

3.5.4 Observation

A main outcome of PioLaG are landscape maps with information about distribution and abundance of vegetation types (in terms of cell frequencies). Further, grazing pressure is determined both for each single cell and per camp unit. The context-specific vegetation zoning and pattern formation can provide an informative basis about the causal relationships of management decisions and their environmental consequences.

3.5.5 Input data

Various input data are needed to run the model (see Tab. 2 and supplementary material B.2). For the current parameterization, some data were directly extracted or calculated from available maps and databases based on GPS coordinates (i.e. precipitation and soil texture) or set manually by the user. Information and data used for parametrization available in peer-reviewed literature were often directly transferable to the model or could be used to develop and improve formulas, such as extents of piosphere zones, vegetation distributions or the effect of clay content and rainfall on shrub encroachment or bush thickening. Other data (e.g. realistic and common values for the number of camps, camp layout, number and position of watering points) were derived from discussions and expert interviews. We held semi-structured interviews with a total of eleven Kalahari farmers in March 2014, with in-depth discussions of specific management practices depending on area, environmental conditions, type of farming and animals kept, etc. We also discussed model features and management practices in the frame of a series of workshops, one with rangeland experts (July 2016, Kimberley, South Africa; 25 participants) and two with commercial farmers (February 2017, Ganyesa and Askham, South Africa; 29 and 28 participants, respectively).

Tab. 2: Overview of the input data needed to run a PioLaG simulation with description and source.

	Input	Unit	Description	Source
Management	Spatial coordinates	degree	Spatial location of farm	User/GPS data
	Farm size	ha	Extent of the farm i.e. simulation extent	User/GPS data
	Camp number	Unit	Total number of camps	User/Farm data
	Camp layout	categorical	Square camps or wagon-wheel system	User/Farm data
	Number and position of watering points	Unit	Total number of watering points on the farm	User/Farm data/classified satellite images
	Stocking rate	ha/LSU	Available hectare per large stock unit	User/Farm animals inventory
	Management type/ Grazing system	categorical	Rotation system or continuous grazing	User
Environment	Number of bush-thickened camps and severity	amount categorical	Have events in the past led to bush thickening in some camps?	User/Farm history data/satellite images
	Grazing capacity	ha/LSU	How much livestock can the farm support sustainably?	User/Farm vegetation inventory/grazing capacity map by the government (Republic of South Africa 1993)
	Soil type/clay content	%	Clay content in the soil	SOTER database for southern Africa (5×5km average resolution) (Batjes 2004)
	Rainfall data	mm/a	Mean annual precipitation	CHIRPS data archive (6×6km average resolution) (Funk et al. 2015)

3.6 Submodels

3.6.1 Initialization: Global parameters

For global parameters, the MAP and relative clay content (as an indicator of soil texture) are read from ASCII maps. The values for MAP and clay content were taken from the CHIRPS dataset (Funk et al. 2015) and the SOTER-based soil dataset for southern Africa (Batjes 2004), respectively. The value for the grazing capacity is available in official grazing-capacity maps for the respective area or has to be estimated based on the condition of the grass sward at the location. In our scenarios we used typical grazing-capacity values for the study region (Republic of South Africa 1993).

3.6.2 Initialization: Farm setup

The farm setup includes parameters for farm size and camp arrangement. The water requirements and water utilization of livestock is highly variable among types of animals and dependent on many factors such as foraging behaviour and physiology (Derry 2004). If not being forced to walk longer distances, cattle can be assumed to forage in an area of 3 km around watering points (Tolsma et al. 1987). In South Africa, farm camps in commercial systems are often smaller in size than, for example, in Australia or compared to rangelands in communal areas of South Africa. Accordingly, grazing gradients are usually much shorter and between 1-2 km (Smet and Ward 2005), which corresponds to a typical Kalahari 4-camp grazing system with 800-ha camps (Keyser, pers. comm. 2017). However, camps may be smaller and possess two watering points less than 1 km apart, resulting in overlapping piospheres. In contrast, in unfenced Kalahari savannas, the often observed zone of bush thickening may extent over several kilometres (Reed et al. 2015).

PioLaG offers two basic options for camp arrangement according to what is commonly found in the semi-arid Kalahari region: (a) camps in grids or rows with watering points, often installed at central junction points; (b) pie-shaped camps in a wagon-wheel fashion with a central watering point (Supplementary material B.3, Fig. B. 2 and Fig. B. 3). However, the number of watering points is flexible and they can be placed anywhere within a camp.

3.6.3 Calculation: Stocking ratio

The stocking rate describes the average area of rangeland made available to each livestock unit and is a key parameter of rangeland management (Trollope et al. 1990; Allen et al. 2011). The stocking rate affects vegetation condition and composition according to animal density and herbivore-use intensity. Hence, it depends on factors like season, precipitation, and herbage production. In this regard, within PioLaG, the stocking ratio sets the stocking rate into relation to the grazing capacity of the rangeland, where grazing capacity is the actual area needed to keep an animal without detrimental effects on the rangeland (Trollope et al. 1990). The stocking ratio is calculated as:

$$stocking\ ratio = \frac{grazing\ capacity\ [ha\ LSU^{-1}]}{stocking\ rate\ [ha\ LSU^{-1}]} \tag{1}$$

An LSU refers to a large stock unit defined as "an animal with a mass of 450 kg and which gains 0.5 kg per day on forage with a digestible energy percentage of 55 %" [Meissner (1982) cited in Trollope et al. (1990)]. To keep the model simple, PioLaG differentiates classes of stocking ratios that are based on discussions with Kalahari farmers and rangeland scientists in 2017: 'understocked' (if stocking ratio < 0.9), optimally stocked (≥ 0.9 and < 1; i.e. stocking rate slightly below grazing capacity), 'overstocked' (≥ 1 and ≤ 1.5) and 'severely overstocked' (> 1.5) (see also supplementary material B.2, Tab. B. 1).

3.6.4 Calculation: Herbivore-use intensity

The herbivore-use intensity (*HUI*) describes the livestock effect on a rangeland. It considers grazing and browsing effects, as well as trampling and excretions by the animals [Georgiadis (1987) cited in Perkins and Thomas (1993)]. In PioLaG, *HUI* is used as an auxiliary variable and is calculated using a decreasing logistic function of the cell's distance to the nearest watering point (*dToWP* [m]), a stocking ratio classes-dependent stocking factor *sF* (adjusting the steepness; compare supplementary material B.2, Tab. B. 2), and the calibration constant c_1 = 0.005 m^{-1}:

$$HUI = \frac{1}{(1 + (0.1 \times e^{(-2+(c_1 \times sF \times dToWP))})} \tag{2}$$

The lower the *HUI*, the lower the livestock impact on the cell. The adjustment of the parameters of the logistic curve alters the gradient of the slope according to how heavily stocked the farm camps are (Fig. 15). With increasing stocking rate (i.e. smaller stocking factors when grazing capacity stays the same), *HUI* decreases less steep with increasing distance to watering point, because livestock pressure would be higher and spread out over a larger area. Under an overstocking scenario (*sF* = 0.8), *HUI* approaches zero not before 2.5 km from the watering point. In contrast, understocking (*sF* = 1.5) results in a relatively early drop of *HUI* towards zero already at a distance of about 1.3 km (Fig. 15). When there is no livestock (stocking rate = 0), *HUI* is uniformly set to one across the modelled landscape to account for grazing wildlife.

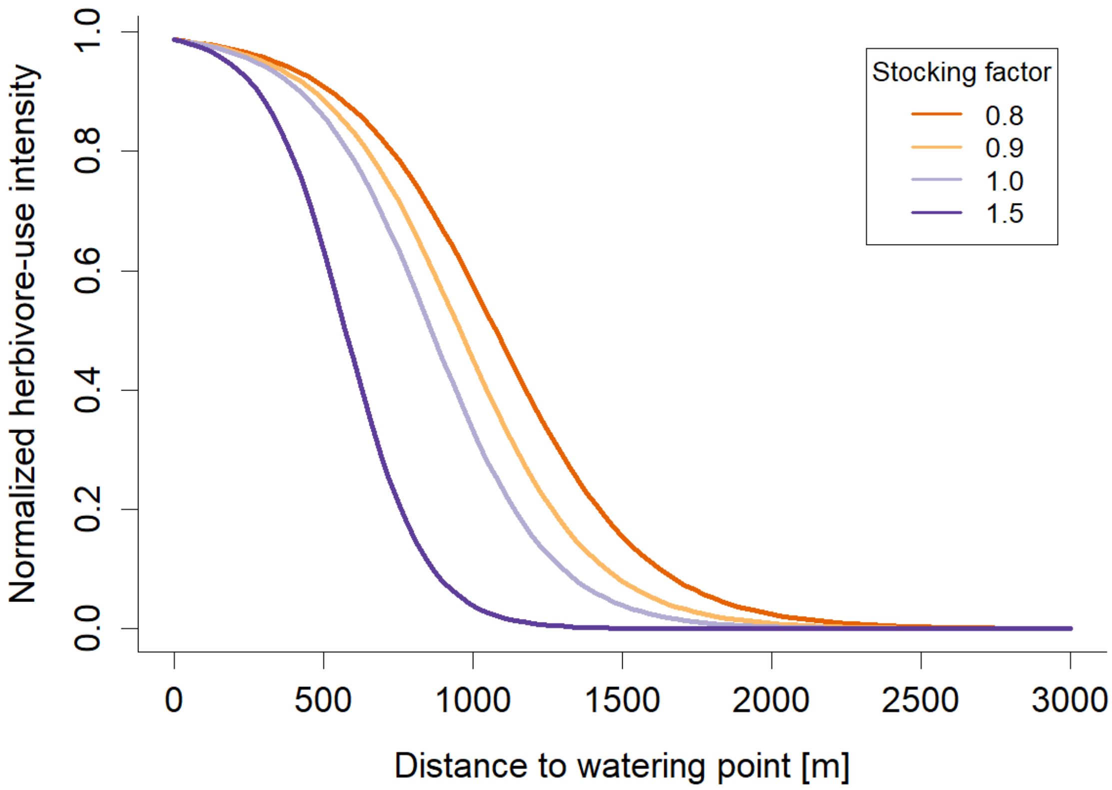


Fig. 15: Relationship between normalized herbivore-use intensity (HUI) and distance to watering point for stocking factors sF = 1.5, 1.0, 0.9, and 0.8 assigned to the stocking ratio classes understocked, optimally stocked, overstocked, and severely overstocked, respectively.

3.6.5 Initialization: Mean annual precipitation and clay content

An important driver of grass:woody vegetation ratios in savanna systems is the amount of precipitation, which is crucial for seed production and seedling establishment, especially of woody species (Barnes 2001; Joubert et al. 2013). In semi-arid African savannas, maximum cover of woody vegetation increases linearly with MAP, but seldom reaches its maximum potential due to frequent disturbances and interactions with other factors affecting the soil water regime (Sankaran et al. 2005). We use clay content as an indicator of soil texture as it was shown to be the most important soil property influencing bush thickening dynamics. Fine-textured clay soils have smaller pores and lower rain water infiltration compared to sandy soils, thus diminishing growth of trees and counteracting an increase in density or cover of woody species even under otherwise favourable conditions and especially during high rainfall years (Kgosikoma et al. 2012; Grellier et al. 2014). Accordingly, *MAP* and soil clay content are parameters used in PioLaG to set upper bounds of possible woody vegetation cell frequency. The effect of *MAP* is calculated based on the linear regression model from Sankaran et al. (2005) with the constant c_2= 0.14 mm^{-1} a:

$$\text{Upper bound of bush frequency (\%)}: maxBush = \frac{(c_2 \times MAP[mm\, a^{-1}]) - 0.42}{100} \qquad (3)$$

The effect of soil clay content on vegetation is accounted for by differentiating the classes low (< 0.3 %), medium (≥ 0.3 % and < 0.5 %), and high (≥ 0.5 %) clay content. These classes are assigned different factors (compare supplementary material B.2, Tab. B. 2) to influence the vegetation type probability of a cell (see also below).

3.6.6 Initialization: Increased woody vegetation frequency

Tree:grass ratios can vary considerably in time, so that a dense woody layer may characterize initial vegetation conditions of one or several whole camps irrespective of the actual piospheres. Accordingly, PioLaG offers the possibility to specify whether and how many camps are already affected by bush thickening at the expense of a perennial grass layer, and at which severity level ('low', 'medium', and 'high'). The factors (Supplementary material B.2, Tab. B. 3) are used in the function that assigns the vegetation types to modify the frequency of 'woody vegetation' cells (Tab. 3).

3.6.7 Assignment of vegetation types and spatial distribution

In PioLaG, each cell is assigned to one of four piosphere zones based on *HUI* (Tab. 3). The zones are based on a basic piosphere pattern commonly described for Kalahari savannas (e.g. Perkins and Thomas 1993; Jeltsch et al. 1997; Moleele et al. 2002; Smet and Ward 2005), i.e. a low vegetated 'sacrifice zone' up to 100-400 m from the watering point, a 'bush thickening zone' with increasing woody vegetation density or cover up to 2000 m (depending on camp size), and the outer zone. In PioLaG, the vegetation gradient in the 'bush thickening zone' is accounted for by separating this zone into a grass- and subsequent woody vegetation dominated zone. The 'grass dominated zone' close to the watering point is characterized by annual and/or unpalatable species, whereas more disturbance-sensitive and perennial forage grasses dominate where *HUI* and competition by woody vegetation (i.e. the frequency of 'woody vegetation' cells) is low. The outer zone can represent conditions from a least impacted grazing reserve with a balanced tree:grass ratio to overall dominance of woody vegetation depending on the pre-set level of bush thickening in the selected camp.

Each cell in the simulated landscape is assigned a '*bushFactor*' (Eq. 4), calculated as a multiplicative function of the MAP (via '*maxBush*', compare Eq. 3), clay content ('*soilBushFactor*') and *HUI* (after natural log transformation). The *bushFactor* describes the probability of woody vegetation dominating a cell:

$$bushFactor = maxBush \times soilBushFactor \times HUI \qquad (4)$$

The vegetation type is then assigned according to the probabilities shown in Tab. 3. The probabilistic variation accounts for environmental noise. The cells containing a watering point are always set to 'bare soil'. In a subsequent step, cells set to woody vegetation dominance are further categorized as dominated by either young or mature woody vegetation. ‘Young woody vegetation’ describes vegetation dominated by seedlings and saplings (< 2 m in height) and ‘mature woody vegetation’ describes vegetation dominated by larger trees (≥ 2 m in height). The ratio of cells dominated by young woody vegetation to cells dominated by mature woody vegetation is pre-set as 4:1 based on field evidence (Dreber et al. 2014; Harmse et al. 2016; Angassa and Oba 2010). Young woody vegetation is modelled in a clustered spatial pattern, because clustering of young woody vegetation is commonly observed, likely due to limited seed dispersal (Hesselbarth et al. 2018). Clustering is achieved through swapping of 'young woody vegetation' cells of the outer piosphere zone with randomly chosen neighbouring cells until most 'young woody vegetation' cells have at least two other cells with the same vegetation type in their Moore neighbourhood, i.e. the eight adjacent cells to the central cell (Balzter et al. 1998). If the option of bush-thickened camps is selected, the relative frequency of the vegetation types in the outer piosphere zone within the selected camps is altered by using a correction factor (except for bare ground and palatable perennials). The 'bushFactor' (Tab. 3) is multiplied with this correction factor, which is set to 1, 0.5 or 0.33 for a high, medium, or low level of bush thickening, respectively. Consequently, with a correction factor of 1, bush thickening in the outer piosphere zone is as high as in the woody vegetation dominated zone.

Tab. 3: Probability (P) of occurrence of the five vegetation types in PioLaG in each of four piosphere zones depending on herbivore-use intensity (HUI). 'max_HUI' is water-point specific, i.e. it is the highest cell-wise HUI in the model across all cells assigned to the same watering point. 'bushFactor' is the probability of (young and mature) woody vegetation dominating a cell.

Piosphere zone	Herbivore-use intensity	Vegetation type				
		Bare ground	Annual grasses (A)	Unpalatable perennials (UP)	Palatable perennials (PP)	Woody vegetation (WV)
Sacrifice zone	*HUI* ≥ 0.99 × *max_HUI*	0.9	0.1	0	0	0
Grass dominated zone	0.83 × *max_HUI* ≤ *HUI* < 0.99 × *max_HUI*	0	0.7	0.3	0	0
Woody vegetation dominated zone	0.05 × *max_HUI* ≤ *HUI* <0.83 × *max_HUI*	0	0	*bushFactor* + 0.4	1 - *P*(UP) - *P*(WV)	*bushFactor*
Outer zone	*HUI* < 0.05 × *max_HUI*	0	*bushFactor* + 0.1	*bushFactor* + 0.5	1 - *P*(UP) - *P*(WV) - *P*(A)	*bushFactor*

3.6.8 Effect of grazing system

There are various land tenure types in Kalahari savannas including commonage and private as the most common [for an overview refer to Kong et al. (2014)]. In commonages, the rangelands are communally-owned and managed or used with often little to no camp infrastructure. In contrast, independently managed private farms are usually based on a multi-camp system with the associated grazing management varying according to farming objectives, animal type, climate-related constraints, and personal preferences. Camps are either grazed in a continuous or rotational manner, whereas the utilization pressure differs with the stocking ratio and timing of resting periods for the vegetation to recover (Tainton et al. 1999). In this respect, PioLaG enables the recreation of different landscapes such as large, single-camp rangelands with an open and continuous grazing (as often found in communal areas) or multi-camp systems that allow for a more sophisticated type of grazing management. However, the model uses simplified estimations for the calculation of the effect of the management system because in reality there are many individual and complex schemes that depend on the philosophy, flexibility, and immediate response of land users to current environmental, vegetation, and livestock conditions. PioLaG allows the user to disable the effect of rotational grazing. This functionality enables the exploration of effects of rotational grazing on the spatial distribution of vegetation types, by being able to compare rangelands resulting from conditions that differ only in presence and absence of rotational grazing. Farms with multiple camps are usually under rotational grazing by default.

In PioLaG, rotational grazing is modelled via its benefit for perennial grasses (Tainton 1999). Both precipitation and the resting period are key factors for regeneration of perennial grasses. Thus, a function increases the number of cells dominated by perennial grasses, based on the current number of cells being dominated by perennial grasses ('*numPGC*', [cells]), MAP ('*MAP*', [mm*a^{-1}]), length of the vegetation resting period ('*RP*', [weeks]), and the constant c_3= 0.2 [a]:

$$Increase\ in\ perennial\ grass\ cells = floor\left(numPGC \times \frac{\left(\frac{RP}{4\ weeks}\right) \times \left(\frac{MAP}{100\ mm}\right) \times c_3}{100} \right) \quad (5)$$

The increase in the number of perennial grass cells is implemented by converting a corresponding number of randomly selected cells from their current vegetation type to 'palatable perennial grass' and 'unpalatable perennial grass' cells in a ratio of 60:40. In case of continuous grazing (the whole simulated area being a single camp), the model does not consider any further changes in the number of perennial grass cells.

3.6.9 Output

PioLaG output includes distribution maps of dominant vegetation types, locations of watering points, and camp and farm boundaries. The output is saved in separate ASCII grid files with a spatial resolution of 30 m x 30 m. This universal format is ideal both for further analyses and as an input for rangeland simulation models. Additionally, PioLaG is able to directly output the piosphere pattern for a single watering point, as well as *HUI* as a function of the distance to the watering point, and saves them as a text or image file.

3.6.10 Model performance

In order to test the performance of PioLaG, we generated landscapes 12 km × 12 km in extent with a single central watering point. This allowed us to analyse the dominance distribution of vegetation types over long distances from the watering point. Results for different environmental and management conditions are presented in the following. The complete parameterization for each scenario can be found in supplementary material B.5 and the PioLaG model in NetLogo is available from the authors on request.

3.6.11 Sensitivity analysis

For the sensitivity analysis, we used a revised version of the Morris's elementary effects screening (Campolongo et al. 2007) to identify the most influential parameters and their interaction effects (Morris 1991; Thiele et al. 2014). As central output variables, we analysed the relative amounts of bare soil, annual grasses, unpalatable and palatable perennial grasses, as well as young and mature woody vegetation. As input parameters of interest, we varied number of bush-thickened camps, soil type (relative clay content), MAP and stocking ratio. In Morris screening, μ is the overall effect (first-order effect) of a parameter (called 'factor' in Campolongo et al. 2007) on the respective output. Positive and negative values of μ indicate the direction of the effect. μ^* denotes the absolute value of μ. The higher the value of μ^*, the stronger the effect. Morris screening also reports the SD of the elementary effects (σ) for each parameter. Elementary effects varying a lot (high σ) indicate that other parameters also have an effect on the output variable, i.e. there is an interaction between parameters but this may also be due to non-linearity (Menberg et al. 2016).

3.7 Results and discussion

3.7.1 General piosphere patterns

PioLaG recreated radial grazing gradients that revealed distinct patterns in the dominance distribution of vegetation types including bare ground. The corresponding piospheres were clearly visible in form of zones of differing width and vegetation composition around watering points (for an example see Fig. 16). The zone immediately surrounding the watering point, i.e. the 'sacrifice zone', was dominated by cells denoted as 'bare ground' with few interspersed 'annual grass' and 'unpalatable perennial grass' cells. The latter two dominated the next zone together with some 'young woody vegetation' cells. This zone was followed by a belt of increased frequency of cells denoted as 'young woody vegetation' and 'mature woody vegetation', indicating a transitional state towards bush thickening. At a recommended stocking rate (e.g. 13 ha LSU^{-1} at a grazing capacity of 12 ha LSU^{-1} in Fig. 16), this zone extended to 2 km from the watering point with woody vegetation reaching highest values within a distance from around 0.8 km to 1.5 km. 'Palatable perennial grass' cells dominated the outer piosphere, as being characteristic for a grazing reserve (Fig. 16). Overall, these basic spatial characteristics and the vegetation zoning resembled patterns described in studies of Kalahari savannas (for references see above).

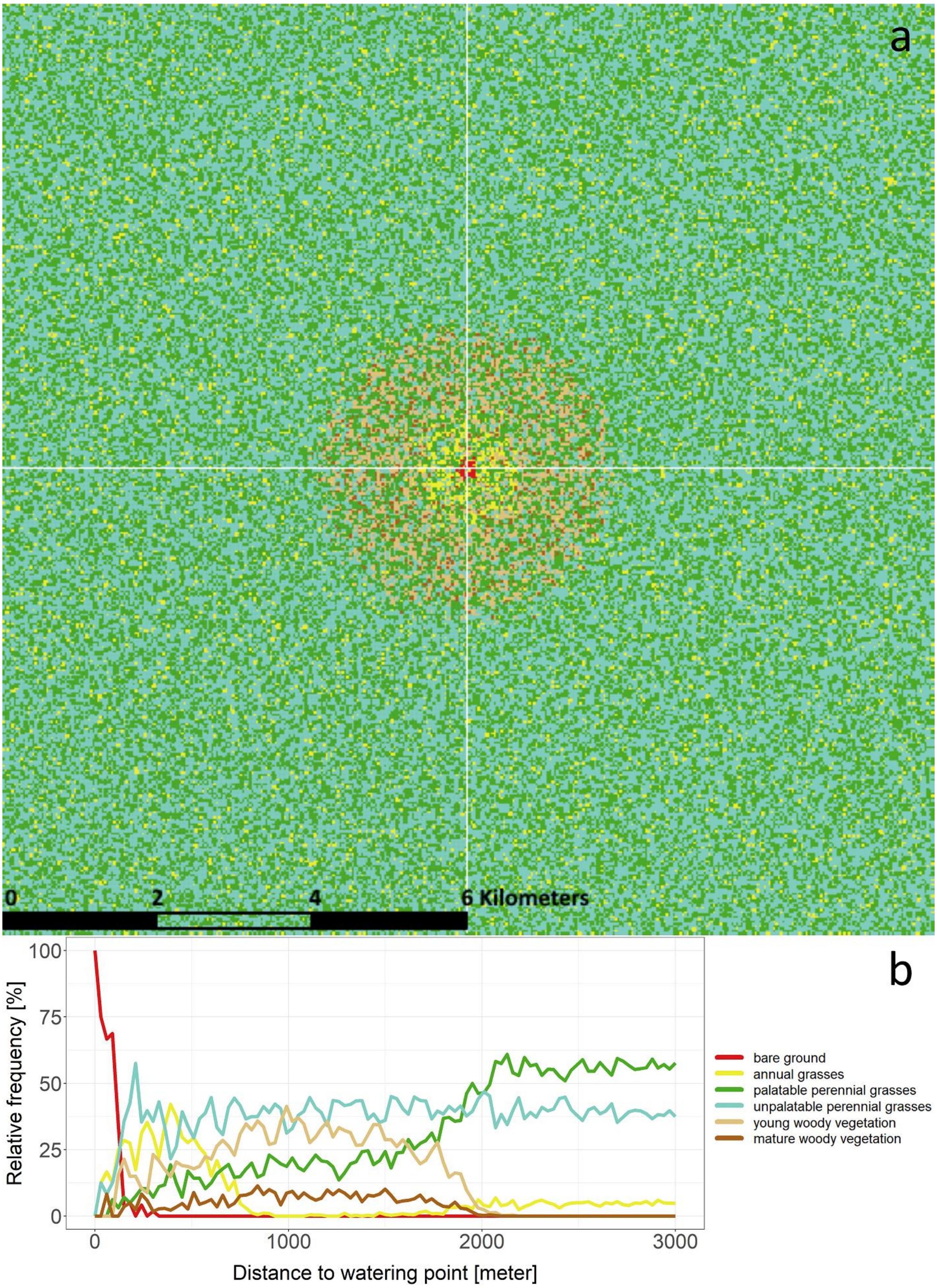


Fig. 16: (a) Generated landscape of an example simulation run with an optimally stocked rangeland, divided into four camps (white lines) with one central watering point. (b) Piosphere pattern graph of the above landscape (averaged over the 4 camps), illustrating the change in relative frequency of vegetation types with distance to the watering point. Parameter settings: MAP = 405 mm/a, stocking rate = 13 ha/LSU, grazing capacity = 12 ha/LSU, stocking ratio = 0.92 (optimally stocked), clay content = 0.03 (further details in supplementary material B.5, Tab. B. 6).

3.7.2 Different herbivore-use intensities

The effect of an increasing stocking rate on the simulated rangelands was observed as the spatial expansion of piosphere zones (Fig. 17; grazing capacity: 12 ha LSU^{-1}). In general, the total area dominated by woody vegetation (except for unpalatable perennial grasses) increased with increased stocking. At under-stocked conditions (20 ha LSU^{-1}), the zone with cells dominated by woody vegetation extended to 1.5 km from the watering point (Fig. 17a). At a recommended stocking rate (13 ha LSU^{-1}) and under severely over-stocked conditions (6 ha LSU^{-1}), this zone extended to a distance of 2 km and 2.5 km, respectively (Fig. 17b, c). Despite these differences, the maximum relative frequency of 'woody vegetation' cells (young and mature) was similar across all stocking rates (Fig. 17). The area covered by bare soil generally increased with increasing stocking rate. While bare soil was concentrated less than 100 m from the watering point at under-stocked conditions (Fig. 17a), it extended to a distance of about 200 m under severely over-stocked conditions (Fig. 17c). In the under-stocked scenario, 'annual grass' cells were most frequent in the area of 50 m to 500 m from the watering point. With increasing stocking rate, this zone extended to 1000 m with peaks at around 40 % of relative frequency. Generally, 'annual grass' and 'woody vegetation' frequency showed a directly opposed pattern, even though recovery of annual grasses was limited following the decrease of woody vegetation further away (Fig. 17). At a low stocking rate, palatable perennial grasses showed an almost linear increase from the watering point up to 1300 m distance before levelling off at 55 % relative frequency (Fig. 17a). With increasing stocking rates, this off-levelling shifted until a distance of 2500 m under over-stocked conditions (Fig. 17b, c). The relative frequency of cells dominated by unpalatable perennial grasses was not much influenced by the stocking rate and fluctuated after 50 m to 100 m from the watering point at a frequency between 30-50 % (Fig. 17).

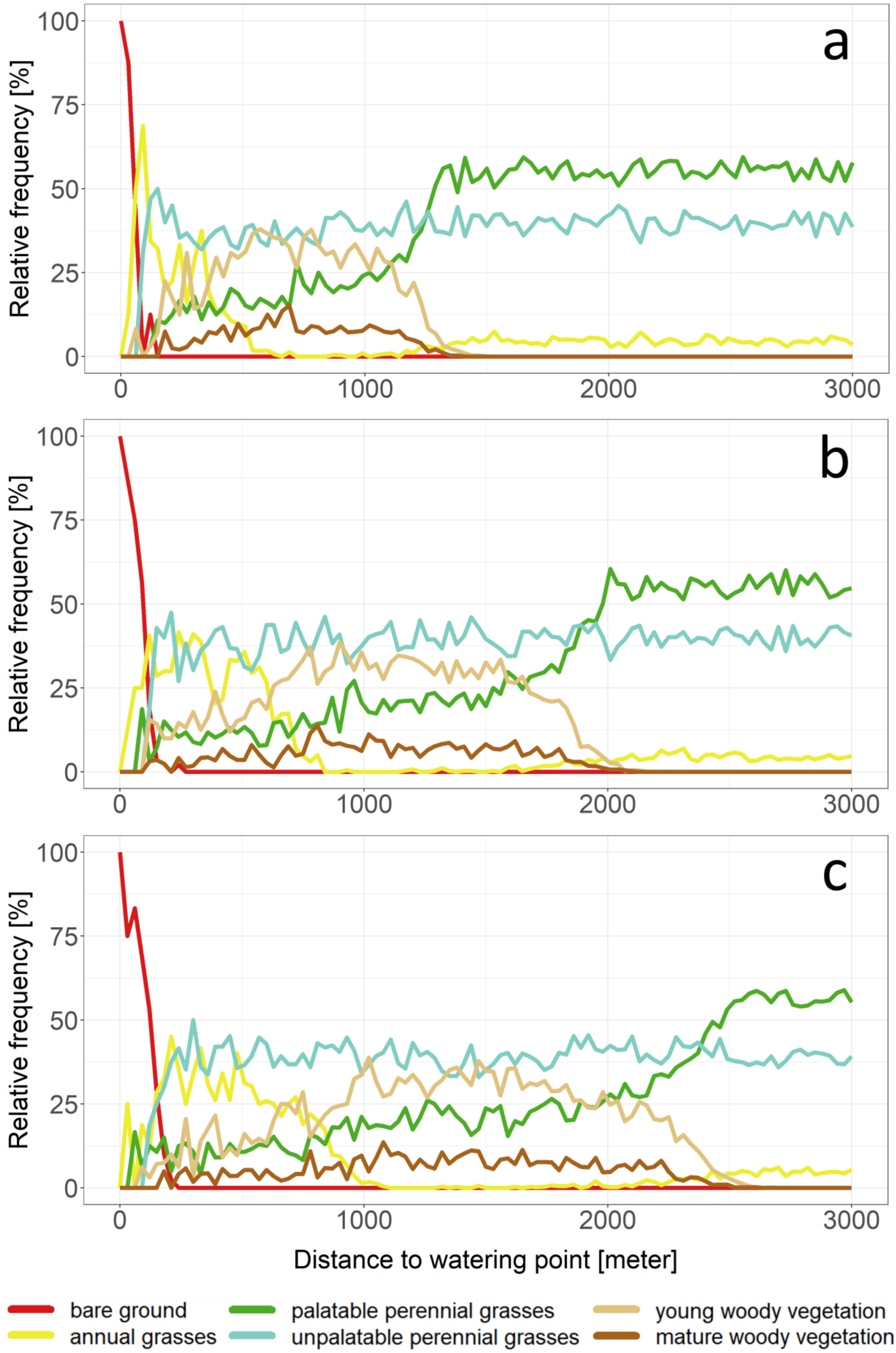


Fig. 17: Comparison of model outputs with different pre-set stocking rates (SR): (a) below recommended SR, (b) recommended SR and (c) above recommended SR. For all parameter settings refer to supplementary material B.5, Tab. B. 7-Tab. B. 9).

This response of the output landscapes to varying herbivore-use intensities concurs with studies from arid and semi-arid savanna systems showing that (1) higher grazing pressure promotes the growth of annual generalist species and reduces the competitiveness of especially palatable perennial grasses (van Rooyen et al. 1994; Fynn and O'Connor 2000; Dreber et al. 2011), and (2) changes in the competitive environment can facilitate the increase of woody species (Skarpe 1990; Weber and Jeltsch 2000; Harmse et al. 2016). Further, the different output landscapes and vegetation responses show that PioLaG is able to account for the fact that shape and spatial extent of piospheres are not static (compare Introduction).

3.7.3 Mean annual precipitation and clay content

With increasing MAP, the piosphere pattern and zoning became more distinct (Fig. 18). Mature and especially young woody vegetation were more frequent in a scenario with high MAP (490 mm a^{-1}) and low relative soil clay content (5 %) compared to low MAP (124 mm a^{-1}) and high clay content (27 %). In the first scenario, the frequency of 'woody vegetation' cells (young and mature) peaked at 1200 m distance from the watering point (59 %; Fig. 18a). The frequency of 'unpalatable perennial grass' cells was highest between 300 m and 600 m and slightly levelled off at 30 % to 50 % thereafter. Palatable perennial grasses were mostly suppressed (up to 20 % frequency) but increased towards dominance beyond 1700 m from the watering point (Fig. 18a).

In the low MAP–high clay scenario, 'woody vegetation' frequency reached only a maximum of 36 % at a distance of 990 meter from the watering point (Fig. 18b). 'Unpalatable perennial grass' cells dominated at a distance between 100 m and 1700 m. Beyond 600 m, their frequency varied quite constantly between 30 % and 45 %. The palatable perennial grasses increased almost linearly along the gradient until a constant frequency around 55 % was reached at a distance of 2000 m.

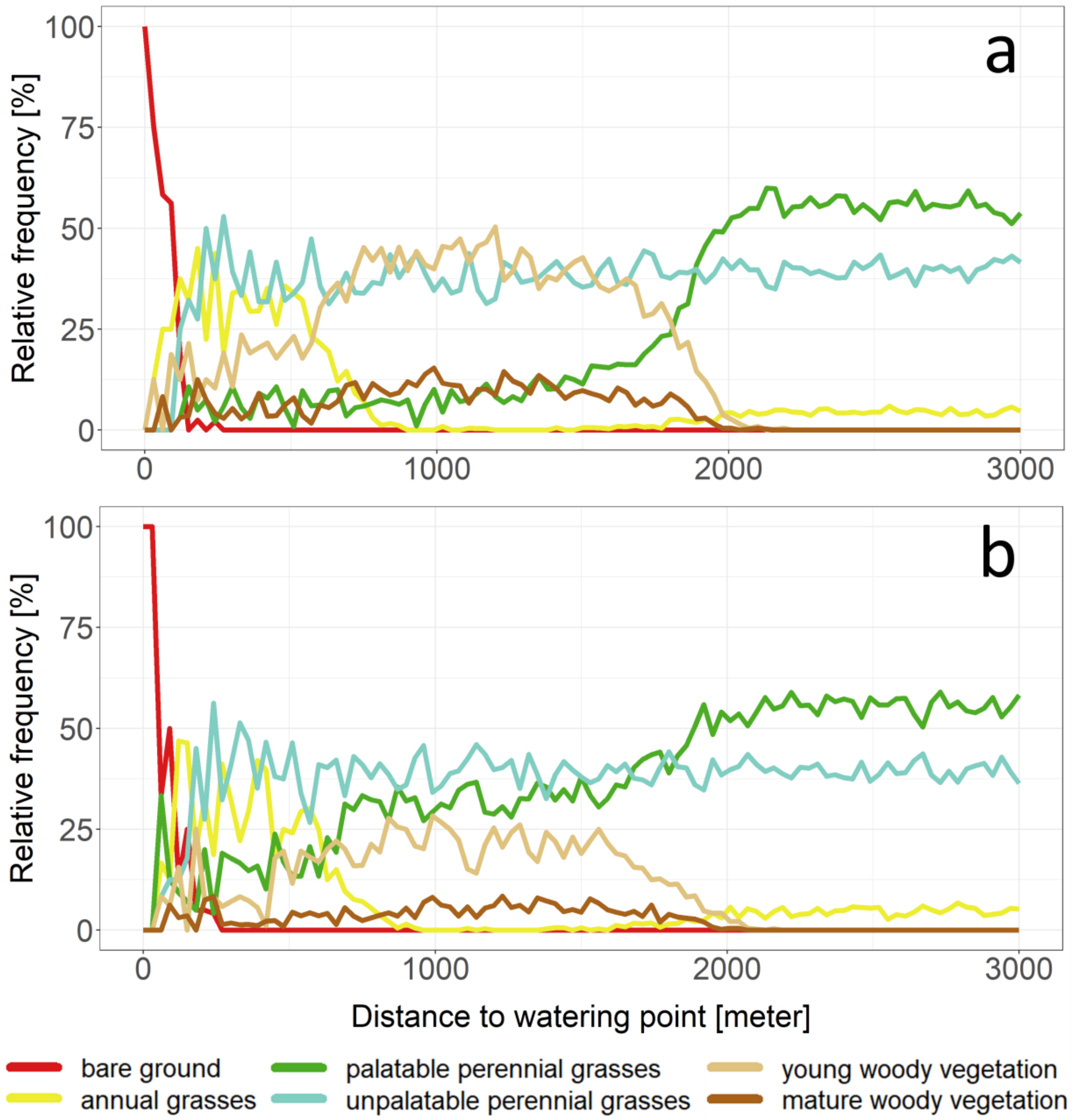


Fig. 18: Piosphere graphs of a scenario with (a) high mean annual precipitation (490 mm/a) and low clay content (5 %) in the soil and (b) with low mean annual precipitation (124 mm/a) and high clay content (27 %). For all parameter settings refer to supplementary material B.2, Tab. B. 10 and Tab. B. 11.

As expected, the opposing clay and precipitation scenarios led to basically unchanged piosphere patterns compared to the default simulation (cf. Fig. 16 and supplementary material B.4, Fig. B. 4). The observed zoning and vegetation responses in relation to precipitation is in line with model results of Jeltsch et al. (1997) from another Kalahari savanna. They also found higher precipitation to result in more distinct piosphere zones, as well as an extended zone of bush thickening (Jeltsch et al. 1997b). This can be expected as the establishment of woody vegetation in arid to semi-arid savannas is primarily limited by moisture availability (Sankaran et al. 2005). Our results are also in accordance with studies showing that higher soil clay contents can counteract the positive effect of high precipitation on recruitment and growth of woody vegetation (Kgosikoma et al. 2012; Grellier et al. 2014).

3.7.4 Effect of grazing system

In comparison to the use of a rotational grazing system (Fig. 16), the setting of an overstocked continuous (open) grazing system (Fig. 19) led to an increased number of 'palatable perennial grass' and 'unpalatable perennial grass' cells. Under continuous grazing, the relative frequency of 'woody vegetation' cells was only slightly higher but extended over a larger area than under rotational grazing with recommended stocking rate (Fig. 16b). However, these effects were not as strong as expected. Continuous grazing with high animal numbers usually result in more widespread bare soil and a higher cover and/or density of woody vegetation (Teague et al. 2013). However, since only the dominant vegetation type is represented per cell, low to moderate changes in absolute vegetation may be masked, and thus are not quantified and visible.

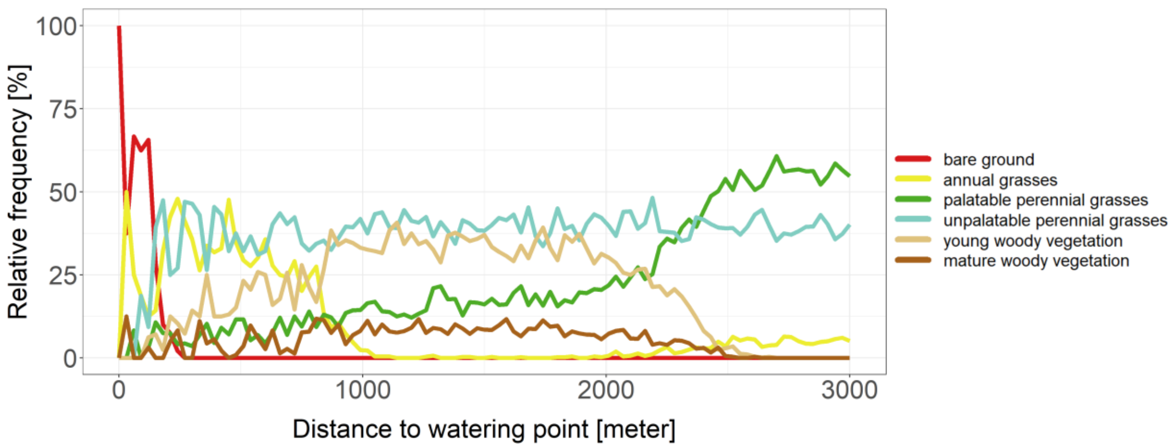


Fig. 19: Piosphere pattern of a landscape with an open grazing system (no camps). For all parameter settings refer to supplementary material B.5, Tab. B. 12.

3.7.5 Bush thickening in outer piosphere

Factors such as mismanagement over longer time periods and under extreme weather conditions (e.g. droughts) can result in permanent states of dominant woody vegetation irrespective of the actual grazing gradient (Pickup et al. 1994; Harmse et al. 2016). Accordingly, pre-defining certain camps as having an overall higher woody vegetation density resulted in the outer piosphere being dominated by 'woody vegetation' cells at the expense of 'perennial grass' cells (Fig. 20). Also, 'annual grass' cells could be observed in greater numbers. This is reasonable because these grasses are often better adapted to intense disturbances and may cope better with increased bush cover than perennial grasses (Dreber et al. 2011; Harmse et al. 2016).

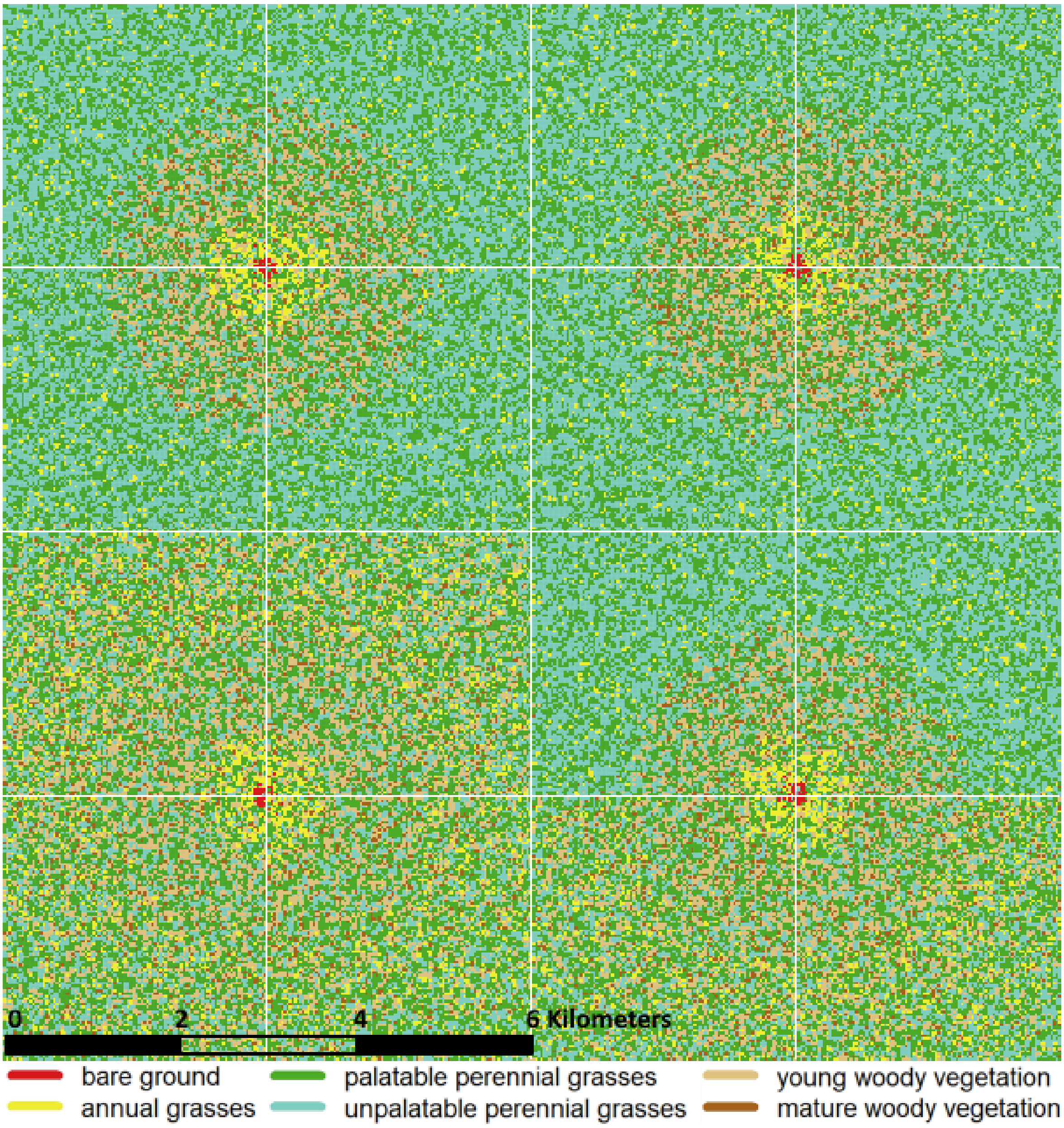


Fig. 20: Simulated landscape with four watering points and 16 camps, of which six were pre-set as severely bush thickened (lower part of figure). For all parameter settings refer to supplementary material B.5, Tab. B. 13.

3.8 Sensitivity analysis

In the sensitivity analysis, most parameters behaved as expected, even though not necessarily exactly as in reality because of the abstract, non-temporal approach of PioLaG. The parameters *MAP* and number of bush-thickened camps had the largest effect on the frequency of 'palatable perennial grass'- and 'woody vegetation' cells. Overall, the input parameters showed a lot of interaction which is expected for such a complex system.

3.8.1 First-order effects

The relative amount of bare ground in the landscape was only affected by stocking ratio (Fig. 21), and only weakly so, likely because bare ground appeared as the dominant vegetation type only within the sacrifice zone. Regarding annual grasses, the number of bush-thickened camps had the largest elementary effect (Fig. 21). This reflects the association of 'annual grass' and 'woody vegetation' cells in the outer piosphere zone at pre-set higher levels of bush thickening, as described above. In contrast, *MAP* had a slightly negative effect on annual grasses, which may result from its simultaneous positive effect on woody vegetation and the resulting competition (Fig. 21). Likewise, palatable perennial grasses were negatively affected by *MAP* but also by the number of bush-thickened camps, as both increase the woody vegetation at the expense of this vegetation type. Clay content counteracted increases in woody vegetation (as described by Kgosikoma and Mogotsi (2013) and Grellier et al. (2014)) and consequently had a positive effect on (palatable and unpalatable) perennial grasses. In addition to competition also disturbance played a role: the higher the overall grazing pressure (stocking rate), the fewer 'palatable perennial grass'-cells occurred (Fig. 21). For unpalatable perennial grasses, similar effects of the input parameters were observed with the difference that the initially set number of bush-thickened camps had a weak effect, and direction of this effect was equivocal (Fig. 21). This is because the number of unpalatable perennial grass cells is not directly set by the function that assigns the vegetation types (see Tab. 3). Its value rather depends on the frequency of the other vegetation types present in the outer piosphere zone. The parameter effects on young and mature woody vegetation reflected the positive relationship with the number of bush-thickened camps and beneficial conditions for woody recruitment and establishment created by an increase of *MAP* (e.g. Sankaran et al. 2005) and increased grazing pressure (stocking ratio) on competitive strong grasses (e.g. Skarpe 1990), especially in non-clayey soils (see above; Fig. 21).

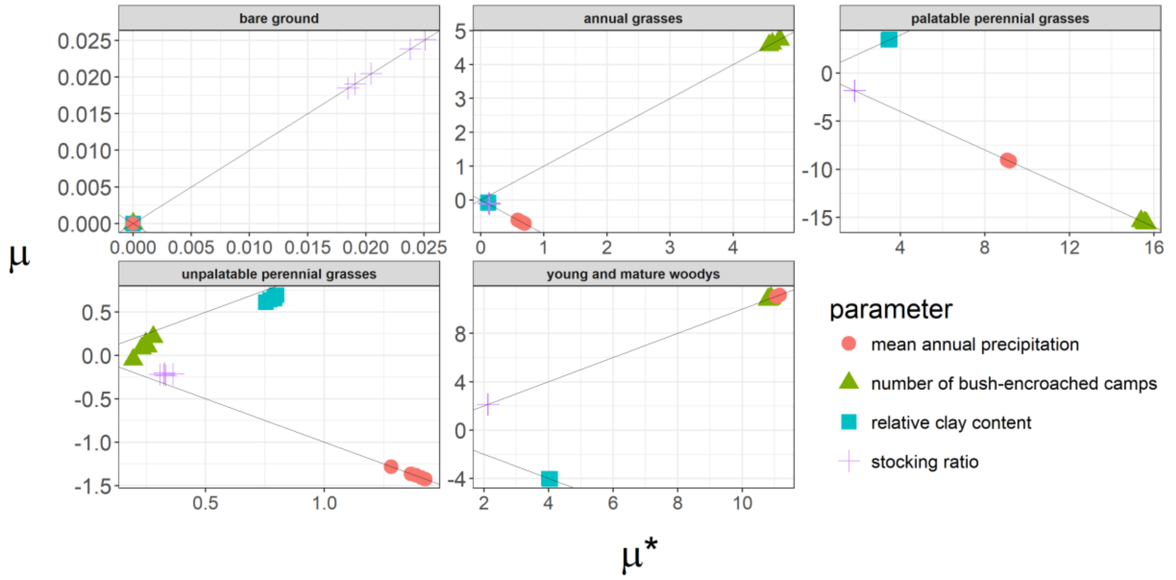


Fig. 21: Results of the sensitivity analysis illustrating the absolute mean values (μ*) on the x-axis and real mean values (μ) on the y-axis of the elementary effects which show the magnitude and direction of the first-order effect of the four input parameters.

3.8.2 Interaction effects

There were no parameters important only because of their first-order effect ($\sigma/\mu^* \leq 0.1$), i.e. no (almost) linear responses with respect to the parameters. Hence, the effects of the analysed parameters on the output variables were interlinked. For the relative amount of bare ground, the stocking ratio showed an almost monotonic behaviour and a small interaction effect with the other parameters (Fig. 22). In case of annual grasses, both *MAP* and number of bush-thickened camps displayed a monotonic behaviour (σ/μ^* ratio between 0.1 and 0.5). While *MAP* exhibited only very little interaction, the number of bush- thickened camps interacted more strongly with the other parameters (Fig. 22). For unpalatable perennial grasses, most parameters showed a σ/μ^* ratio > 1, indicating large interaction effects and/or a non-linear behaviour. *MAP* behaved differently in having an almost monotonic effect (Fig. 22). For palatable perennial grasses, the number of bush-thickened camps had a stronger overall effect than *MAP*. However, both parameters had about the same σ, i.e. they experienced the same interaction with other parameters. When set in relation to the total effect on the output variable, *MAP* had a larger relative interaction effect compared to the number of bush-thickened camps (larger direct effect with the same sigma) (Fig. 22). All parameters for young and mature woody vegetation showed an almost monotonous behaviour (σ/μ^* ratio between 0.5 and 1) and an increasing absolute interaction effect in the order of stocking ratio, relative amount of clay, number of bush-thickened camps and *MAP*. However, when set in relation to the total effect on the output variable, the relative interaction effect was similar among the parameters (Fig. 22).

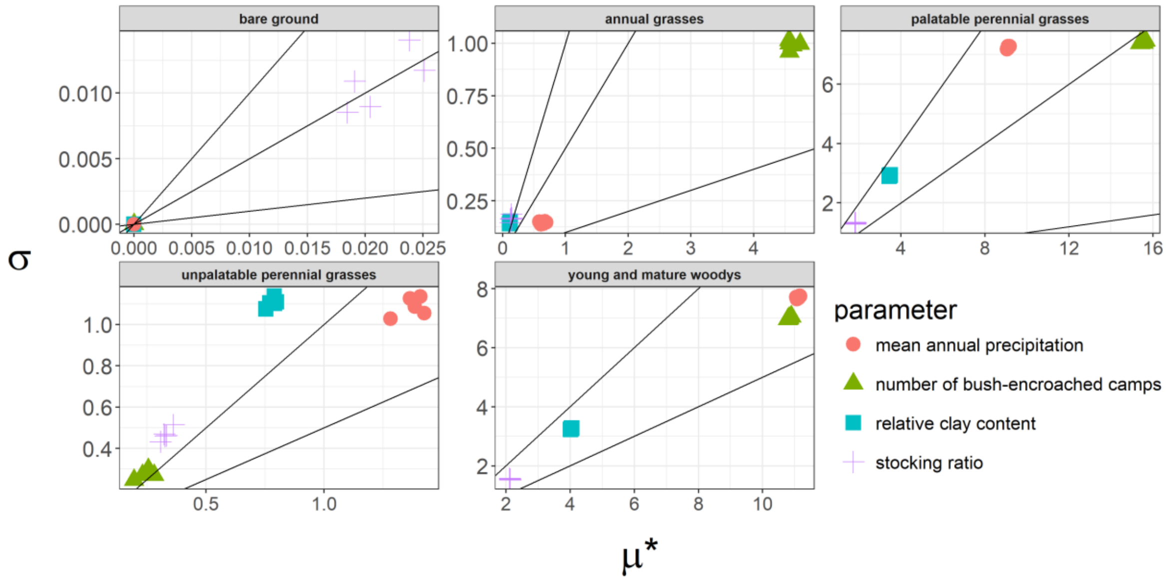


Fig. 22: Absolute mean values (μ*) on the x-axis and the standard deviation of the elementary effects (σ) for each parameter on the y-axis show the interaction of the input parameters i.e. the second-order effects. The auxiliary lines show the ratios of σ/μ* = 1, 0.5 and 0.1.

The parameters *number of bush-thickened camps*, *MAP*, and *clay content* showed strong interaction in affecting the output variables *palatable perennial grasses* and *young* and *mature woody vegetation*. This is because the availability of soil moisture plays a major role for bush thickening and is highly dependent on the *clay content* in the soil and on *MAP* (see also *first-order effects*). The input parameter *number of bush-thickened camps* strongly influences the vegetation composition through its effect on the '*bushFactor*' (Eq. 4), whose product is used to calculate the frequency of the different vegetation types.

3.8.3 Similarity to observed piospheres

To verify how realistic the output of the landscape generator PioLaG is, we compared piosphere patterns created with PioLaG with patterns identified on aerial images from our reference savanna system in the southern Kalahari. This revealed a good match of the basic patterns (for detailed results and discussion see supplementary material B.1). The general PioLaG outputs were also comparable to piosphere patterns described in scientific literature for similar savanna systems as outlined below. However, it should be noted that the appearance of real piospheres can vary greatly in a local area, which, apart from patchy rainfall, may primarily relate to differences in land management and grazing history. Accordingly, the basic vegetation zoning described for piospheres in the savanna literature varies to some extent.

Peaks of increased density or cover of trees and shrubs along grazing gradients are reported to occur at quite different distances from watering points in Kalahari savanna rangelands: 20 m - 200 m (Tolsma et al. 1987), 50 m - 800 m (Perkins and Thomas 1993), 150 m - 250 m (Moleele et al. 2002) and 200 m - 400 m (Smet and Ward 2005). At the recommended stocking rate for the Kalahari reference system, PioLaG generated a frequency-peak of woody vegetation at a distance around 700 m - 1200 m from the watering point (in a scenario with 405 mm *MAP*), which corresponds to findings of Tobler et al. (2003) from a more humid savanna system. However, other scenario settings would result in different patterns with dominant woody vegetation also closer to the watering point. This shows that woody vegetation-affecting submodels in PioLaG deliver patterns that are absolutely within the spatial range of actually observed zones with increased bush cover or density. The hump-shaped response of the relative woody frequencies in PioLaG was also comparable to simulation outputs of a vegetation model for another Kalahari savanna by Jeltsch et al. (1997). Accordingly, the simulations of the woody vegetation can be considered solid.

Except for some disturbance-tolerant species, herbaceous vegetation often shows a hump-shaped distribution or decreasing trend along grazing gradients towards watering points, especially many perennial grasses decrease under increasing herbivore use intensity (Van Rooyen et al. 1991; Todd 2006; Wesuls et al. 2013). These response patterns were similarly evident in the PioLaG landscapes. The additional distinction between palatable and unpalatable perennial grasses also revealed that the latter were generally more abundant close to the watering point. This resembles preferential grazing patterns and concurs with descriptions by Perkins and Thomas (1993), Smet and Ward (2005), and others (Thrash and Derry 1999). Clearly it was not possible to make such a distinction of the herbaceous layer depicted on the aerial images, but overall herbaceous vegetation increased with distance from the watering point before levelling off (supplementary material B.1, Fig. B. 1). Therefore, as for the woody vegetation, the output for simulated herbaceous vegetation is reliable in mimicking observed patterns.

It is not trivial to compare the zoning and composition of vegetation at specific distances from watering points between PioLaG outputs and observed patterns. The causes leading to the specific patterns described in the cited studies and depicted on aerial images are complex and highly site-specific and context-dependent. Information about the factors determining shape and extent of the piosphere are often not available in detail or completely unknown, as in the case of the random sample of piospheres from aerial images. Further, PioLaG simulates a single dominant vegetation type for a 30 m × 30 m cell, which certainly leads to scaling issues since vegetation types (including bare ground) with low to moderate frequency are not output by PioLaG. It is therefore not possible to recreate piospheres exactly matching a case from the real-world. However, thanks to its flexibility, PioLaG allows to simulate diverse scenarios representing a solid approximation of what can be found in savanna rangeland systems.

3.9 Limitations of the model

Real landscapes are often structurally diverse and show much environmental heterogeneity caused by a multitude of partly interacting system-internal and external drivers across spatial scales. Moreover, extreme climatic events and management decisions of the past may still be reflected in current vegetation patterns, both at the level of species and communities. This complexity cannot be accounted for by a landscape generator like PioLaG and needs to be considered when interpreting generated simplified landscapes in comparison to real landscapes. Our chosen modelling approach, which integrates scientific expert knowledge and perspectives from practitioners, does not fail to produce useful landscape representations; on the contrary. However, there is room for improvement and PioLaG offers the flexibility to add parameters and to adapt processes and routines as needed. A model is only as good as the input data that is used to parameterize and run a simulation. The science of savanna vegetation is a recursive process and with the help of models like PioLaG data gaps become evident and can guide researchers in data collection as required. New data can then be used to refine models and advance outputs toward even more realistic savanna vegetation patterns at local to landscape scale.

3.10 Conclusions

PioLaG proved to be a multifunctional landscape generator for southern African savanna rangelands. The created vegetation patterns and the influence of cause-and-effect relationships were in line with the findings of other modelling studies and field observations. PioLaG is optimized for climates with a MAP between 100 to 650 mm. However, it can be altered to various environmental conditions and landscape properties and considers the consequences of different management settings. Thus, it can be used for or adapted to a wide range of grazing systems in different biotic and abiotic contexts, such as Australian or South American savannas but also other arid to mesic grassland ecosystems with an increasing or invading tree or shrub component. The simple output feature allows to create various ASCII grids of vegetation type, farm and camp borders, as well as watering point positions showing the effects of environmental change and different management decisions on the spatial vegetation distribution. Such output can be used for environmental education and training, understanding of complex interactions and insights into cause-and-effect relationships. Another use of the ASCII maps is as input data for rangeland models that usually need qualitatively precise, yet user-defined and context-specific input data about initial vegetation conditions. This is especially beneficial for scientists since field data are often limited and repeated simulations and analyses require model runs with many equivalent but not identical realistic landscapes. Overall, these features make PioLaG a highly flexible landscape generator for different ecosystems and regions and a powerful tool for many research questions.

4 Midessa rangeland model

4.1 Introduction

Savannas are complex systems with many interacting processes that are not yet fully understood. Being able to estimate the effect of various management decisions under current and different future environmental influences is the key to finding and adapting optimal management strategies. To gain insights in the complex spatio-temporal, multi-scale cause-and-effect relationships it is helpful to use the power of simulation models (Grimm and Railsback 2013). The goal of the model is to increase the understanding of the complex savanna system and its processes as well as to aid as a decision support tool to help farmers find optimal management strategies and allowing them to test and compare different management decisions and the effect on the vegetation and livestock. This is why we created the **dynamic, multi-functional rangeland Model for the simulation of cross-scale vegetation dynamics in space and time for an Integrative Decision Support System for sustainable rangeland management in southern African savannas (MIDESSA)**. Midessa is based on the partially redesigned and extended 'Molopo' rangeland model by Sebastian Hanß (Hanß 2013).

In the following, I will give a detailed description of all the processes and factors considered in the model and how they were implemented to create a realistic representation of the real world. A detailed html-handbook with an overview of all functions, parameters, and classes can be found on the data DVD (see appendix D). Further, I will show and discuss model results for different scenarios to observe and understand the model behaviour. I will then compare it to other studies and talk about the limitations of the model and possible extensions to improve the model in the future.

The ODD (Overview, Design concepts, Details) protocol standardizes the description of individual-based simulation models (Grimm et al. 2006, 2010, 2020). Even though Midessa is not an individual-base model (IBM), we follow the ODD protocol as closely as possible to provide a complete and comprehensive model description.

4.2 Purpose and patterns

The Midessa rangeland model simulates temporal and spatial vegetation pattern dynamics in response to environmental influences and livestock management in arid and semi-arid savannas in southern Africa. A special focus lies on the emergence of bush-encroachment and on finding parameters and management combinations to avoid this type of land degradation and ensure instead a sustainable and productive land use.

4.3 Entities, state variables, and scales

The modelled rangeland is grid-based with cells 30 m × 30 m in size (0.09 ha). A cell represents the model's entity and smallest spatial unit, and is assigned several different properties. The most important of these properties and state variables are the spatial *x*- and *y*-coordinates, camp and farm ID, dominant vegetation type, soil moisture and the amount of biomass.

The cell properties define the local conditions, whereas several contiguous cells of the same type form patches on a larger scale (e.g. clumps of woody vegetation in a grass-dominated matrix) (Tab. 4). The landscape scale encompasses all cells of the model with a variable total extent, i.e. the size of the landscape is determined at model initialization. Midessa is spatially explicit such that the spatial arrangement in the status of neighbouring cells can produce emerging patterns at larger spatial scales. In so doing, Midessa accommodates the important fact that ecological processes taking place at certain spatial scales become manifest in spatial patterns at other scales (Levin 1992).

Tab. 4: Spatial scales in the Midessa model.

Spatial unit	Meaning and examples
Cell	Smallest spatial unit of the model (30 m × 30 m) Seed germination and growth is calculated on this scale
Multiple cells	Camp unit; variable; mean camp size in Molopo area 100-400 ha Spatial vegetation transition acts on this scale The precipitation clouds have a variable size of several cells
Landscape	Total extent of the model; one or more farms; variable; 1,000 to 10.000 ha Temperature and soil properties are set on this scale

The smallest time unit in the model is the daily resolution in which processes like precipitation, soil moisture updates and the check for germination potential happen (Tab. 5). At the monthly scale, temporal vegetation transitions, growth, grazing/browsing, fire and the livestock condition are updated. On the multi-month scale, the rain-use efficiency is calculated using a precipitation memory of several months. The largest temporal scale used by Midessa is the annual time scale on which spatial transition of vegetation types, seed production, seed dispersal and the mortality and removal of wood happen.

Tab. 5: Temporal scales in the Midessa model.

Temporal scale	Meaning and examples
Daily	Precipitation, updating of the soil moisture and the check for germination potential happen on a daily scale
Monthly	The temporal vegetation transition, growth, grazing/browsing, fire, arboricide application and the livestock condition are updated on a monthly scale
Multi-month	The rain-use efficiency is calculated using a precipitation memory of several months
Yearly	The spatial transition, seed production and dispersal and the mortality and removal of wood happen on an annual time scale

4.4 Process overview and scheduling

Midessa considers various processes and drivers to realistically simulate the vegetation dynamics of savanna rangelands at the landscape level. At the cell level, the vegetation at a certain place and time is characterized by the dominant vegetation type and the amount of dead & alive biomass. At the level of vegetation processes, these properties may change due to germination, vegetation growth and mortality & decay. Finally, vegetation growth is a function of vegetation vigour (green boxes in Fig. 23). Vegetation can be consumed by grazing, browsing and fire (black boxes). These processes are, in turn, at least partly affected by rangeland management. The management decision on the farm usually depend on the past and present spatio-temporal vegetation dynamics which are the basis for the farmers' decision on wood removal, animal type and abundance, as well as spatial distribution of the livestock (grazing system) (blue boxes). Finally yet importantly, abiotic factors and processes affect the spatiotemporal vegetation dynamics. Here, Midessa explicitly considers the effects of precipitation on vegetation growth and vigour, of temperature on vegetation growth and fire dynamics, and of soil moisture on germination as well as on the amount of dead & alive biomass (red boxes). These main drivers for vegetation development (especially precipitation and temperature) are directly influenced by climate change (IPCC 2014). These causal effects are translated into a temporal scheme. Proceeded by the initialization, the different submodels are run either monthly or annually (Fig. 24). During the initialization, the landscape with all its different layers is set up and the temporal precipitation dynamics (daily amount of rainfall) for the entire simulation extent. For further details, see 4.6 Initialization. Beginning with the monthly run processes, Midessa then determines the spatial distribution of the precipitation (4.8.1), the temporal vegetation transition (4.8.6), the vegetation vigour (**Error! Reference source not found.**), the vegetation biomass growth (4.8.5), the effect of grazing and browsing (4.8.10) and of possible fires (4.8.7). After every twelve iterations (January to December), i.e. at the end of each year and before the new year starts, the annually performed submodels are run. These begin with the determination of the spatial vegetation transitions (4.8.6) and are followed by seed dispersal (4.8.8) and vegetation mortality (4.8.9) after which the layer with the dominant vegetation types is updated and the month-year circle starts again.

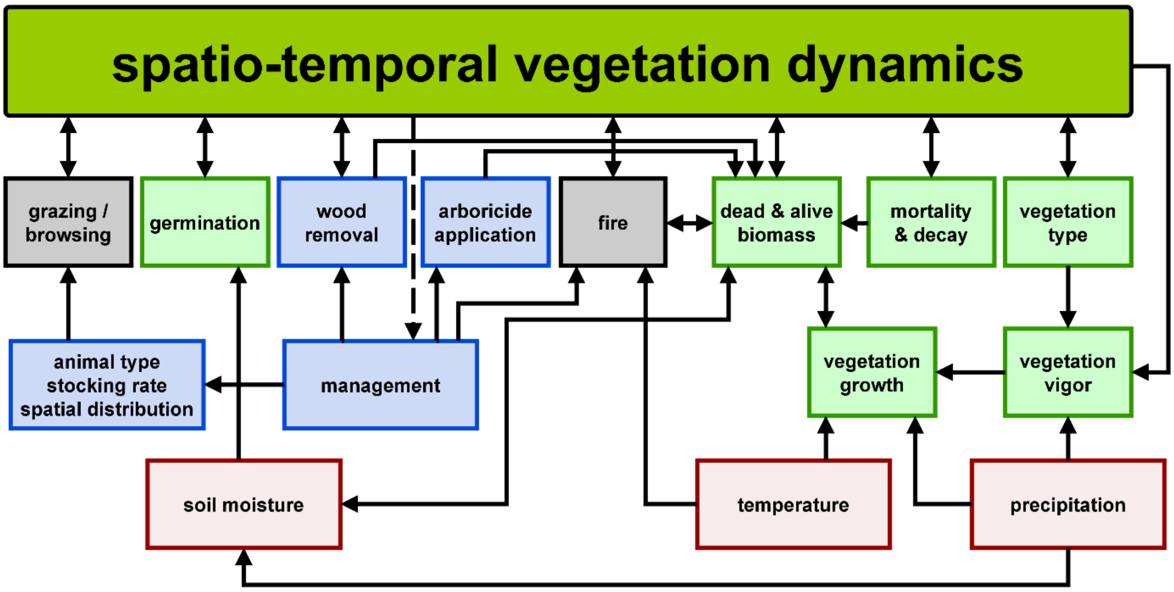


Fig. 23: Causal diagram of the most relevant processes, drivers and variables in the model. Solid arrows show influence; dashed arrow indicates feedback. Processes in red boxes are influenced by climate change; green boxes are vegetation related; blue boxes are influenced by humans; black boxes are other drivers.

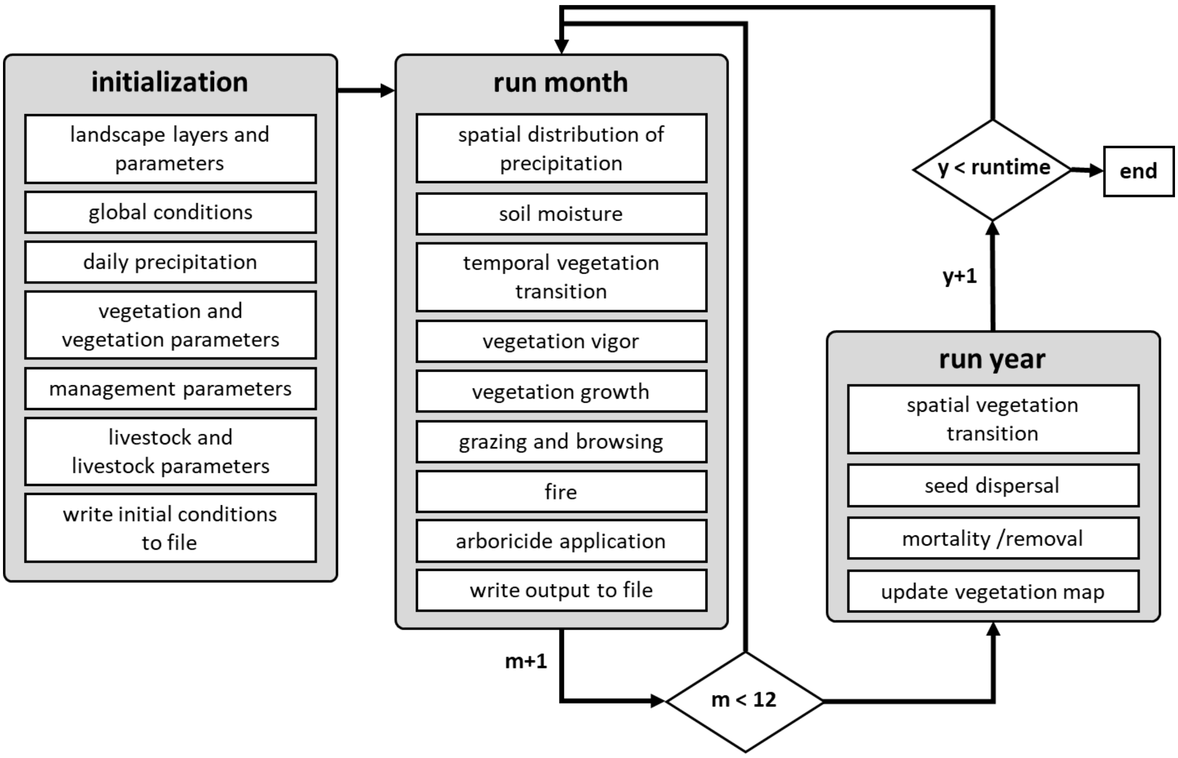


Fig. 24: Flow chart of the Midessa model with the main ecological and technical processes. m: counter for months, y: counter for years, runtime: total temporal simulation extent.

4.5 Design concepts

4.5.1 Basic principles

Midessa is a spatially-explicit (grid based), process-based model for the simulation of vegetation dynamics in southern Africa savannas. The basic principle underlying this model is the reaction and dynamics of different vegetation types to various environmental and rangeland management factors. Due to the low rainfall in these savannas, regarding **environmental drivers**, Midessa has a focus on the precipitation and the associated soil moisture, which are the main determinants for biomass production, establishment, and competition of the vegetation. One unique feature of Midessa is the realistic spatially heterogeneous rainfall distribution. Via user-defined clouds, the daily precipitation is distributed randomly in patches over the landscape. To simplify simulations, the model does not consider explicit species but rather representative basic **plant functional types**. This allows the universal use of the model in a broader range of areas with different vegetation. For simplicity, there is also only one dominant vegetation type per cell in Midessa, which allows an easier simulation of the change and transition dynamic. This does not mean that in reality solely one vegetation type can be found on the cell, instead it is usually always a mix of different vegetation types, but one type can often be indicated as dominant for one particular cell at one point in time. **Management decisions** by farmers are another focus of the model. The farmers can implement a camp rotation system for their farm. This allows having livestock in one camp and moving the livestock to another camp after a certain amount of time; allowing the grass in the former camp to regrow. Based on the camp rotation system, the farmers define grazing pressure on the vegetation by setting stocking densities. Livestock is not modelled on an individual base, to avoid unnecessary calculations and too much detail, but instead is implemented as a herd with a certain stocking density. Stocking densities represent the concentration of livestock on the veld usually expressed as hectare of veld for each livestock unit (Trollope et al. 1990). Farmers can also influence the vegetation dynamics by altering the fire regime. This can be done by either creating fire breaks to stop fires from spreading, by keeping a high grazing pressure and thus little biomass amounts on the veld so that there is not enough fuel for a hot fire, or by actively starting a fire to fight bush encroachment. The complex spatio-temporal vegetation dynamics are a result of the interactions of these and other processes on different temporal and spatial scales.

The Midessa model was implemented in C++ using the QT Creator IDE (Version 4.13.0) based on QT (Version 5.15.0, MSVC 2019) and compiled with MinGW 5.3.0 for C++. The model code is available upon request. The input maps where created with PioLaG, a piosphere landscape generator implemented in NetLogo (Hess et al. 2020). Adaption of the parameter file for different scenarios, analysis of results and creation of the graphical output was done using R (Version 4.0.2 64-bit) in RStudio (Version 1.3.1093).

4.5.2 Emergence and interaction

One of the key mechanisms for the emerging vegetation patterns, the model's main output, is the temporal vegetation transition i.e. vegetation succession that occurs on a monthly base and is coupled to the amount and spatial distribution of precipitation. There are interaction effects between the different **vegetation types** during the temporal vegetation succession but also during the spatial succession. This interaction represents mainly the competition for resources, namely soil moisture and space, to build up vegetation biomass and produce seeds. There is also an interaction between the vegetation biomass on a cell and the animal density on the farm and the condition of the farm animals (livestock). Also fire has a complex interaction with the vegetation type and amount of biomass on the cell. It can only start when sufficient biomass fuel is available but is able to destroy biomass if the conditions are right. The savanna vegetation dynamics and cause-and-effect relationships influenced by environmental factors and management decisions show a complex interaction network of the different system components. The interactions take place at different temporal and spatial scales (cf. Levin 1992).

4.5.3 Adaptation and objectives

The livestock as a unit shows an adaptive behaviour as it circles around the watering points in attempts to graze and aborts grazing when 'it' is satiated. This grazing behaviour is modelled as direct objective seeking as the ongoing attempts are done to fulfil the goal of reaching a threshold of grazed biomass to become satiated. When the maximum walking distance is reached, the search for food begins again at the watering point. After three attempts, the attempts to get satiated are aborted (see 4.8.10 Livestock grazing and browsing).

4.5.4 Sensing

During the spatial vegetation transition, the focal cell will sense the presence of neighbouring cells. When at least five of the neighbouring cells are of the same vegetation type, this surrounding vegetation type will (under certain conditions; see 4.8.6 Vegetation Transition) replace the vegetation type of the focal cell. Another submodel in which sensing occurs is the grazing and browsing function. Here the livestock herd senses fodder availability and satiation. Fodder increases the livestock condition if reached quickly and decreases livestock condition if reached only after several attempts or if not reached at all. The livestock also indirectly senses thirst through the *water dependency* parameter, which describes the need of the herd to go back to a watering point to quench their thirst.

4.5.5 Stochasticity

Midessa uses stochasticity in several submodels to solve ties, and to generate randomness and environmental noise, and their effects on the different processes. Precipitation is one of the most influential factors and in the simulations; the **clouds** that indicate the specific location of rainfall are distributed mostly randomly over the landscape, leading to heterogeneous precipitation patterns (see section 4.8.1). When there is a draw in the **temporal vegetation transition** submodel (for details see 4.8.6) between several vegetation types for the establishment in a new cell, a random number generator is used to decide who will get the chance to establish. Also in the **biomass reduction** during grazing, stochasticity is used as a factor to account for environmental noise and grazing inefficiencies (for details see 4.8.10). **Trampling of livestock** occurs around the watering points in the landscape and increases the probability that the cells on which the livestock attempts to graze are turned from their current vegetation type to bare soil (for details see 4.8.12). The **mortality and decay** submodel simulates environmental noise by means of adding or subtracting up to 10 % to the specified decay and mortality rates of the dead and alive biomass of the different vegetation types (except for bare ground which has no biomass and the alive biomass of annual grasses which dies off completely) (for details see 4.8.9). The **fire** submodel uses randomness to select the location of potential cells that a fire could occur on and then also in the decision whether a burnable cell will actually burn (for details see 4.8.7). The submodel for **seed dispersal** simulates with a certain probability that the seeds of palatable and unpalatable perennial grasses as well as woody species disperse over a longer distance (for details see 4.8.8). The likeliness for a long distance spread is based on a basic dispersal probability (*seed_base_prob*) and a specific dispersal probability (*[vegetation-type].seed_ratio*) which is unique for the vegetation types.

4.5.6 Collectives

Aggregations of cells with the same vegetation types can be described as a collective as it allows them a chance to spread their vegetation type via spatial transition. Only as a collective with five or more cells of the same vegetation type around the central cell, the overgrowth of the central cell is possible. This collective is not represented explicitly in the model but is an emergent property of the single cells (Grimm et al. 2020).

4.5.7 Observation

The main outcome of Midessa are monthly vegetation landscape maps that show the spatial distribution and abundance of different vegetation type cells. In addition, maps with the alive and dead biomass amount as well as the vegetation condition are available, showing the effects of grazing, fire and other environmental and management factors. These main outcomes can provide information about the effects of different management scenarios and give an insight of the causal relationships between management decisions and environmental factors and the resulting consequences.

4.6 Initialization

The landscape is modelled as a toroidal landscape (world wrap) so the edges of the landscape are connected to form a sort of cube. Initialization begins with the **landscape** itself. The landscape dimensions, the spatial distribution of vegetation types (as a layer), the farm position and number (as a layer) (it is possible to work with different farms in one simulation extent but for runtime and to simplify we only work with a single farm in this study), the management type (communal, commercial, reserve), camp number and layout (as a layer), number and position of watering points (as a layer), as well as soil properties and fire parameters are set up. As input, Midessa can either use classified aerial images (taken by satellites, airplanes or drones), and manually created or adapted maps, or the simpler approach is to use the Piosphere Landscape Generator *PioLaG* (Hess et al. 2020). This landscape generator allows the user to easily create realistic savanna landscapes affected by livestock grazing/browsing. The *PioLaG* user can set important landscape properties for the map like the farm size, the subdivision into camps, number and place of watering points, and other farm infrastructure, as well as precipitation and soil parameters to create a vegetation pattern typical for the conditions that Midessa will be run for. Each cell in the simulation landscape is assigned one dominant vegetation type. To simplify simulations, Midessa distinguishes between bare soil, annual grasses, unpalatable and palatable perennial grasses, as well as young and mature woody vegetation (Tab. 6). The young and mature woody vegetation consists of trees and shrubs and is the vegetation type of bush encroachment. In a next step, the **global conditions** are initialized. The simulation run time, the temperature indices for each month, the cloud dimensions, rainfall parameters, precipitation distribution and other climatic parameters are set. During the initialization of the **vegetation**, spatial and temporal transition thresholds and parameters, the critical soil moisture, basal cover, interception values, memory coefficients, production parameters, cell capacity, basal and specific dispersal probability, seed- and green-biomass mortality, dead biomass decay, palatability, and initial starting values for some state variables (variables starting with *init_values.*) are set up for each vegetation type. In a last step, the management and livestock gets initialized by setting the stocking density, resting- and grazing time, wood removal rate, the number of livestock units for every camp, fodder amount needed by the livestock, trampling intensity and average grazing intensity per camp based on average distance to waterhole and water dependency of livestock (see also 4.4 Process overview and scheduling for an overview of initialization).

4.7 Input data

Input data needed for a simulation run are the 16 precipitation parameters for the rainfall algorithm which can be obtained via spatial coordinates of the farm with help of the rainfall atlas database (Zucchini et al. 1992; Zucchini and Nenadić 2006). To alter the spatial patchiness of the rainfall, the spatial dimension of the clouds can be set with two parameters. Other **climate**-related data are the annual seasonality represented by a monthly temperature index and the specification of the beginning and end of the winter period. **Soil** related input parameters are the soil depth, soil porosity, maximum evapotranspiration and the soil field capacity. **Fire** related input parameters are the relative number of cells that get ignited per 100 000 ha / month and the biomass threshold indicating the (grass) fuel load needed to start a fire. As the **vegetation** dynamics are in the central focus of the Midessa model, there are various parameters concerning the vegetation properties (like palatability, biomass thresholds for vegetation condition, growth parameters, mortality and decay values, maximum carrying capacity of the cells as well as seed related parameters) and parameters needed for the vegetation transition rules (such as vegetation type specific soil moisture minima for establishment and biomass transition thresholds). Important **livestock** parameters are the water dependency of the livestock and their maximum range i.e. maximum possible distance to the watering point as well as the monthly biomass fodder demand of one LSU. Important **management** input parameters are the stocking density (cells per LSU), the number of months of grazing/resting per year and the woody mortality (e.g. wood removal). Most of the mentioned parameters are read from the parameter input file and can be easily adapted by the user. A table with all parameters, default values and additional information can be found in the appendix (Tab C. 1 in the appendix for default parametrization).

Tab. 6: Dominant vegetation types in the model and exemplary species. Some perennial grasses are desirable grazing grasses in dry areas while they are considered less- or unfavourable for grazing in moister areas. (Adapted from: Tainton 1999; Thomas and Twyman 2004; Dalgleish et al. 2012; Hesselbarth et al. 2018; Dreber et al. 2019; see also chapter 1.1 Vegetation).

Vegetation type	Example
bare soil	no, or almost no vegetation
annual grasses	*Schmidtia kalahariensis, Aristida adscensionis*
palatable perennial grasses	*Cynodon dactylon, Digitaria eriantha, Eragrostis lehmanniana, Eragrostis superba, Schmidtia pappophoroides, Stipagrostis ciliata, Stipagrostis obtusa, Stipagrostis uniplumis*
unpalatable perennial grasses	*Aristida diffusa, Aristidia meridionalis, Aristida stipitata, Pogonarthria squarrosa, Stipagrostis amabilis, Stipagrostis uniplumis*
young & mature woody vegetation (trees and shrubs)	*Acacia (Senegalia) mellifera, Acacia (Vachellia) erioloba, Boscia albitrunca, Acacia hebeclada, Lycium hirsutum, Grewia flava, Acacia haematoxylon, Rhigozum trichotomum, Eriocephalus spinescens, Eriocephalus pubescens, Aptosimum spinescens, Rosenia humilis, Tarchonanthus camphoratus, Rhus undulata, Ziziphus mucronata*

4.8 Submodels

4.8.1 Precipitation

Precipitation is included in Midessa because the spatio-temporal precipitation patterns are believed to be one of the most influential and decisive factors for the vegetation dynamics in semi-arid savannas. The intra- as well as inter-annual precipitation amount and variation are of high importance for the establishment and competitiveness of the various vegetation types via their effects on soil moisture and on fire dynamics (see also 1.1 Precipitation).

Amount and temporal distribution of rainfall – Zucchini

During the initialization, the total amount and temporal (daily) sequence of rainfall amounts is calculated in advance for the complete simulation period for the simulated landscape. Midessa uses an algorithm developed by Zucchini et al. (1992) to calculate the occurrence and amount of rainfall. The algorithm uses 16 location-specific parameters that have been parameterized for all of South Africa by Zucchini and Nenadić (2006). These parameters can be obtained with the help of an R script from Zucchini and Nenadić (2006) via the GPS coordinates.

Using the 16 location-specific input parameters as well as seasonality parameters (see Zucchini and Nenadić (2006), Zucchini et al. (1992) for details), first a rainfall probability distribution is calculated (based on the Weibull family). A seasonal Markow chain is used to calculate the probability of rainfall for each day depending on whether rainfall occurred the previous day. This rainfall distribution is only temporal and not spatially explicit.

Spatial distribution of rainfall - Serge

The daily amount of precipitation is then spatially randomly distributed over the landscape based on a simplified version of the SERGE (Spatially Explicit Rainfall GEnerator) algorithm (Eisinger and Wiegand 2008) which uses randomly distributed "clouds" to locate areas that will receive precipitation. The clouds are responsible for the heterogeneous spatial distribution of the daily rainfall predicted by the algorithm from Zucchini et al. (1992). The heterogeneous rainfall can be turned on and off with the parameter *heterogeneousRain*. The amount of rainfall does not change with cloud size or number. The adaptable size of the rectangular rainfall clouds (Parameters *clima.x_cloud_size* and *clima.y_cloud_size*; default = 10 cells) and with that, the patchiness of the rainfall is fixed throughout the entire simulation. This calculation with daily resolution is done on a monthly basis in advance.

The number of clouds that will be created to distribute the rain over the landscape on a given day is calculated by dividing the spatial simulation extent by the cloud size. If the daily rainfall cannot be completely split up into clouds of the prescribed size, i.e. if there is a remainder left over from the calculation, this remainder is used to determine the probability of an additional rain cloud. We use a toroidal landscape approach i.e. if a cloud exceeds the borders of the simulated landscape, it is cut off at the border and continues at the opposite side of the landscape (closed system). This minimizes edge effects (Fortin 1999) and guarantees that the correct amount of rainfall will be distributed over the landscape. Each area under a cloud receives the predefined amount of rain. If several clouds overlap in a certain area, their amount of rainfall for this location is summed up. There is also the option to use spatially homogeneous precipitation.

4.8.2 Soil moisture

Soil moisture is important for the biomass growth of vegetation. Its intra- and inter annual variation can make the crucial difference in determining which vegetation type gets a competitive advantage in terms of survival, growth, seed dispersal and spatial spread. Midessa calculates the daily soil moisture with the help of an algorithm adapted from Meyer et al. (2007) and Rodriguez-Iturbe et al. (1999) . This algorithm calculates the soil moisture of cells based on rainfall of the day and soil moisture remaining from the preceding day. When the rainfall reaches the soil surface, several processes need to be considered. The water infiltrates into the soil adding to the soil moisture while water can be lost through evapotranspiration and leakage. Soil moisture can range between zero (no water in the soil) to one (all pores are filled with water).

$$nZ\frac{ds}{dt} = I(s,t) - E(s) - L(s) \tag{6}$$

The equation to calculate the soil moisture change (Eq. 6) uses: soil porosity (n), active soil depth or rooting depth (Z) [mm], current soil moisture (s) [%], infiltration rate (I) [mm/d], which is the rainfall minus the interception by vegetation, evapotranspiration rate (E) [mm/d], leakage rate (L) [mm/d] and time step (t) [days]. Following Rodriguez-Iturbe et al. (1999), we used the normalized version of the equation where all terms are divided by nZ.

Infiltration (I) is the rainfall that is not intercepted by the vegetation cover but that actually enters the soil and starts to fill the empty pores of the soil. The porosity of the soil can theoretically range between zero (high-density compact soil with no empty (air or water filled) spaces between the soil particles) to one (an empty hole whose volume can be completely filled with air or water). In reality, the porosity of soils ranges between 0.35 and 0.65 mostly depending on soil texture. We set the porosity to 0.373, equalling a bulk density of 1.66 g cm^{-3} representative for the deep weathered sandy soils dominant in the study region (Batjes 2004; Jordaan et al. 2019). When there is enough water storage capacity in the pores of the soil, the infiltration can be equal to the amount of rainfall. If the rainfall amount equals or exceeds the available water storage capacity, all pores are completely filled up with water. **Evapotranspiration** (*E*) is the water lost through evaporation from the soil and vegetation surface as well as through transpiration of the vegetation. **Leakage** (*L)* describes the flow of water into deeper soil layers caused by gravity when the soil water holding capacity is exceeded. The **surface runoff** describes the amount of water that is lost due to either an already saturated ground (all pores in the soils are filled), or due to a sloped landscape and/or a 'sealed' land surface because the top layer of soil is dried out and water might not be able to penetrate into the soil. Surface runoff is not included in the current model version, as most sites used for the calibration of the model were rather flat so that inflow and outflow of water may be considered equal. The surface runoff on sloped sites can be included as a future extension of the model with the help of an aspect-slope map of the landscape (see section 4.11 *Limitations and future* extensions).

4.8.3 Temperature

During winter months, when the temperature is low, the vegetation growth is less than during summer months, e.g. due to high temperature optima of C4 grasses (Wiegand et al. 2004). Midessa considers that temperature has an effect on biomass production (see 4.8.5 Growth, biomass and vegetation condition, Eq. 8). The seasonal temperature change is implemented through the use of a monthly **relative temperature index** (*clima.temperature_index0 - 11*) which represents the seasonality temperature effect on plant production (Fig. 25). The temperature index ranges between zero and one and is purely seasonal, i.e. potential spatial variation is not considered in Midessa. We parameterized the twelve values of the temperature index (one for each month of a year) based on an analysis of field data by Wiegand et al. (2004). We discussed and adapted these values during a workshop (Kimberley, South Africa, July 2016) and meetings with specialists. Further adaption of these indices would allow integrating climate change and the associated change in temperature.

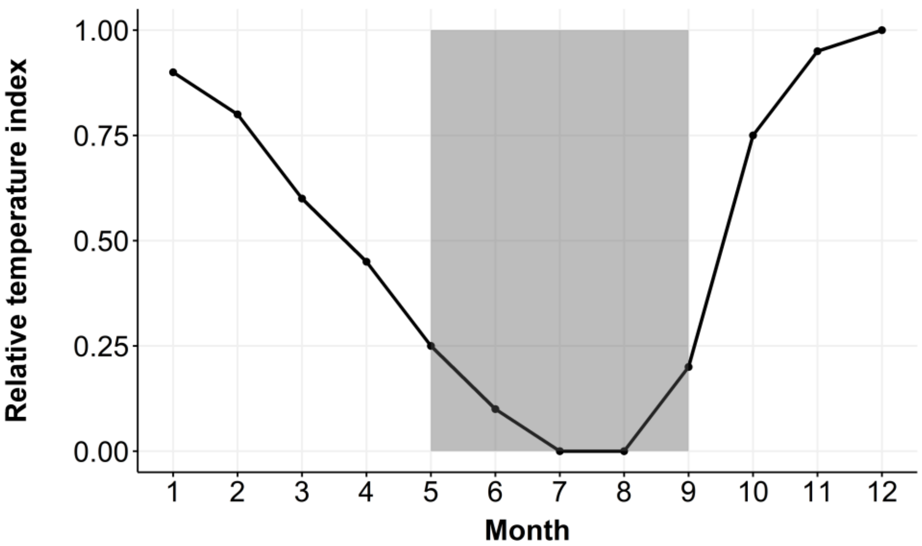


Fig. 25: Seasonal temperature index ranging from zero to one for each month of a year. Winter months are shaded grey. A value of one indicates an optimal temperature for vegetation growth while zero indicates low temperatures that lead to a stagnation of vegetation growth.

Further parameters are the beginning (May) and end month (September) of the **winter season** (*clima.begin_winter* and *clima.end_winter*). These parameters influence the establishment of annual grasses. During summer months, annual grasses can establish in any case on cells with bare soil; while during winter months the germination and establishment conditions (Fig. 26) have to be met for a successful establishment on a cell with bare soil.

4.8.4 Vigour

The vigour is a vegetation memory index for the amount of precipitation in the past and is used in a multiplicative function for the calculation of biomass production (see 2.7.3. Growth, biomass and vegetation condition). More specifically, the vigour helps to quantify the production carryover effects from past months i.e. based on the precipitation in the past it alters the response of production to current growth conditions (see Eq. 8). These memory and carryover effects buffer the fluctuations of vegetation production linked to precipitation when wet and dry years alternate annually and amplify production fluctuations when several dry or wet years occur in a row (Wiegand et al. 2004).

In an investigation of a semiarid grassland in South Africa, Wiegand et al. (2004) found a carryover effect ranging from 1-3 months for medium/poor vegetation condition and 4 years for good vegetation condition. Motivated by these results, we do not explicitly define the length of the memory and carryover effect, but model it indirectly via a memory coefficient *c* that depends on vegetation type and vegetation condition (i.e. $c = c$(vegetation type, condition)). Conditions are classified as poor, medium or good (see section 4.8.5 Growth, biomass and vegetation condition and parameter file for classification thresholds).

In Midessa, the vigour for month m, memory coefficient c , and last month's precipitation on the cell $R(m$-1) is calculated analogous to (Wiegand et al. 2004) with the recursive equation:

$$vigor(m,c) = c \times vigor(m-1,c) + (1-c) \times R(m-1) \tag{7}$$

The memory coefficient c weights the relative importance of the plant condition (vigour) and precipitation, both of the preceding month. Because the vigour is calculated recursively, the total effect of past precipitation that is included in the current calculation of the vigour depends on the value of c and can reach back several months. When c is zero, the current vigour is equal to the precipitation of last month i.e. the effect of last month's precipitation is very strong. With increasing values for c, the effect of last month's precipitation decreases. When c is one, the rain of last month is not relevant for the calculation of the current vigour and only the vigour of the past is taken into account (Wiegand et al. 2004).

4.8.5 Growth, biomass and vegetation condition

The vegetation growth in the Midessa rangeland model is calculated by using an equation based on Wiegand et al. (2004) and O'Connor et al. (2001), with different parametrization for each vegetation type. In reality the growth rates are far more complex and vary a lot between different species and even within one species on the same site (Swemmer and Ward 2019). However, due to the generalizing approach of using one dominant vegetation type per cell, which is representing a diverse mix of different species, the effect of specific growth rates is evened out. The biomass production (*production*) is influenced by the current monthly precipitation ***R***, the temperature (via the monthly temperature index ***TI***; representing seasonality and the corresponding productivity; it ranges between zero and one; see section 4.8.3) and the vigour ***vigor***, (influence of past precipitations; see section **Error! Reference source not found.**). Because the primary production is also highly depended on the current biomass and its absences is a first-order cause of decreased production e.g. in case of land degradation (Wiegand et al. 2004), the basal cover of the vegetation type on the current cell is an important part of the equation with a directly proportional effect on the production.

$$production = (a + b \times vigor \times R \times TI) \times basalCover \tag{8}$$

With ***a* and *b* being production parameters** specific to the different vegetation types and vegetation conditions to shape the actual precipitation use efficiency (see table with input parameter for intercept (a) and slope (b) parameters (*[vegetationType].intercept[vegetationCondition]*) *and [vegetationType].slope[vegetationCondition]*). Given that vegetation on each cell is simplified to the dominant vegetation type, no interaction between vegetation types needs to be considered here. The equation returns the vegetation growth as dry matter green biomass in grams per square meter. In Midessa, this value is converted to kg per cell (900m^2). The basal cover is the proportion of the vegetation on a cell that meet the surface of the soil (Fehmi 2010). It plays a major role for the water status in the cell by avoiding water run-off and thus in increasing infiltration into the ground. A low basal cover indicates a higher percentage of bare soil and thus also a lower potential for biomass growth. The ***maximum basal cover*** ([*vegetationType*].basalcover[HIGH]) on the cell which may be reached under optimal vegetation condition is specific for each vegetation type. The **current basal cover** is estimated via the vegetation condition based on the amount of green biomass on the cell. Parameter thresholds for low, medium and maximum basal cover ([*vegetationType*].basalcover[LOW-MEDIUM-HIGH]) are based on the findings of O´Connor et al. (2001). After calculation of the new vegetation production, the **green biomass** is updated. The value of green biomass is restricted by the carrying capacity ([*vegetationType*].capacity) on that cell, for the specific vegetation type.

The green biomass is the active, living biomass on a cell. The dead biomass or necromass is calculated in the submodel 4.8.9 (Mortality and decay of vegetation and seeds) and will remain on the cell until it is e.g. eaten or burned. Because the dead biomass is still occupying space on the cell, it is considered when calculating the monthly increase of green biomass.

$$biomass_{green}(\mathrm{t}) = biomass_{green}(\mathrm{t}-1) + production \times \left(1 - \frac{\mathrm{biomass_{dead}}(t-1) + biomass_{green}(t-1)}{\mathrm{cc}}\right) \tag{9}$$

The sum of green and dead biomass is bounded by the **carrying capacity (*cc*)** [kg cell^{-1}]. *cc* is vegetation-type specific and specific to a given cell. This is because each vegetation type has a maximum carrying capacity (*cc_max*), i.e. a maximum possible amount of biomass that can fit on a cell (values derived from O´Connor et al. (2001)), and because the biomass production also depends on the actual basal cover in a given cell. These considerations are incorporated as follows. The current carrying capacity on the cell is calculated by multiplying the maximum carrying capacity (cc_{max}) with the ratio of the **actual basal cover** ($\mathrm{basalCover_{actual}}$) to the **maximum basal cover** ($\mathrm{basalCover_{max}}$):

$$cc = cc_{max} \times \frac{basalCover_{actual}}{basalCover_{max}} \tag{10}$$

For mature woody species the value was doubled in comparison to young woody vegetation to account for their greater biomass while only a third of the perennial grasses' biomass was taken as maximum for annual grasses.

The **vegetation condition** plays an important role during the spatial vegetation transition. It is set based on the amount of green biomass on the cell and can be *poor*, *medium* or *good*. The different thresholds (based on O'Connor et al 2001) that define the classification borders are spat_transition.biomass[*vegetationType*][*condition*] in the parameter file. The threshold for poor vegetation condition of perennials is 100 kg / ha after Jeltsch et al. (1997).

4.8.6 Vegetation Transition

The vegetation transition is one of the most important functions when it comes to the creation of the realistic vegetation pattern. In the Midessa model, we distinguish between two types of vegetation transition: The spatial transition and the temporal transition. In combination, they represent the vegetation successions as an effect of competition processes mainly for soil moisture, space and seed production. These factors are mainly influenced by environmental impacts and management decisions especially grazing pressure. The optimal goal for a savanna-farmer's sustainable land management is to have high quality, nutritious grasses in abundance to sustainably feed his/her livestock. The farmer will try to guide the development and succession of vegetation types towards a high abundance of highly nutritious palatable perennial grasses by a flexible response to ecological and socio-economic changes (Kellner 2009). The management goal is to counteract the degradation to annual grasses or even bare soil or shrubs and aid in the recovery of the valuable palatable perennial grasses. It is important to avoid amplifying the degradation by bad management decisions such as overgrazing. This is especially important as degradation usually happens a lot faster than recovery and after crossing certain thresholds, recovery sometimes might even not be possible (Abel and Blaikie 1989; Kellner 2009). Due to the approach of using only one dominant vegetation type per cell, the current values for vigour, biomass and soil moisture remain the same during the temporal transition of vegetation types and are inherited by the new vegetation type. The rules for the succession and threshold were refined during discussions with experts during a series of workshops, one with rangeland experts (July 2016, Kimberley, South Africa; 25 participants) and two with commercial farmers (February 2017, Ganyesa and Askham, South Africa; 29 and 28 participants, respectively).

Temporal Vegetation Transition

The temporal vegetation transition is modelled on a monthly basis. It simulates the natural succession and dynamics of the different vegetation types. On each cell, the current conditions for the respective vegetation types are checked to determine the continuation of the current vegetation type or the transition to another vegetation type (Fig. 26). The rules and conditions for transition (germination, establishment, dormancy, and death) are specific for each vegetation type (for parameters see *C.1 Default parametrization for the Midessa* rangeland model - section *Vegetation)*. The transition is mainly based around the availability of free space (Grubb 1977), soil moisture, and seeds. Other factors that have an effect on the vegetation transition are severe fires, the growth of woody plants, trampling, and seasonality. A **severe fire** can kill all vegetation types (woody vegetation cells cannot be initial ignition points) and turns the corresponding cell to bare ground while resetting the cells biomass volume to zero. The conversion of young woody to mature woody vegetation happens through **natural growth**. During this conversion, a share of the green biomass is transformed to dead biomass. **Trampling** can occur in the vicinity of watering points on cells of all vegetation types except mature woody vegetation and convert the cell type to bare ground (see 2.7.11 Trampling of livestock). Both **heavy grazing** and **removal by humans** can be causes for the conversion to bare ground. This is modelled by setting the cell type to bare ground if the biomass value of a cell falls below 100 kg ha^{-1} (Jeltsch et al. 1997b). The **seasonality** only plays a role for the transition of annual grasses as these die with the start of the winter season and their green biomass is converted to dead biomass. In this case, the vegetation type of the cell does not change to bare ground but is maintained as annual grasses.

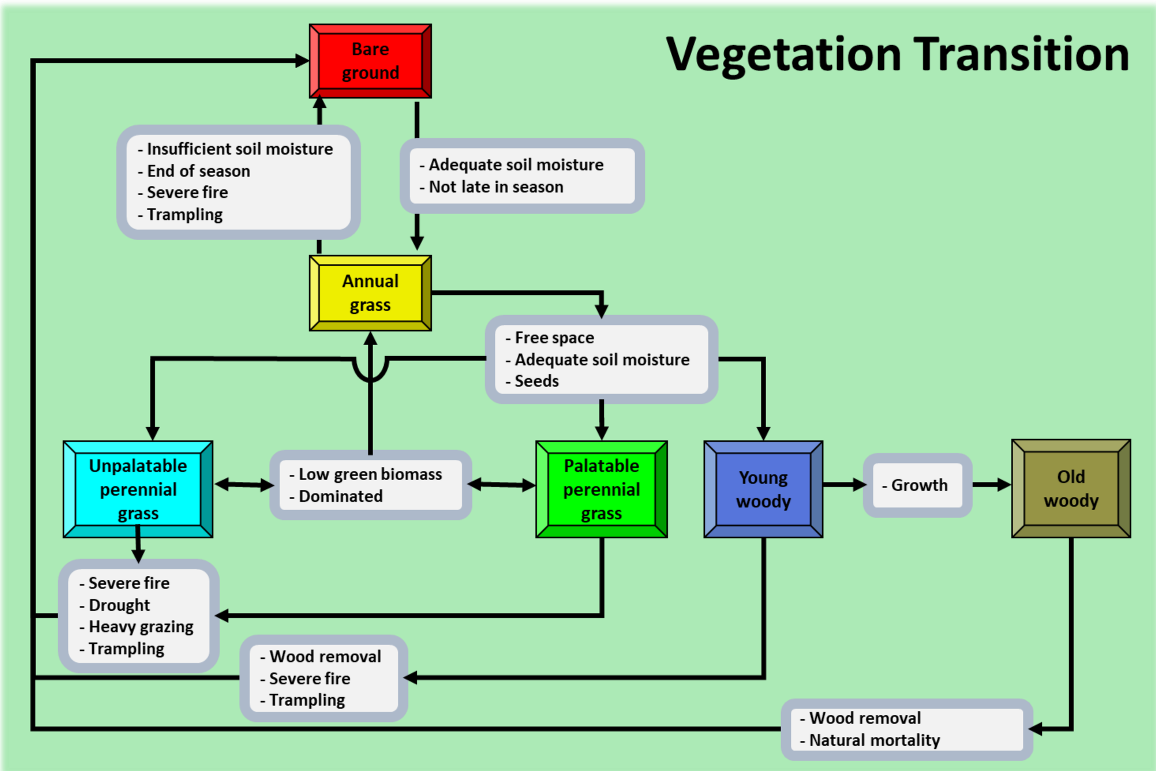


Fig. 26: Overview flow chart of the spatial and temporal vegetation transitions of the different vegetation types and the corresponding conditions that need to be met. The coloured boxes represent the dominant vegetation type on the current cell. Arrows indicate the possible ways of transition if the conditions in the rounded boxes are met. The conversion of one vegetation type to another via bare ground is possible when germination occurs within the same month. Detailed rules and thresholds can be found in Tab. 7, Tab. 8 and Tab. 9.)

The **temporal sequence of the vegetation transitions** begins with checking whether trampling has taken place. Cells in which intense trampling has occurred will be turned to bare ground and seedlings killed. The *trampling intensity* is based on the distance of the cell to the nearest watering point within that camp (see 4.8.12 Livestock trampling). Then, for cells dominated by young woody vegetation, the **growth** of the vegetation becoming mature woody vegetation is simulated. Next, on all non-bare and non-woody vegetation cells the vegetation types' thresholds are compared with the current soil moisture conditions to check for **drought** and the resulting transition to bare ground. The monitoring of soil moisture is done on a daily basis to calculate how many days the vegetation experienced un-/favourable conditions. The maximum number of days without sufficient water that annual grasses can survive before dying is the same as the minimum number of dry days that bare ground needs to 'establish'. Further rules and default parameter values can be found in Tab. 7, Tab. 8 and Tab C. 1. As a last step, the conditions for **germination and establishment of seedlings** are checked. If there have been favourable soil moisture conditions, and free space and seeds are available (see Fig. 26, Tab. 7 and Tab. 8), the respective vegetation type can germinate from seeds. If there are already seedlings present on the cell and the "survival for one month" conditions are met, the particular vegetation type can establish. For example for annual grasses to germinate on bare ground (free space), adequate soil moisture (minimum 30 %) has to be available and it must not be too late in the season as the annual grasses die with the beginning of the winter season. Annual grass seeds are considered to be always available (see 4.8.8 Seed dispersal). In the next time step (i.e. month) this germinated seed can then establish if the conditions (sufficient soil moisture for at least 20 days) are met. It is possible that several vegetation types germinate in the same month and cell but only one can establish and become the dominant vegetation type. The most assertive vegetation type is determined by the rules and conditions in Tab. 7 and Tab. 8. In case of a tie, i.e. when two or more vegetation types have equal chances to dominate a cell, the decision is made randomly.

Tab. 7: Live stages and conditions for the development of annual grasses with default parametrization (see Tab C. 1 in the appendix for all parameters).

Annual grass event	Rules
Germination The conditions are favourable so that the annual grass seeds can germinate.	Soil moisture minimum 30 %. Cell has to be empty i.e. bare soil. Seeds are assumed to be always available
Establishment The germinated seeds can establish (survive the first month) and grow into proper plants.	Survival for one month = Sufficient soil moisture (30 %) for at least 20 days in a row in the current month
Dormant state The conditions are not good enough to allow the plants to grow and increase biomass. They are however able to sustain their current state.	Soil moisture is between 10 % and 30 % OR Soil moisture is higher than 30 % but for less than 20 days per month
Death The conditions are so bad that the plants die.	Soil moisture less than 10 % for > 10 days OR End of growing season is reached OR A severe fire occurs

Tab. 8: Temporal vegetation transition rules for perennial grasses and young woody vegetation with default parametrization (see Tab C. 1 in the appendix for all parameters).

Perennial grass and woody vegetation events	Rules
Germination The conditions are favourable so that the perennial grass seeds can sprout.	Soil moisture minimum 50 %. Cell has to be empty i.e. bare soil Seeds have to be available
Establishment The germinated seeds can establish (i.e. survive the first month) and grow into proper plants. *Germination + Establishment = Change of Vegetation type on the cell*	Survival for one month = Sufficient soil moisture (50 %) for at least 30 days in the current month
Dormant state The conditions are not good enough to allow the plants to grow and increase biomass. They are however able to sustain their current state. E.g. during winter months and in dry periods	Soil moisture is between 10 % and 50 % OR Soil moisture is higher than 50 % but for less than 20 days
Death The conditions are so bad that the plants die.	Soil moisture is less than 10 % for > 10 days OR A severe fire occurs

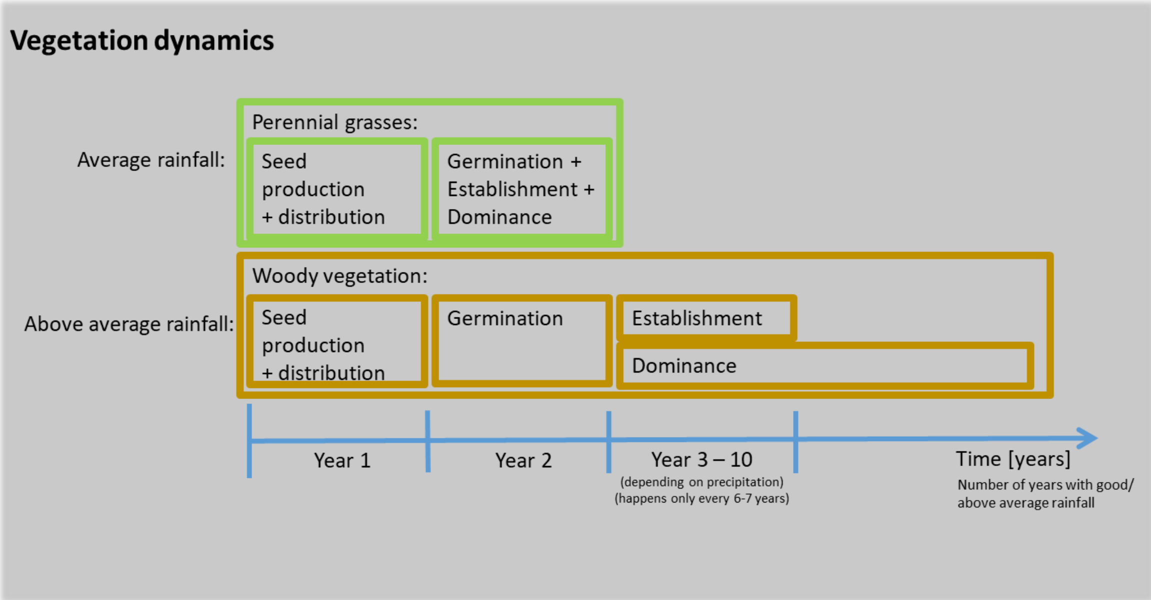


Fig. 27: Development and competition (through production/biomass advantages and overgrowth) of perennial grasses and shrubs during average and above average rainfall years. See also: Wiegand et al. (2005).

In average-rainfall years (compare thresholds *temp_transition.soil_moist_min[vegetationType]* and *temp_transition.on_switch[vegetationType]),* the perennial grasses and the woody vegetation produce seeds and spread them in the landscape (see 4.8.8 Seed dispersal). In the next year, the dispersed seeds of the perennial grasses and woody species can germinate. However, the rainfall conditions may not be good enough to allow the young woody species to substantially increase biomass and establish. The perennial grasses however will germinate and establish if sufficient soil moisture (lower than for woody species) is available (see Tab. 8). Thus, the perennial grasses will be dominating the germinating woody species and will be the dominant vegetation type on the cell. The woody species' seeds however will be able to sustain at the current cell (with a slight decay rate) and can wait for another chance to germinate and establish during better conditions. This represents in the model the dormant state of seedlings as gullivers (suppressed juveniles) (Higgins et al. 2000) under the grass layer, waiting for better conditions, which can be observed in reality. In an above average rainfall season, which occurs in reality only every 6-7 years region (World Bank Group 2021), the woody species will then have the chance to establish and dominate the perennial grasses and thus become the dominant vegetation type on the cell (Fig. 27).

Spatial vegetation transition

The spatial vegetation transition occurs annually in the model. It simulates the ingrowth and takeover of the vegetation in the focal cell by surrounding vegetation types and with that, the change of the dominant vegetation cell type (Fig. 28). The spatial vegetation transition only affects focal cells with bare ground, annual grasses in poor condition as well as palatable and unpalatable perennial grasses in medium and poor condition (Tab. 9). Woody species on the other hand will not be challenged and overgrown by the neighbouring vegetation. We assume that woody plants usually have access to water in deeper layers and thus a competitive advantage (Walter 1971; Walker et al. 1981; Ward et al. 2013) although the competitive strength also depends on the factors that influence the proportion of available water in the upper and deeper soil layers (e.g. precipitation patterns and soil type; Teague and Smit 1992). The vegetation condition is based on the living biomass on a cell (see section 2.7.3 "growth and biomass" for further details.) The less biomass there is on a cell, the more sparsely it is vegetated and the freer space there is for colonization by competing/neighbouring vegetation types. If the condition of any vegetation type in the focal cell is good, it cannot be invaded. Bare ground on the other hand will always be conquered by the surrounding vegetation if there are five or more cells of the same vegetation type present in the Moore neighbourhood (Tab. 9).

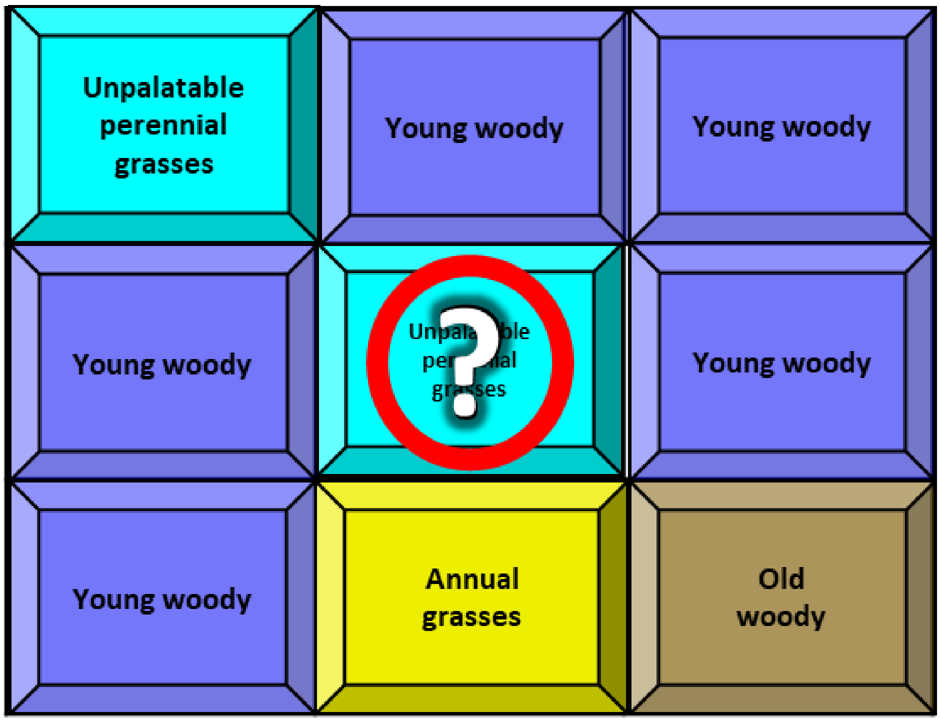


Fig. 28: Illustration of spatial transition. When at least 5 cells in the Moore neighbourhood of the focal cell are of the same type, spatial transition becomes possible. The occurrence of spatial transition is possible at the end of each year, between December and January. See Tab. 8 with requirements for vegetation condition and type.

Tab. 9: Rules for the (non-)occurrence of spatial transition depending on vegetation type in the focal cell and its vegetation condition.

Focal cell	Vegetation condition	Transition
Any vegetation	good	no transition
Woody	any	no transition
Bare	any	possible
Annual	medium	no transition
Annual	poor	possible
Perennials	medium	only transition to bare soil
Perennials	poor	possible

4.8.7 Fire

Fire plays an important role in rangeland dynamics and as an adversary of shrub encroachment (Scholes and Archer 1997). A farmer can influence the amount of fire events as a management option by avoiding (fire bans, firebreaks, keeping a small fuel load (i.e. grass vegetation biomass)) or by promoting fires (setting fires / prescribed burning, high fuel load). The *firefreq* parameter combines both these farming decision and natural causes of fire. The parameter describes the number of ignited cells per 100 000 ha/month. Each month a number of *firefeq* cells is spatial randomly selected as *ignition cells* and will be tried to set on fire. Only cells with annual or perennial grasses can be ignited as initial fire start cells. Young and mature woody vegetation as well as bare ground cannot be ignited. The selected ignition cells will actually catch fire with a certain probability calculated after Jeltsch et al. (1997). For this, the minimum biomass to start a fire is $biomass_{fire\_threshold}$ [kg/cell]. Only if the total biomass ($biomass_{total}$) on the cell is bigger or equal than the threshold to start a fire, there is a chance of the cell actually catching on fire. If the threshold is exceeded, the probability of a selected cell to catching fire (*fire_probability*) is:

$$fire\_probability = \sqrt{\frac{biomass_{total} - biomass_{fire\_threshold}}{biomass_{fire\_threshold}}} \tag{11}$$

When a cell catches fire, all the vegetation on it is burned down. The green and dead biomass of the cell are set to zero, the fire dies down and the cell is converted to bare ground.

In reality, the fire may spread to adjacent cells, usually cells that are opposite the wind direction where sparks get carried by the wind. In Midessa, wind direction is not explicitly modelled. Instead, all eight adjacent cells in the Moore neighbourhood are prone to ignition by a spread of the fire. Therefore, all eight cells are checked to determine if they are already burning and if they could burn. Susceptible for a fire spread are not only annual and perennial grass cells but also young woody cells. This is because a spreading fire may be hot and strong enough to damage young woody vegetation. If the cell is not already burning and the vegetation type susceptible to fire, the same processes as above take place i.e. a check of biomass threshold and ignition according to the *fire_probability*. Cells with mature woody vegetation are never damaged by fire.

Instead of using the simplistic fire approach described here, there is also a more sophisticated model available by Limberger et al. (2020) which offers numerous specific fire setting options. This ***Sa****vanna* ***Fi****re* ***M****odel* (SaFiM) is generically implemented and can be used as an extension submodel for Midessa.

4.8.8 Seed dispersal

Seed dispersal and with that, one of the chances for the spatial spread of vegetation types occurs annually (after the last month of the year) in the model. The seeds of annual and perennial grasses as well as of the woody vegetation are considered in Midessa, but not modelled explicitly. Instead, we use a seed bank approach, which allows us to set one value (*seed index*) for the seed availability for each cell and vegetation type. The *seed index* variable ranges from zero to one, with zero meaning no seeds of that specific type are available on the cell and values above zero meaning that seeds are present. One single cell can contain seeds of different vegetation types at the same time.

It is assumed that the seeds of annual grasses are omnipresent and always available everywhere in the landscape. This was done to reflect the many seeds produced by annual grasses that can also disperse easily over longer distances (Tainton 1999). Unpalatable and palatable perennials have the same seed dispersal rules.

There are two types of seed dispersal, the close range type into the neighbouring and surrounding cells and the long range type representing a transport of the seed via wind, animals, etc. over longer distances (Dean et al. 1999). The latter is implemented as randomly occurring somewhere within the simulated landscape. When seeds are dispersed to a cell, this cell's seed bank value for the specific vegetation type seed is set to one. The rules for **short-range dispersal** depend on vegetation type. Annual grasses are omnipresent. For perennial grasses, the distance of dispersal depends on the vegetation condition. With increasing condition, the seeds will spread further. Cells with perennial grasses in a poor vegetation condition will only produce seeds in the current cell. If the perennial grasses are in medium condition, the seeds will be produced and spread on the current cell and the eight surrounding cells. If the perennial grasses are in great shape, the seeds will be on the current cell and in the 24 (=8+16) surrounding cells. Young woody vegetation only produces and disperses seeds on the current cell that it is growing on while mature woody vegetation additionally disperses seeds into the eight surrounding cells in the direct Moore neighbourhood (Tab. 10). The chance for the production and **long range dispersal** of the seeds of perennial and woody vegetation on any cell depends on a base probability (*seed_base_prob*) that is multiplied with a vegetation type specific seed probability (*[vegetation-type].seed_ratio*) (Tab. 11). Seed mortality is implemented such that the seeds of perennial grasses and woody vegetation in the seed bank will degrade over time at a fixed, linear rate (see section 4.8.9 Mortality and decay of vegetation and seeds).

Tab. 10: Annual dispersal patterns and probabilities of seeds for close and long range. The seeds of all vegetation types and conditions are always produced and dispersed in the current cell that the vegetation is on.

Vegetation type	close range (spread from focal cell)	long range (occurrence on each cell in landscape)
Annual grasses	omnipresent	omnipresent
Perennial grasses	**Poor condition** Seeds only disperse in the focal cell **Medium condition** Seeds also disperse into 8 surrounding cells **Great condition** Seeds disperse into the focal and the 24 surrounding cells	base probability × vegetation type specific (palatable or unpalatable) probability
Young woody vegetation	Seeds only disperse in the focal cell	base probability * woody vegetation specific probability
Mature woody vegetation	Seeds disperse into the focal and the 8 directly surrounding cells	base probability * woody vegetation specific probability

Tab. 11: Parameter values for long-distance seed distribution.

Parameter	Value	Description
seed_base_prob	0.1	base probability
[P_PER].seed_ratio	0.6	palatable perennials seed probability
[U_PER].seed_ratio	0.3	unpalatable perennials seed probability
[Y_WOODY].seed_ratio	0.1	young and mature woody vegetation seed probability

4.8.9 Mortality and decay of vegetation and seeds

The mortality submodel is run annually (after the last month of the year) and ensures that the vegetation in the model may die and decay over time. The model distinguishes between dead and alive (green) biomass (Tab. 12). After a year, the green biomass of **annual grasses** (if not already consumed by livestock) is completely turned into dead biomass. The **palatable** and **unpalatable perennial grasses** die off at a rate of 35 % annually with some environmental noise (+/-10 %).

(McClaran and Van Devender 1995; Zimmermann et al. 2010). The dead biomass of annual and perennial grasses decays with some environmental noise (+/-10 %) at a 35 % decomposition rate. The default parameters of the two types of perennial grasses are equal but of course, they can be parameterized individually. The **biomass** of green young and mature **woody vegetation** turns partially (35 % +/-10 %) into wood (i.e. dead biomass). Dead wood does not decay per default in Midessa; instead, it accumulates over time. By altering the decay parameter of dead woody biomass a constant (fire) wood extraction rate can be simulated. In reality woody vegetation will die, besides from fire, at a slow rate influenced majorly by drought stress (Case et al. 2019). The **seeds** deposited in the cells also gradually die off at an annual rate (currently 30 %).

Tab. 12: Parameter and parameter names of annual rates for decay and mortality of vegetation and seeds.

Parameter	Vegetation type	Value	Unit
seed mortality *[veg.type].seed_mortality*	palatable perennial grasses	0.3	a^{-1}
	unpalatable perennial grasses	0.3	a^{-1}
	young woody vegetation	0.3	a^{-1}
mortality of green biomass *[veg.type].mortality_green_biomass*	annual grasses	1	a^{-1}
	palatable perennial grasses	0.35	a^{-1}
	unpalatable perennial grasses	0.35	a^{-1}
	young woody vegetation	0.35	a^{-1}
	mature woody vegetation	0.35	a^{-1}
variance of mortality *[veg.type].var_mortality_green_biomass*	annual grasses	0	a^{-1}
	palatable perennial grasses	0.1	a^{-1}
	unpalatable perennial grasses	0.1	a^{-1}
	young woody vegetation	0.1	a^{-1}
	mature woody vegetation	0.1	a^{-1}
decay of dead biomass *[veg.type].decay_dead_biomass*	annual grasses	0.35	a^{-1}
	palatable perennial grasses	0.35	a^{-1}
	unpalatable perennial grasses	0.35	a^{-1}
	young woody vegetation	0	a^{-1}
	mature woody vegetation	0	a^{-1}
variance of decay *[veg.type].var_decay_dead_biomass*	annual grasses	0.1	a^{-1}
	palatable perennial grasses	0.1	a^{-1}
	unpalatable perennial grasses	0.1	a^{-1}
	young woody vegetation	0.1	a^{-1}
	mature woody vegetation	0.1	a^{-1}

4.8.10 Livestock grazing and browsing

The livestock is not modelled on an individual animal basis, but as a representative livestock unit with a predefined animal density per area. With this simplification, the pattern of grazing is recreated in a way that saves computing power while recreating realistic effects on the vegetation dynamics. Grazing and browsing is modelled for each camp separately on a monthly base. Grazers will not eat on young woody or mature woody cells while browsers do. The representative livestock entity will first make a maximum of three attempts to graze the green biomass and then a maximum of three attempts for the dead biomass. As soon as the amount of fodder to get satiated is reached, the livestock will stop grazing. They start from the watering point and circle outwards around the watering point. The increase of radius is the size of one cell (30 m). During each attempt one third of the currently (i.e. in this attempt) present biomass of the cell is consumed. The livestock increases the distance to the watering point on the search for fodder until they are satiated or reach their maximum distance i.e. their home range.

The livestock condition ranges from 0 to 100. It represents the fitness, general condition and state of health of the livestock. If the livestock gets satiated on the first attempt, the livestock condition is increased (+1) to the next higher state. If they get satiated on the second attempt, the livestock condition does not change. This is to reflect that the amount of energy used to gather sufficient biomass fodder is about equal to the energy gained from the fodder. If the livestock ge ts satiated only at the third attempt, the livestock condition is decreased (-1) one stage. If the livestock is not satiated after the third attempt of grazing/browsing, it experiences a strong decrease (-3) of livestock condition. Very high, unsustainable stocking rates will result not only in a strongly decreased vegetation biomass, but also in poor livestock condition. Livestock condition is thus a good indicator for veld quality and correctly adapted management. The equation for biomass reduction (*biomassReduction*) [kg/cell] for each cell and round (max. 3) of grazing is adapted from Jeltsch et al. (1997):

$$biomassReduction = cB \times gI \times pal \times stochasticity \tag{12}$$

The **consumed biomass (*cB*)** [kg/cell] is 33 % of the available biomass on the cell. The **palatability (*pal*)** [rel. amount] is the palatability of the vegetation type i.e. the edible proportion of the biomass on the cell. The palatability is specific for the vegetation type and kind of livestock. **Stochasticity** (*stochasticity*) is a random number between zero and two to account for inefficiency of grazing and random effects. The **grazing intensity (*gI*)** (see Eq. 13) is adapted from Jeltsch et al. (1997), using an exponential function to describe the decreasing effect of livestock density and grazing action with increasing *distance* [cells] from the watering point and decreasing *water dependency* [dimensionless] of the livestock. It thus represents the spatial distribution of livestock in a camp due to the attractiveness of a watering point and the associated decrease of area for grazing. The water dependency of the livestock can range between zero (not depending on a watering point) to minus one (highly water dependent).

$$gI = 2 \times e^{-distance \times waterDependency} \tag{13}$$

The spatial distribution of the livestock around a watering point is driven by the livestock's dependency on water and the need for fodder. The water dependency limits their maximum range away from the watering point, while sufficient fodder/ biomass can usually be found in greater abundance with increasing distance from the watering point (McNaughton 1985; Andrew 1988; Pickup and Bastin 1997; James et al. 1999; Thrash and Derry 1999).

4.8.11 Management

The farmer of a southern African rangeland has many different management options. The most important of these options are implemented in the Midessa rangeland model. The **stocking rate** (Definition: Trollope et al. 1990) is one of the most important factors when it comes to making adequate and sustainable management decisions for a rangeland. A good balance has to be found between the economic short-term interests of the farmer and the long-term sustainability and profitability of a farm even in drought periods and over several decades (Tainton 2000). The stocking rate should be chosen such that a high gain per hectare is reached with a sustainable number of animals grazing on the farm and overgrazing is avoided (Tainton 2000).

Depending on the farm infrastructure (number and position of camps and watering points), the livestock is distributed heterogeneously over the landscape. They gather at attraction points like watering points, or salt licks and are less abundant in cells furthest away from the attraction points (Andrew 1988).

The **average grazing and browsing intensity ($gI_{average}$)** based on the average cell distance to the nearest watering point (see Eq. 13 for the cell-based grazing intensity (gI) in chapter 4.8.10 *Livestock grazing and browsing*) can be used as an overall description of the grazing pressure on the farm. The $gI_{average}$ is also necessary for the calculation of the expected fodder demand per camp. A high fodder demand of the livestock can only be satisfied with a lot of biomass and may lead to poor livestock condition if there is a lack of biomass such that the livestock cannot get satiated. A central unit for livestock management and comparing grazing intensities is the area per large stock unit. A **large stock unit (LSU)** is a predefined *standardized animal* "with a mass of 450 kg and which gains 0,5 kg per day on forage with a digestible energy percentage of 55 %"(Trollope et al. 1990). The Modell does not use an individual based modelling approach, but instead we use the livestock density on the farm expressed in ha per LSU (see 4.8.10 *Livestock grazing and browsing*). To estimate the **expected fodder demand [kg]**, the absolute number of LSU per camp (*#_of_LSU*) [LSU] is multiplied with the average grazing intensity per camp ($gI_{average}$) [dimensionless] and with the monthly fodder demand per LSU (*fodderDemandLSU*) [kg / LSU] (Eq. 14). The absolute number of LSU per camp (*#_of_LSU*) [LSU] is calculated by dividing camp size [cells] by stocking rate [cells / LSU] (Eq. 15).

$$expected\_fodder = \#\_of\_LSU \times gI_{average} \times fodderDemand_{LSU} \tag{14}$$

$$\#\_of\_LSU = \frac{camp\_size}{stocking\_rate} \tag{15}$$

The farmer can change the **grazing intensity** by altering the available hectares per large stock unit i.e. the amount of animals on the farm. The stocking rate in the model is set in cells per LSU with a cell being 0.09 ha.

Another important management option of the farmer is if and what kind of **camp rotation system** is used for a controlled grazing of the livestock. In a camp rotation system, not all camps are grazed simultaneously. Instead, the livestock is rotated from camp to camp only staying a certain time in one camp before being moved to the next camp. This gives the vegetation on the resting camps time to recover and regrow and grazing is concentrated on the camp not at rest. Some farmers also keep a backup camp for very dry seasons, that is not grazed in the normal camp rotation period but is kept aside when there is a special fodder demand, often due to environmental factors (drought years) (see chapter 2 *Farmer interviews and input from workshops*). In the model, the type of camp rotation system can be set by defining the grazing time for the camps of a farm (*management.grazing_time*). All the camps of a farm have the same grazing-/resting pattern. When a grazing time of two months is set in the parameter file, the first camp of the farm will be grazed for two months while the other camps are at rest. Then, the cattle is moved to the next camp where it will graze for two months while the other camps are at rest. This rotation circulates through all camps throughout the simulation period. When camps are at rest with no livestock on them, it increases the livestock density (i.e. the number of Large Stock Unit) on the camp that is currently grazed; in comparison to an open grazing system where the livestock distributes over the whole farm. To calculate the actual herd size (*actual_herd_size*) for each camp during the initialization, the number of LSU is multiplied with the ratio of total months of a year to grazing months on the camps (Eq. 16):

$$actual\_herd\_size = \#\ of\ LSU\ \times \frac{months_{total}}{months_{grazing}} \tag{16}$$

4.8.12 Livestock trampling

The trampling of livestock can lead to a complete destruction of vegetation (except for mature woody vegetation). It usually occurs around livestock attraction points like watering points and decreases with distance from these points (Jeltsch et al. 1997b). With a certain probability, calculated for each cell with Eq. 17 (with factor c_n = -0.3 [m^{-1}] and *distanceToNearestWateringPoint* [cells]), the cells on which the livestock walks e.g. to graze are turned from their current vegetation type to bare soil and all seedlings are killed. Thus trampling also prevents the establishment of new vegetation for that month.

$$probablity\_of\_trampling = e^{c_n \times distanceToNearestWateringPoint} \quad (17)$$

4.8.13 Arboricide application

The application of arboricide is common practice to control bush encroachment and keep the amount of woody vegetation at levels that will allow a lot of grass fodder for the livestock. Arboricide is either applied manually on the ground in forms of e.g. little pellets that are put at the stem of a tree, or if bush encroachment levels are higher, it is applied via aeroplane. In reality, the application of arboricide should be repeated after several years to make sure any surviving and regrowing trees will be killed.

In the model, we used a simplified approach by using a user-defined threshold of the relative amount of woody vegetation cells per camp at which the arboricide will be applied. The conditions are checked every month and as soon as any camp reaches a higher relative number of cells with woody vegetation than the threshold, the arboricide will be applied. The application of arboricide in the model will instantly and randomly convert 90 % of the cells with woody vegetation will to bare ground. Also the green and dead biomass is set to zero. A second treatment will not be done explicitly. The application of arboricides can be turned on and off via the parameter file.

4.9 Results and discussion

The default test scenario uses a landscape created with the PioLaG Piosphere Landscape Generator (Hess et al. 2020). It has a spatial extent of 400 x 400 cells i.e. 12 x 12 km (14.400 ha) with a spatial resolution of 30 x 30 meters. This section of a landscape covers the area that is influenced by one watering point, which is, in this case, located in the centre of the map. On a real farm, there are several watering points distributed over the farm. Ideally, the watering points are distributed quite homogenously on the farm and camps so that the livestock can alternate between the watering points and the fodder, i.e. grass biomass, and reach all areas of the farm. Usually, only as few watering points as necessary will be installed on a farm to save costs. Importing the farm- and vegetation data from PioLaG works smoothly and with the correctly formatted parameter file (for an example see Tab C. 1 in the appendix) and a designated output folder, the model can easily be started. The model was implemented in such a way that explanatory error messages will show up if data is missing or something is wrong. All simulations were run for at least 60 years (720 months).

4.9.1 Model run with default parametrization and with different scenarios

I ran simulations with the default parametrization (see Tab C. 1 in the appendix) to check the general model performance and the resulting vegetation patterns. To be able to see the development of the dominant vegetation types on the simulated farm over time, I plotted the relative number of cells for the different vegetation types (Fig. 29). The simulations started with a low amount of bare soil (1 %), annual grasses (4 %), young (2 %) and mature (3 %) woody vegetation, while the unpalatable (52 %) and palatable (39 %) perennial grasses dominated the farm. The relative number of both perennial grasses started to decrease directly (with slight fluctuations); they gradually decreased until month 700 where they reached less than 5 %. The woody vegetation, however, showed a gradual increase throughout the simulation period. First, the number of cells dominated by young woody vegetation started to rise from less than 5 % up to about 32 % in month 100 while the mature woody vegetation was at 3 %. The young woody vegetation reached then the biomass threshold so that its relative amount decreased and the relative amount of mature woody vegetation increased. From here on, the young woody vegetation continuously decreased while the mature woody vegetation increased to 97 % in month 1200. The cells with bare soil and annual grasses showed a similar pattern all through the simulations. In the process, the annual grasses were always just behind the values of relative bare soil abundance. Shortly after the beginning of the simulation in month 3, they reached a maximum of 21 %. After this initial peak, they only occasionally showed higher values up to 10 % and from month 300 onward only up to a maximum of 3 %.

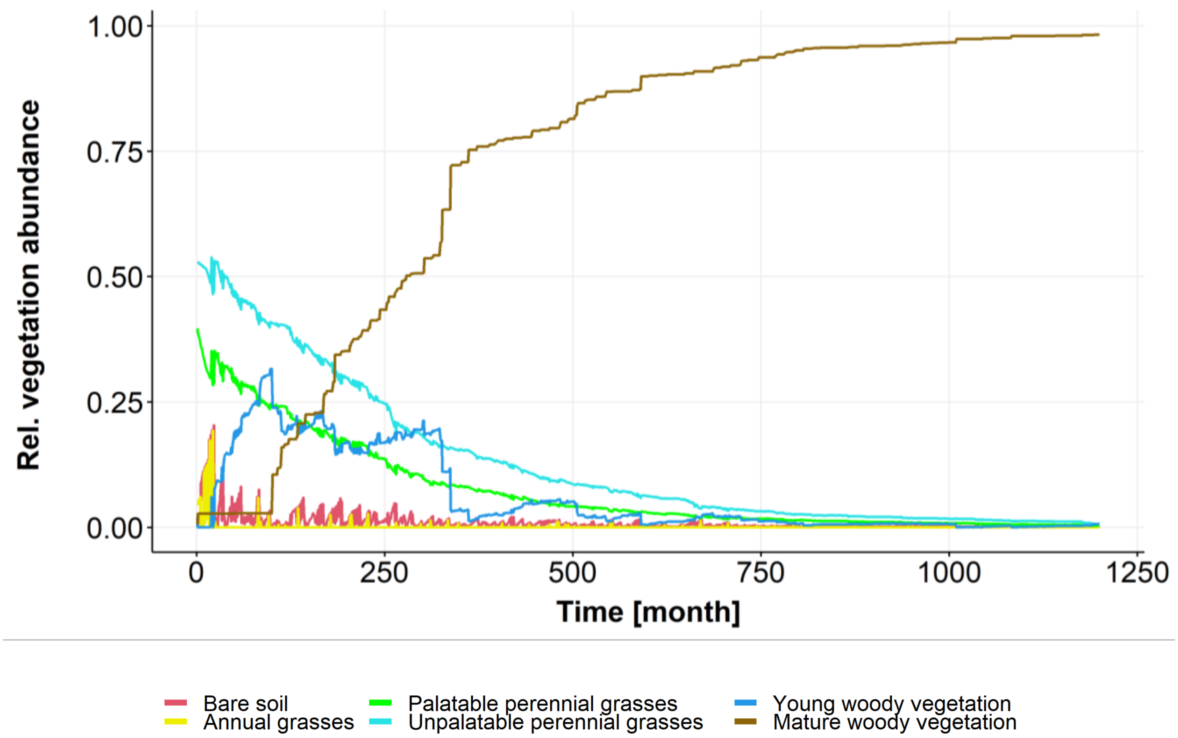


Fig. 29: Relative abundance of dominant vegetation types over the course of the simulation period (1200 months i.e. 100 years).

These vegetation patterns were the result of a simulation without any measures against bush encroachment and no implementation of a strict limiting lifespan of trees and shrubs. The general development represents, in an exaggerated way, the increasing trend of bush encroachment in southern African savannas. The very high relative abundance of mature woody vegetation towards the end of the simulations might theoretically occur in reality, but is rather unlikely as the veld will not sustain many animals anymore so the grazing pressure would be reduced. This is not the case in the model, the stocking density remains the same over the complete simulation period. Also, self-regulating mechanisms such as self-thinning due to intra-specific competition, natural mortality by reaching the lifespan without any new recruitment, and density-related diseases and calamities would also likely prevent such an extreme bush encroachment but rather lead to a natural patch-dynamic system where different patches are temporarily dominated by different vegetation types. This succesional alternation of patches between (1) an open savanna dominated by grasses, (2) a bush-encroached savanna dominated by shrubs and bushes, and (3) a mature *Acacia* savanna dominated by single standing trees will lead to an equilibrium of vegetation types at larger spatial scale (Wiegand et al. 2005).

Results: input file camps and watering points --- The farm was divided into four equally sized camps which were separated by fences so that the livestock could only move within one camp at a time (Fig. 30, left). After a certain time, when the farmer decided that the grazing time ends (Parameter *management.grazing_time*), the livestock was directly moved to the next camp. The previously grazed camp could then rest and the vegetation could regrow. In the centre of the camps, there was a watering point that supplied the livestock on all four camps with drinking water. Livestock needs to drink regularly; therefore, the animal movements and the associated trampling around the watering point were very high. The trampling decreased with distance to the watering point (Fig. 30, right).

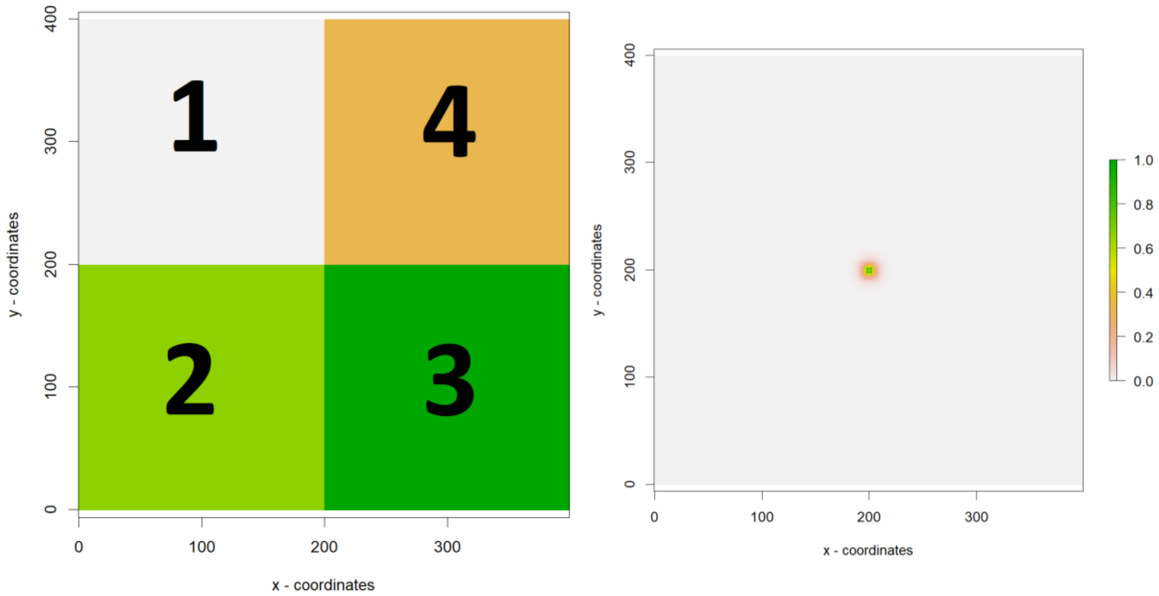


Fig. 30: Left: Division of the farm in four equal sized camps. The number of camps as well as their position and the camp id are defined in the input file. Right: Trampling intensity: A central watering point supplies all surrounding camps with water. Trampling by livestock is intense at the center and decreases with distance to the watering point. The unit of the coordinates of x- and y-axis are 30 m cells.

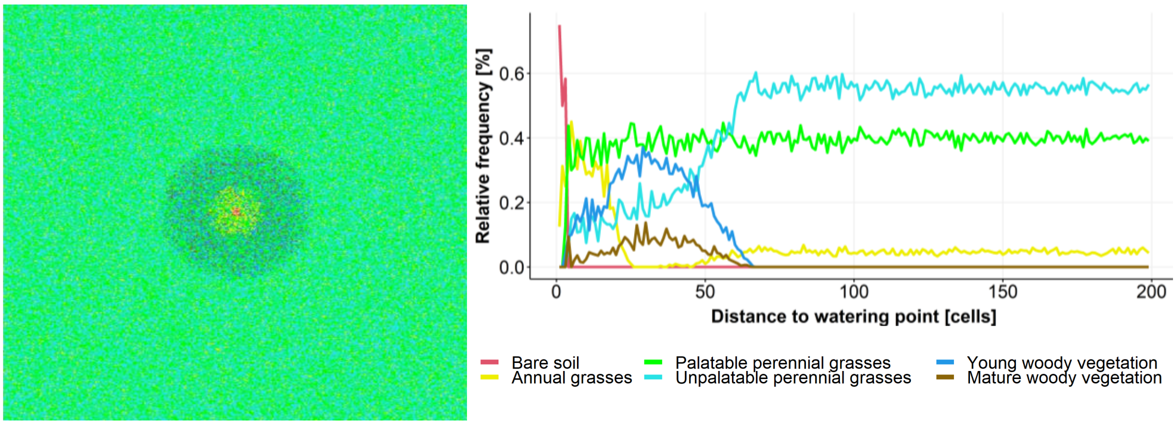


Fig. 31: Left: Landscape map with the dominant vegetation type at the beginning of the simulations. Right: Piosphere graph of the relative abundance of the different vegetation types in the radii with increasing distance from the watering point. The distance unit is cells (one cell = 30 m side length).

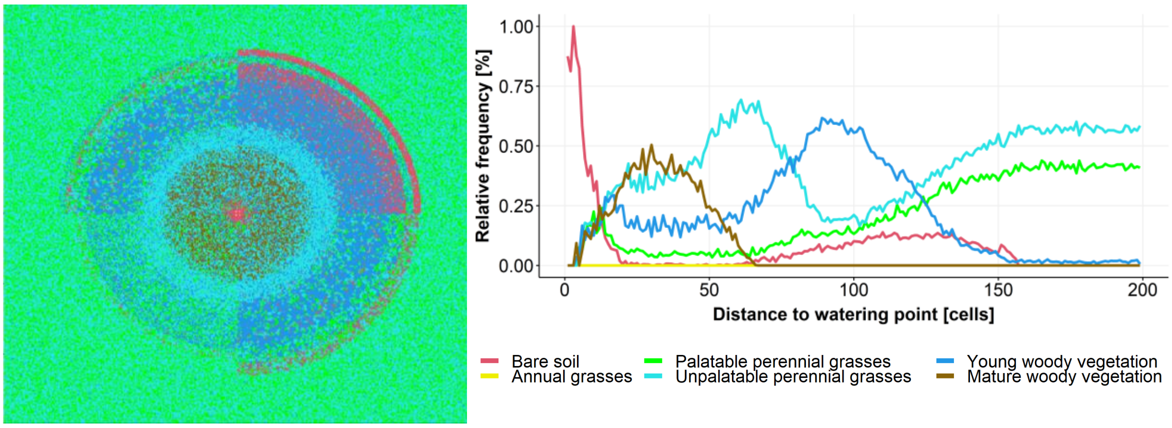


Fig. 32: Left: Landscape map with the dominant vegetation type in January of year 5. Right: Piosphere graph of the relative abundance of the different vegetation types in the radii with increasing distance from the watering point. The distance unit is cells (one cell = 30 m side length).

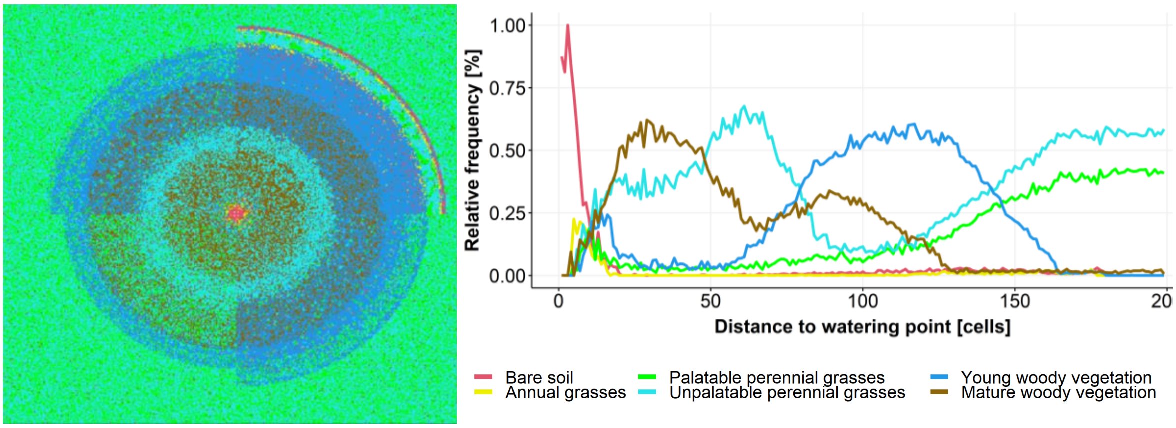


Fig. 33: Left: Landscape map with the dominant vegetation type in January of year 10. Coordinates x and y in meters. Right: Piosphere graph of the relative abundance of the different vegetation types in the radii with increasing distance from the watering point. The distance unit is cells (one cell = 30 m side length).

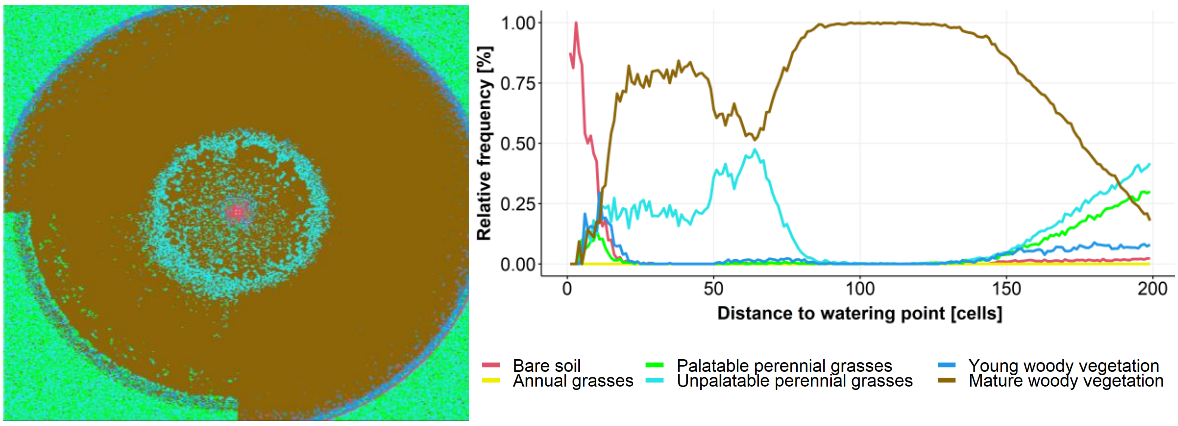


Fig. 34: Left: Landscape map with the dominant vegetation type in January of year 30. Right: Piosphere graph of the relative abundance of the different vegetation types in the radii with increasing distance from the watering point. The distance unit is cells (one cell = 30 m side length).

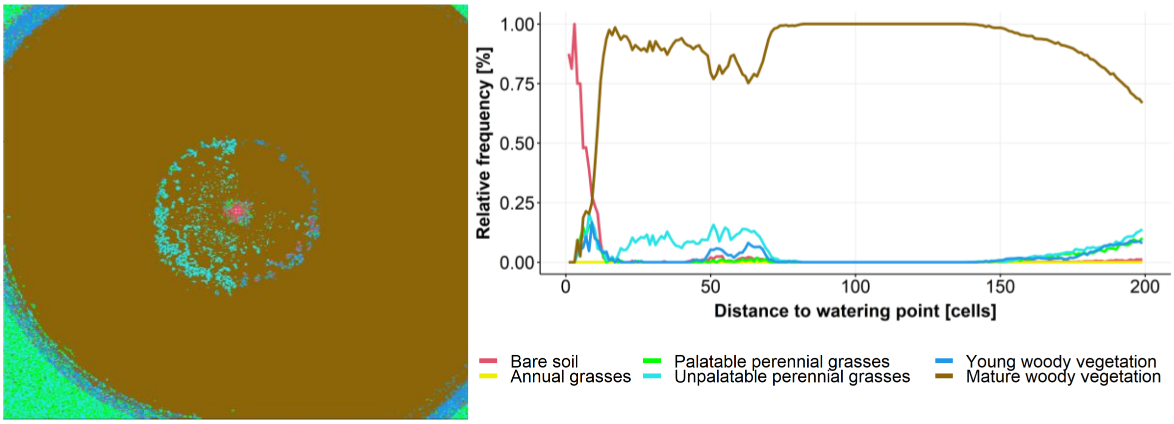


Fig. 35: Left: Landscape map with the dominant vegetation type in January of year 60. Right: Piosphere graph of the relative abundance of the different vegetation types in the radii with increasing distance from the watering point. The distance unit is cells (one cell = 30 m side length).

Results: piosphere --- In the following, I present and discuss the development of the spatial distribution of vegetation types across the landscape over the course of the simulation, specifically with regard to piosphere patterns. A piosphere is a spatially concentrated form of land degradation caused by ecological impacts such as trampling or defecation around watering points or other points of attraction. The relative vegetation type abundance in dependence of the distance to the watering point can be an indicator for land degradation. The distinct radial patterns around the watering points can be distinguished as (a) sacrifice zone, (b) grass dominated high disturbance zone, (c) intermediate disturbance bush-encroachment zone, and (d) the low disturbance grazing reserve. The sacrifice zone right around the watering point is largely vegetation free with only few annuals and severely degraded often beyond the point of reversibility. The high disturbance zone is dominated by annual and unpalatable perennial grasses while the bush-encroachment zone is dominated mainly by young and mature woody vegetation with reduced grass cover. The low disturbance grazing reserve usually shows the highest occurrences of perennial palatable forage grasses and a typical vegetation composition and structure (Tolsma et al. 1987; Jeltsch et al. 1997b; James et al. 1999; Thrash and Derry 1999; Teka et al. 2018).

The **initial landscape** (Fig. 31) showed a very short disturbance piosphere pattern of only up to 5 cells (150 meters) with a high relative abundance of bares soil (75 %) and annual grasses (peak at 43 %). This zone was followed by a disturbance zone with a dominating abundance of palatable perennial grasses (ca. 38 %), and unpalatable grasses (10 % to 40 %) and with a peak of young (38 %) and mature (8 %) woody vegetation at a distance of 30 cells from the central watering point. Subsequently, this started a constant zone with slight fluctuations in the unpalatable perennial grasses (around 55 %), palatable perennial grasses (40 %), and annual grasses (4 %). Already after **five years**, an expansion of the disturbance zone was visible in the piosphere graph (Fig. 32). The sacrifice zone had extended outward to a width of about 13 cells. The annual grasses reached a peak of 100 % relative abundance at a distance of three cells to the centre. The palatable perennial grasses had a small peak (24 %) at a distance of 12 cells, and then their relative abundance dropped to 6 % and then, slowly increased again after a distance of ca. 70 cells (2100 m). At a distance of 155 cells, the palatable perennial grasses reached again a value of around 40 % rel. abundance as in the initial landscape. The unpalatable perennial grasses showed a peak of 70 % at a distance of 60 cells then dropped to start rising again from a distance of 100 cells to the initial 55 %. The young woody vegetation that was on the initial landscape had grown in biomass and turned into mature woody vegetation. This created a peak (50 %) of mature woody vegetation in distances of 30 cells away from the watering point. The young woody vegetation increased in total and had a peak (62 %) at a distance of 99 cells after which it decreased continuously to 2 % rel. abundance at 154 cells distance for the rest of the simulation. In the landscape map with the dominant vegetation types, the camp arrangement became visible (Fig. 32) because the four camps were grazed alternately leading to different vegetation patterns. The top right camp showed an outer ring of bare soil at a distance of about 350 cells (10.5 km) caused by livestock that was currently grazing in that zone. The different piosphere zones became noticeable; there was a centre of bare soil, a zone with mature woody vegetation followed by unpalatable perennial grasses, which was then followed by a wider bush encroached zone and palatable perennial grasses on the outer areas. After **ten years**, the trend of the spreading of the piosphere zones continued (Fig. 33). Especially the mature woody vegetation increased the width of main occurrence in total from four cells to 300 cells with two peaks at 29 cells (62 %) and 89 cells (34 %). The young woody vegetation dropped in abundance at distances between 18 and 64 cells (ca. 4 %), but increased at greater distances creating a wide plateau of high relative abundance (ca. 56 %) between a distance of 95 and 130 cells. The palatable and unpalatable perennial grasses decreased by a few percent overall and reached their peak only at a greater distance of 40 % at 65 cells and 58 % at 65 cells, respectively. The zone of bare dominance remained roughly unchanged in the close range to the watering point while there are some smaller, up to 3 %, fluctuations in relative abundance between distances of 100 and 180 m. The annual grasses showed a little hump with a maximum of 22 % rel. abundance between a distance of 3 and 17 cells. In addition, in the landscape map, the outward spread of the radial vegetation pattern became visible. Especially the belt of mature woody vegetation with a distance between 70 and 120 cells stands out (Fig. 33). After **thirty years,** the piosphere graph looked very different (Fig. 34). At almost all distances, the most abundant vegetation types were bare soil (0 to 11 cells distance) and mature woody vegetation (11 to 188 cells distance). Between 5 and 83 cells of distance from the centre, also the unpalatable perennial grasses occurred regularly with up to 48 % rel. abundance at a distance of 64 cells. The outer 12-cell distance was dominated by unpalatable perennial grasses. In this outer area, from a distance of 140 cells to the edge of the farm at 200 cells, the palatable and unpalatable perennial grasses showed an increase (up to 30 % and 40 % respectively). In addition, on the landscape map, this strong drift into bush encroachment was visible as most of the map was now brown, i.e. mature woody vegetation. This bush encroachment had spread so far that it reached the centre parts of the horizontal and vertical borders of the landscape. In the lower left camp, the bush encroachment had not yet advanced as far as in the other three camps. There was still the central patch of bare soil as in the years before and around it, with some distance, a circle of unpalatable perennial grasses. In addition, the corners of the landscape were still mainly palatable and unpalatable perennial grasses (Fig. 34). After **60 years**, the landscape was highly bush encroached (Fig. 35). Bare soil still had a 100 % peak at the watering point location. The distance 5 to 16 cells was covered by a mix of bare soil, palatable and unpalatable perennial vegetation as well as young and mature woody vegetation. The woody vegetation then dominated the remaining space in the landscape at distance 88 to 143 even with 100 % abundance. There was an increase of palatable and unpalatable perennial grasses as well as young woody vegetation towards the edges of the landscape, starting at a distance of about 55 cells. The landscape map at year 60 is almost completely dominated by mature woody vegetation (Fig. 35). Only the central sacrifice zone is mainly bare soil with some palatable and unpalatable grasses. A disturbance ring up to a distance of 76 cells also contained few unpalatable perennial grasses as well as young woody vegetation and bare soil. In the corners of the landscape, there was still some of the original vegetation structure composed of palatable and unpalatable perennial grasses as well as some (now mature) woody vegetation.

Discussion: piosphere --- The model simulations showed a realistic behaviour and created realistic vegetation distribution patterns also around the watering points. The piosphere pattern, i.e. the typical radial grazing pattern around watering points caused by the attraction of the livestock and their trampling and grazing patterns, is clearly visible and develops towards a bush encroached camp over the simulation period. Up to 13 cells around the watering points are characterized by the sacrifice zone, which consists mainly of bare ground with few annual cells. It is caused by the trampling and faeces accumulation of livestock which are highest in direct vicinity to the highly frequented watering point and decreases with distance (Lange 1969; Andrew 1988). The next zone surrounding the watering point after the sacrifice zone is the unpalatable grass dominated zone followed by the woody dominated (bush encroached) zone. The inner Piosphere zones, formed by the interaction with livestock, constantly increase in size over time, and are only limited by the boundaries of the camp. Thus, the forage biomass represented by vegetation types, increases with distance to the watering point. The difference between forage biomass close to and far away from the watering point becomes bigger over time. At the edges of the camp, we see the outer zone, which is mostly undisturbed grazing reserve. If the camp was bigger or if the stocking rate was significantly less, this zone would be bigger. Also, due to the circular browsing approach (see 4.8.10 Livestock grazing and browsing), the edges of the camp are mostly untouched, which would probably not occur under real life conditions. Here, the grazing function could be improved to a more randomized grazing pattern to also consider the very corners of the camp for grazing as well.

Results: precipitation --- The **mean annual precipitation** in the default scenario was 282mm with an annual minimum of 99 mm, a maximum of 632 mm, and a SD of 88 mm. The mean monthly precipitation was 28 mm with 378 months without any rainfall (minimum), a monthly maximum of 128 mm, and an SD of 21 mm.

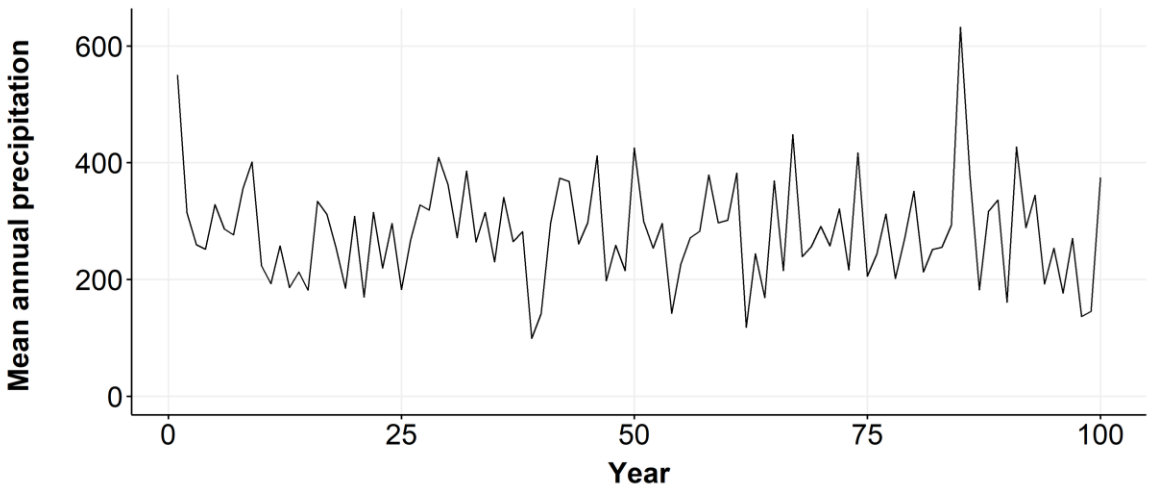


Fig. 36: Mean annual precipitation [mm/year] over the course of the simulation extent (100 years).

Discussion: precipitation --- The zucchini rainfall algorithm worked well and as expected (Zucchini and Nenadić 2006). The algorithm produced a reasonable, temporally heterogeneous rainfall pattern that also contained some extreme wet and dry years (Fig. 36). Also, the intra-annual precipitation was modelled heterogeneously on a daily scale in the model which, in combination with the also considered simplified soil texture, is together with the MAP, an important factor for the vegetation dynamics in water-limited savannas (Tietjen 2015). The 16 parameter necessary to use the zucchini algorithm could theoretically be adapted for climate change or the algorithm itself could be adapted and extended for different climate change scenarios. In the default scenario, the homogeneous rainfall was used. This was done because a heterogeneous rainfall (which is described in 4.9.4 Homogeneous vs heterogeneous rainfall) results in a very complex and highly random (cloud positions are assigned randomly) vegetation pattern that makes it difficult to see the effects of other drivers of vegetation dynamics. In real life usage of the model, the heterogeneous rainfall should thus be turned on (parameter *heterogeneousRain*) to get the most realistic results. For analysing single factors and processes though, it can be helpful to stick to a classic, simplified, homogeneous precipitation pattern.

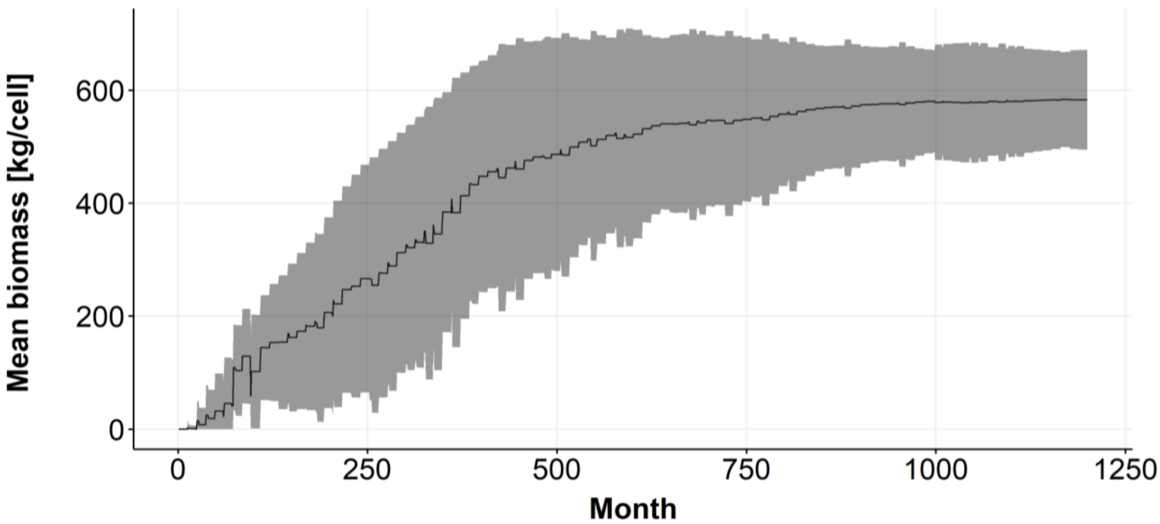


Fig. 37: Mean monthly dead biomass available on the cells in the lanscape. Grey envelope indicates standard deviation.

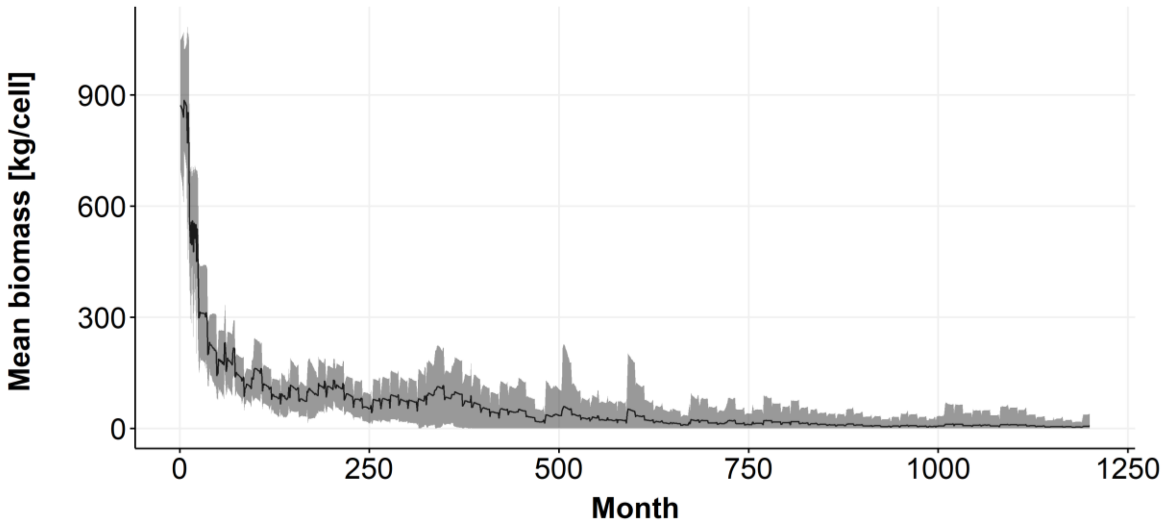


Fig. 38: Mean monthly green biomass available on the cells in the landscape. Grey envelope indicates standard deviation.

Results: dead and alive biomass --- The green, i.e. alive, biomass started at an average value of circa 870 kg per cell and quickly dropped within 80 months down to an average level of 140 kg per cell. The alive biomass then decreased (with few short incremental peaks) further over the course of the simulation time until it reached less than 10 kg per cell at the end of the simulated period. The dead biomass, however, started at a value of almost 0 kg per cell. The dead biomass then increased almost linearly for 400 years to an average weight of 460 kg per cell. The incremental rate then declined leading to a landscape average of 580 kg per cell at the end of the simulation period.

Discussion: dead and alive biomass --- The alive biomass, which was the fodder for grazing livestock, decreased very quickly, likely as an effect of intense grazing as well as competition with woody vegetation for environmental resources (soil moisture). This was problematic for the livestock, as they need about 300 kg of fodder per month to stay in optimal condition (Parameter *animal.fodder_per_lsu*). The dead biomass on the other hand, which consists of dead grass biomass but also of non-growing parts of the woody vegetation, (stems) was at an advantage and increased. While the palatable dead grass biomass could be eaten by livestock, the dead woody biomass could not be eaten and thus accumulated over time, only limited by the carrying capacity on the cell as well as natural decomposition.

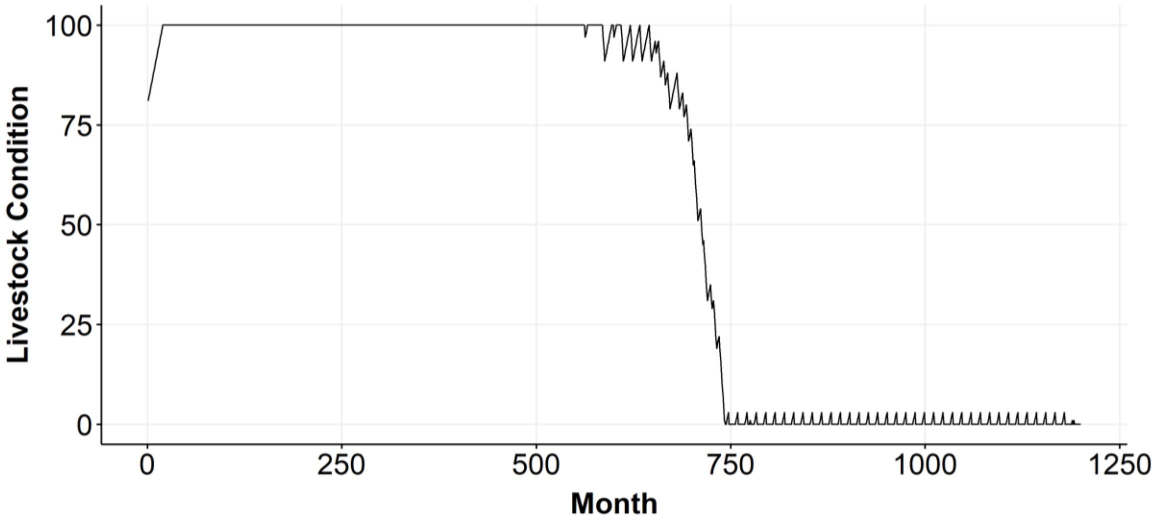


Fig. 39: Development of the livestock condition over the course of the simulation period for the default scenario.

Results: livestock condition --- The initial **livestock condition** started at the default value of 80 and moved within 3 months to the maximum value of 100 (Fig. 39). The livestock condition could be maintained at this level until the first drops occured in month 560. After an 8-months phase of small ups and downs, the livestock condition dropped rapidly to zero within one year. From then on, in month 740, it did not recover. There were only periodic and very small rises (3 units) in the livestock condition, but these were very short-lasting and went directly back to zero. These low level fluctuations were then recurring until the end of the runtime after 100 years.

Discussion: livestock condition --- In the first 46 years of the simulation, there was sufficient fodder to keep the livestock satiated and thus, at optimal **livestock condition**. Therafter however, the farming system broke down, due to the fixed stocking rate and thus constant grazing pressure in combination with the decreasing amount of cells dominated by palatable grassed. It is interesting to see this tipping point where the veld could not sustain the livestock anymore due to too little grazing ressources because of bush encroachment (cf. Fig. 29). The decrease of livestock condition to zero, which can be equated with (near) death, will usually not happen in reality as the farmer will (a) adapt the stocking density by e.g. selling livestock, (b) supply additional fodder to the animals, or (c) allow livestock to graze on backup camps that were specifically reserved for droughts. The effects of feeding on livestock condition are just rough estimates as the concrete vegetation species composition and the particular nutritious value are not modelled explicitly. The livestock condition is, however, an important indicator because the stocking rate is in the current model version constant throughout a simulation run. Thus, a decrease in the livestock condition can be a clear indicator for unsustainable farming and thus the need to adapt management accordingly to ensure survival and well-being of the livestock.

Discussion: default scenario --- Thanks to the realistic input maps from the piosphere landscape generator PioLaG, the model does not go through a long initial settling phase at the beginning of the simulations. Instead, the vegetation dynamics stabilized quickly and showed a rather smooth pattern from start to end. The spatial and temporal patterns and trends were in line with the results of other studies (Jeltsch et al. 1997b; Groeneveld 2003; Derry 2004; Teka et al. 2018). The results of the default parametrization seem plausible for a not sustainably managed farm that is experiencing strong bush encroachment over the long time period of 100 years. Because the rangeland model is centred on bush encroachment and the possible ways to influence and stop this degradation trend to allow for sustainable farming, it is beneficial that bush encroachment is present in the default scenario so that different theories and scenarios can be tested.

4.9.2 Mean annual precipitation

The amount of precipitation is one of the most influential variables for the dynamics of savannas and an important driver of tree:grass ratio (Barnes 2001; Joubert et al. 2013). To see the effect of the mean annual precipitation in the model, I simulated scenarios with 204 mm, 400 mm and 635 mm mean annual precipitation that were distributed either spatially homogeneous or spatially heterogeneous over the landscape, while all other parameters were kept unchanged. The temporal distribution was in both cases heterogeneous (see also 4.8.1 Precipitation).

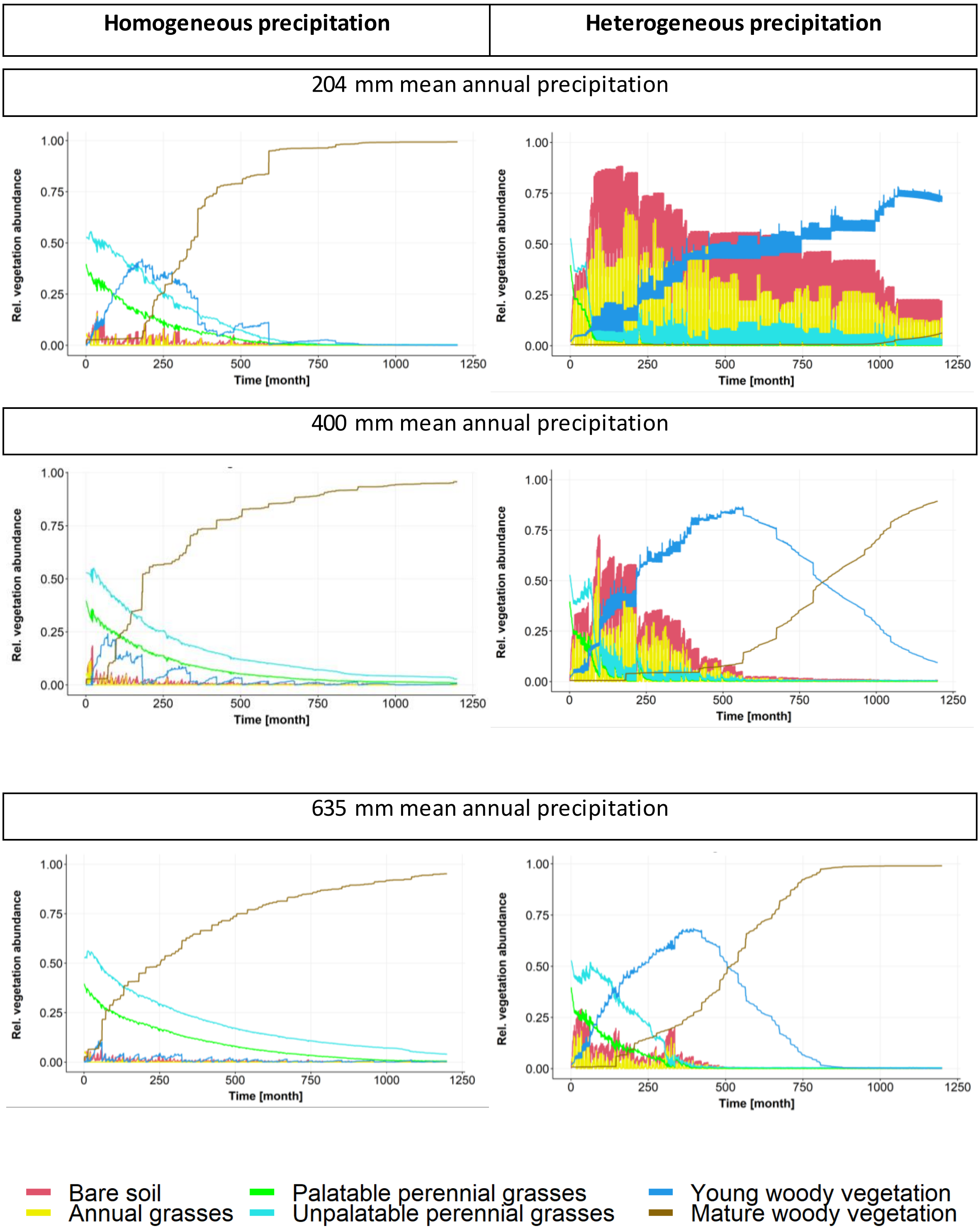


Fig. 40: Development of relative vegetation abundance over the course of the simulation time (100 years).

In the scenario with a **homogeneous rainfall of 204 mm**, the palatable and unpalatable perennials dropped rather quickly within 50 years from 40 % and 53 % relative abundance to less than two percent respectively. The woody vegetation, however, showed a strong increase. First, the young woody vegetation increased from less than two percent to 42 % in month 180. At this time, the biomass threshold for the conversion to mature woody vegetation was reached. Thus, the young woody vegetation started to decrease while the mature woody vegetation increased. In month 180, the mature woody vegetation raised from a plateau at 3 % to 84 % relative abundance in month 590. In month 59, a large portion of young woody turned mature so that this vegetation type experienced an increase of relative abundance up to 94 %. It then slowly increased for the rest of the simulation period until an end value of 99 %. The bare soil and annual grasses only had small fluctuating peaks with maximum values of 17 % and 16 % respectively. The amplitude of the fluctuations decreased and after month 750, both vegetation types made up less than 1 percent each.

In the scenario with a **homogeneous rainfall of 400 mm**, the pattern was quite similar to the 204 mm scenario with the difference, that the disturbance pattern of the different dominances of the vegetation types was reduced in time. The relative abundance of the palatable and unpalatable perennials dropped a bit slower within 100 years from 39 % and 52 % relative abundance to less than four percent respectively. The woody vegetation showed again a strong increase. First, the young woody vegetation increased from less than two percent to 24 % in month 70. At this time, the biomass threshold for the conversion to mature woody vegetation was reached. Thus, the young woody vegetation started to decrease (with slight increases every ca. 7 months) while the mature woody vegetation increased. In month 70, the mature woody vegetation raised from a plateau at 3 % relative abundance following a logistic curve to 95 % in month 1200. The bare soil and annual grasses only had small fluctuating peaks with maximum values of 18 % and 11 % respectively. The amplitude of the fluctuations decreased and after month 580, both vegetation types made up less than 1 percent each.

In the scenario with a **homogeneous rainfall of 635 mm**, the pattern was almost the same as in the 400 mm scenario. The relative abundance of the palatable and unpalatable perennials dropped within 100 years from 39 % and 51 % relative abundance to less than one and four percent respectively. The woody vegetation showed again a strong increase. First, the young woody vegetation increased from less than two percent to 10 % in month 50. Already in the second month of the simulations, the biomass threshold for the conversion to mature woody vegetation was reached. Thus, the young woody vegetation started to decrease quite early and only showed very small and decreasing peaks of less than 5 percent for the rest of the runtime, while the abundance of the mature woody vegetation increased. The bare soil and annual grasses only had very small fluctuating peaks with maximum values of 10 % and 4 % respectively. The amplitude of the fluctuations decreased and after month 300, both vegetation types made up less than 1 percent each.

In the scenario with a **heterogeneous rainfall of 204 mm**, very strong fluctuations with a great amplitude dominated the vegetation pattern. The palatable and unpalatable perennials dropped very quickly within 7 years from 40 % and 52 % relative abundance to four and eight percent respectively. From this point on, both perennial grasses fluctuated strongly until the end of the simulation with maximum rel. abundance values of 22 % and 21 % respectively. The young woody vegetation, however, showed a strong, gradual increase over almost the whole simulation period up to 78 % in month 1060. At this point, first cells reached the biomass threshold to turn into mature woody cells. Thus, the young woody vegetation slowly started to drop from month 1060 onward and the mature woody vegetation started to rise slowly from its value of less than two percent up to 6 % at the end of the simulation period. Strongest fluctuations occurred in the abundance of bare soil and annual grasses. Almost all lines in the graph occurred because of having dropped from a high relative abundance to zero. Highest values of bare soil abundance were between month 80 and 220 with up to 89 %. Thereafter, the relative abundance of bare soil gradually decreased until a value of 22 % at the end of the simulation period. Annual grasses showed a very similar pattern but with a smaller magnitude. Maximum values of 68 % relative abundance for annual grasses were reached in month 180 and gradually decreased thereafter to 13 % at the end of the simulation period.

In the scenario with a **heterogeneous rainfall of 400 mm**, the strong fluctuations were already a lot less dominant compared to the heterogeneous rainfall scenario with 204 mm. The palatable perennial grasses dropped from 40 % relative abundance gradually to 3 % in month 100; then increased again to 14 % relative abundance and gradually dropped again to less than 1 %. These fluctuations repeated slowly until, in month 570, the relative abundance reached less than two percent and stayed this low for the rest of the simulation period. The unpalatable perennial grasses first started to decrease from 52 % to 39 % within the first two months, but then showed a gradual increase up to 52 % just to drop again in month 7 to 4 %. From there on, the pattern was similar to that of the palatable perennial grasses. The young woody vegetation showed again a strong, gradual increase which peaked in month 565 with a relative abundance of 86 %. From this point on, the relative abundance of the young woody vegetation decreases almost linearly to a value of 9 % at the end of the simulation period. The mature woody vegetation started to increase in month 180 from one to four percent and the relative abundance then increased at continuously decreasing intervals until it reached a value of 90 % at the end of the simulation period. Strongest fluctuations still occurred in the abundance of bare soil and annual grasses. This pattern was caused by rapid switches between high relative abundance values of up to 72 % (month 90) to lower values between 27 % and 1 % in 1-3 months. The trend of both bare soil and annual grasses was decreasing after month 215 and both vegetation types reached values below two percent in month 675.

The overall pattern of the **heterogeneous rainfall scenario with 635 mm** mean annual precipitation showed a state between the pattern of the heterogeneous rainfall scenario with 400mm MAP and the pattern of the homogeneous rainfall scenario with 204 mm MAP. The overall time that young woody vegetation was the most dominant further decreased to the advantage of the mature woody vegetation. Young woody vegetation increased almost linearly with small fluctuations up to 68 %

rel. abundance in month 390 after which it decreased again almost linearly with even smaller fluctuations. The mature woody vegetation started a logistic increase of relative abundance from less than 2 % in month 150 to 97 % in month 820 and increased from there up to 99 % until the end of the simulation time. The unpalatable perennial grasses first started to decrease slightly from 52 % to 42 % within the first three months, but then showed a short increase up to 52 % in month six and then dropped almost linearly to less than 2 % relative abundance in month 385. The palatable grasses, however, decreased with little fluctuations from 39 % to less than 2 % in month 370. Bare soil and annual grasses still showed a lot of fluctuations, but with an overall smaller magnitude compared to the other scenarios with heterogeneous precipitation. In addition, their abundance pattern was very similar again with annual grasses having in general only two-thirds the abundance of bare soil. Bare soil showed a decrease from 20 % to less than two percent in month 490 with three increase peaks occurring at month 30 (29 %), 140 (20 %), and 330 (20 %).

Discussion --- The increase of MAP resulted in a visible alteration of relative vegetation distribution. In addition, whether the precipitation was distributed homogeneously or heterogeneously over the landscape made a big difference in the relative vegetation pattern. In both types of scenarios, a higher mean annual precipitation led to an increase of mature woody vegetation in a shorter time period. It appears that the temporal course of the pattern of relative vegetation abundance was compressed with increasing precipitation. However, the difference between the 400 mm and 635 mm MAP scenarios with homogeneous rainfall were not very big in terms of abundance of the mature woody vegetation. All scenarios except 204 mm with heterogeneous rainfall reached a very high (>90 %) woody vegetation abundance at the end of the simulation period. The 204 mm with heterogeneous rainfall scenario had a relative abundance of 72 % for the young woody vegetation and 6 % for the mature woody vegetation after 100 years of simulation. However, it can be expected, that the pattern would develop analogously to the other scenarios. According to Sankaran et al. (2005) and Scholes et al. (2002), woody vegetation should be largely absent below 100 mm MAP, and maximum potential tree cover then increases linearly up to about 80 % relative abundance at a MAP of ca 600 mm. A reason for the high woody vegetation abundances at the end of the Midessa simulations could be a too-efficient use of the available soil moisture for the woody vegetation. Another reason could be that because the soil type is modelled simplified in Midessa, some restrictions or promoting factors have not been correctly represented in the model, e.g. sandy soils have shown to support higher woody cover (Sankaran et al. 2005). Another reason is likely that the dead woody vegetation (e.g. tree stems) does only decay very slow or not at all per default in Midessa, and instead, it accumulates over time thus there is little chance for mature woody cells to turn into bare soil or grasses as it would be in reality due to small-scale events such as intra-specific competition and self-thinning (Wiegand et al. 2008). However, it may be due to scaling issues and due to the simplified vegetation type approach that these small-scale events do not become visible.

The decay of woody vegetation is in reality a very slow process that is often unnoticed but should be visible over longer time periods like the 100 years in the model. By altering the decay parameter of dead woody biomass *[veg.type].decay_dead_biomass],* a constant wood decay or self-thinning rate could be simulated. Ideally, this would not be a constant parameter, but dependent on the age, biomass or density of the woody vegetation on a cell and the climatic conditions. This should be adapted in future Midessa versions because in reality, woody vegetation will die at a sl ow rate influenced majorly by drought stress (Case et al. 2019). Another pattern that is particularly noticeable is the very strong fluctuations of bare soil and annual grasses, and to a lesser extent also of perennial grasses and young woody vegetation. These fluctuations only occur with heterogeneous precipitation and a decrease in amplitude and temporal duration with increasing precipitation amounts. In the 204 mm scenario, they are seen throughout the simulation period; in the 400 mm scenario, they occur until about the 500th month; and in the 635 mm sce nario, they are seen only in the first 300 months and with much lower amplitude and mainly in the bare ground and the annual grasses. This is likely due to not meeting establishment requirements (see also Fig. 26) that is, for example, because of drought stress the annual as well as perennial grasses and young woody vegetation cannot sustain on a cell which then changes to bare soil and thus leads to high fluctuations in relative abundance of the different vegetation types.

4.9.3 Stocking rate

The variation of the stocking rate [hectare per Large Stock Unit] can have a big impact on vegetation dynamic, as it is a major factor in reducing palatable annual and perennial biomass from the veld, creating an imbalance in the competitive strength between grasses versus woody vegetation. The stocking rate must be adapted based on precipitation, available biomass, grass species available, etc. and varies very much within southern Africa. Similarly, the grazing capacity is the number of hectares needed to sustain a large stock unit for several years without any degradation to the veld (Trollope et al. 1990). The actual stocking rate should be a bit below this value (pers.com. during farmer interviews). In South Africa, the long-term grazing capacity ranges between 120 ha/LSU in the very arid, harsh areas and 2 ha/LSU in the humid savannas with lots of biomass (Republic of South Africa 1993). For the scenarios, I used more extreme values to test model behaviour and see trends in the effect of stocking rate. The simulations were run for 100 years with 56, 222, 777, and 4440 cells/LSU which correspond to 5, 20, 70, and 400 ha/LSU respectively. Except for the stocking rate, the default parametrization was used with heterogeneous and homogeneous precipitation.

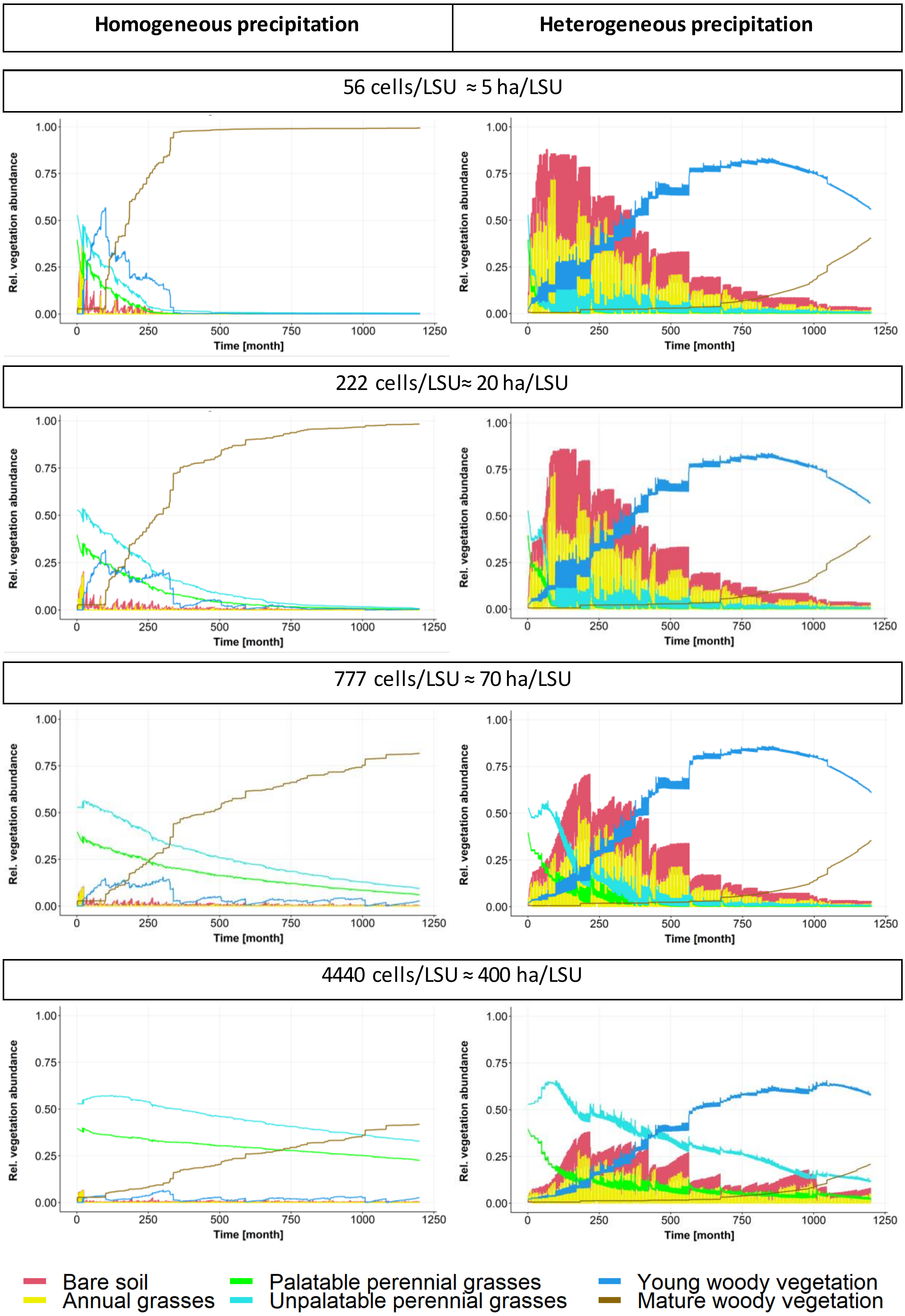


Fig. 41: Relative abundance of vegetation types over time for four different stocking densities. Different y-axis were chosen to see the details of the vegetation pattern development.

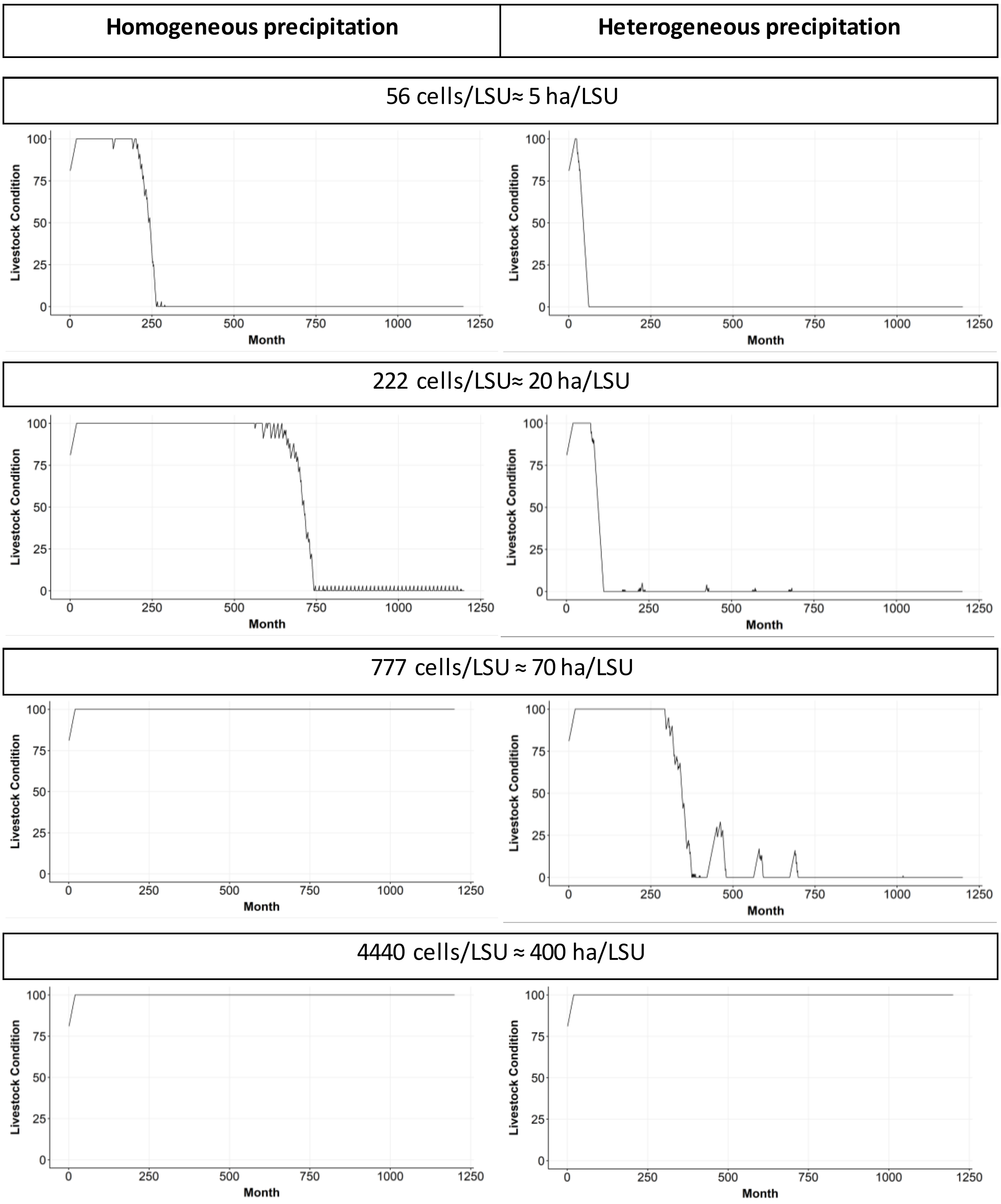


Fig. 42: Development of livestock condition over the course of the simulation period for different stocking densities [LSU/cell].

Results: relative abundance of vegetation --- On the succession graph that shows the development of the dominant vegetation types over the course of the simulation extent, we can see that with a decreasing stocking rate (more area per animal), the successional sequence of vegetation types was extended over a larger time. With only **5 ha per large stock unit (LSU) or 56 cells/LSU and homogeneous precipitation**, the entire landscape was already from month 140 mostly and from month 340 almost exclusively dominated by mature woody vegetation. Young woody vegetation had a peak at 56 % in month 100 and then dropped gradually to less than one percent in month 335. Palatable and unpalatable perennial grasses decreased from 39 % and 52 % to below two percent in month 260 and 450 respectively. Bare soil and annuals showed a similar pattern but the annual grasses did not show quite a high amplitude; reaching maximums of 38 % and 37 % respectively and decreased to values below two percent in month 300. With a stocking rate of **20 ha/LSU under homogeneous precipitation**, the total dominance of mature woody vegetation happened later. The mature woody vegetation was mostly dominant at month 145 with 33 % relative abundance and increased from thereon up to 99 % in month 1200. Young woody vegetation had a peak of 32 % in month 100 and then dropped gradually to less than one pe rcent in month 720. Palatable and unpalatable perennial grasses decreased from 39 % and 52 % to below two percent in months 735 and 870 respectively. Bare soil and annuals showed again a similar pattern but to a lesser extent than in the 5 ha/LSU scenario. They reached a maximum of 20 % relative abundance in month 20 and decreased with many small fluctuations to values below two percent in month 320. In the scenario with **70 ha/LSU and a spatially homogeneous precipitation** pattern, the mature woody vegetation increased gradually to 82 % at the end of the simulation time. The abundance of the young woody vegetation can be separated into two zones. First, it increased linearly to a maximum of 14 % and then fluctuated around 12 % until month 340, where it dropped to an average of 2 % rel. abundance until the end of the simulation. The unpalatable perennial grasses first increased in month 20 up to 56 % relative abundance. Then, the palatable and unpalatable perennial grass decreased smoothly over the course of the simulation period from 56 % and 39 % to 9 % and 6 % respectively. In the scenario with **400 ha/LSU and homogeneous precipitation**, the mature woody vegetation increased almost linearly up to 42 at the end of the simulation extent. The young woody vegetation did not exceed values of 6 % relative abundance and often showed fluctuations to zero. The palatable and unpalatable perennial grass decreased slightly over the course of the simulation period from 53 % and 39 % to 33 % and 22 % respectively. The unpalatable perennial grasses also showed an increase in the beginning starting at month 40 with a maximum relative abundance of 57 %. The bare soil and annual grasses were represented only to a very small extent throughout the simulation period. They showed a pe ak up to month 35 with a maximum of 6 % relative abundance after which both vegetation types stayed below 3 % with many small fluctuations to zero.

With spatially **heterogeneous precipitation** patterns, there was a high abundance of strongly fluctuating bare soil and annual grass cells. However, with a decreasing stocking rate (more hectares per LSU) the fluctuation became smaller. At a stocking rate of **5 ha/LSU** bare soil and annual grasses reached values of up to 87 % and 73 % relative abundance in the first 100 months. Palatable and unpalatable perennial grasses dropped within a few months to values of 8 % and 12 % respectively and stayed below 9 % and 20 % for the rest of the simulations. The abundance of young woody vegetation increases up to a maximum of 82 % in month 820 after which it declines to reach 55 % at the end of the simulation period. Mature woody vegetation stayed at low values (below 5 %) until month 675 where it suddenly started to increase up to 40 % at the end of the simulation time. The pattern of the scenario with a stocking rate of **20 ha/LSU and spatially heterogeneous precipitation** looks very similar to the before described scenario. Only the palatable and unpalatable perennial grasses showed a higher abundance in the first 85 months (values around 20 % and 40 % respectively). In the scenario with a stocking rate of **70 ha/LSU and heterogeneous precipitation** the bare soil and annual grass cells declined even more in abundance with peaks at 71 % and 54 % in month 210 and month 180 respectively. The palatable and especially the unpalatable grasses showed higher abundances than before. Palatable perennial grasses decreased only slow over 400 months to values below 4 %. The unpalatable perennial even showed a strong increase in the beginning up to 56 % in month 72 and then slowly declined to values less than 2 % in month 400 but showed still for 400 more months fluctuations of around 5 %. The abundance of woody vegetation cells was largely unchanged in comparison to the before mentioned scenarios with heterogeneous precipitation. In the very low stocked scenario with **400 ha/LSU and heterogeneous precipitation** the palatable and unpalatable perennial grasses showed a higher overall abundance. Palatable perennial grasses started with an abundance of 40 % and declined slowly, reaching 2 % at the end of the simulation period. In the month 100 to 1150, the palatable perennial grasses showed values around an average of 10 % relative abundance. The unpalatable perennial grasses showed an increase to a relative abundance of 65 % in month 100 from where it very slowly declined to 12 % at the end of the simulations. The abundance of bare soil and annual grass cells is overall smaller than in the other scenarios with heterogeneous precipitation. The bare soil reaches a maximum of only 38 % in month 220 followed by a steep drop to 7 %. From there on it recovers again to a maximum of 32 % followed again by a drop. This pattern repeats with decreasing amplitude until the end of the simulations. The annual grasses follow the pattern of bare soil again, at about 10 % lower abundance. The young woody vegetation still shows an increase but the maximum is reached later, around month 1400, and only up to a maximum value of 66 % relative abundance. The mature woody vegetation raises only very slowly during most of the simulation period. Only from month 680 onward, the mature woody vegetation reaches values above 3 % increasing up to 21 % at the end of the simulation period.

Results: livestock condition --- In all scenarios, the initial livestock condition started at a value of 80 and increased within 20 months to the maximum livestock condition of 100 (Fig. 42). Scenarios with a spatially homogeneous precipitation pattern had for every stocking rate a higher or equal (400 ha/LSU) average livestock condition in comparison with the spatially heterogeneous precipitation scenario. In the very high stocking scenarios with **5 ha/LSU under homogeneous precipitation,** the livestock condition started, in month 195, to drop gradually until it reached zero in month 280. Thereafter, it remained at the minimum value for the rest of the simulation period. With a stocking rate of **20 ha/LSU under homogeneous precipitation**, the livestock condition stayed at the maximum level for almost half of the simulation period. First drops occurred after month 560 and a drastic drop of the livestock condition value started in month 650 ending in month 745 at a value of zero. After this, the livestock condition fluctuated between three and zero for the rest of the simulation period. For both scenarios with a high stocking rate of **70 ha/LSU and 400 ha/LSU under homogeneous precipitation**, the livestock condition remained at the maximum value of 100 for the whole simulation extent. In the very high stocking scenarios with **5 ha/LSU under heterogeneous precipitation,** the livestock condition then dropped within 40 months to a value of zero and remained that low for the rest of the simulation period. With a stocking rate of **20 ha/LSU under heterogeneous precipitation**, the livestock condition stayed at the maximum of 100 until month 70 after which it dropped rapidly to zero in month 120. After this, only five small spikes can be seen in the livestock condition with values between one and five. With a stocking rate of **70 ha/LSU under heterogeneous precipitation**, the livestock condition stayed a lot longer, up to month 295 at the maximum value of 100 after which it gradually dropped. After the drop to zero in month 380, three big spikes (livestock condition: 34, 17, 16) lasting several months were visible, otherwise the livestock condition was at the lowest value of zero. With a very low stocking rate of **400 ha/LSU under heterogeneous precipitation**, the livestock condition can be sustained at the maximum value of 100 throughout the simulation period.

Discussion: relative abundance of vegetation --- In reality, the stocking rate on a farm can have a strong impact on the overall vegetation dynamics and on the extent and rate of bush encroachment in savannas (Abel and Blaikie 1989; Tainton 1999; Tobler et al. 2003; Teague et al. 2011). The results of the Midessa model also show and support this relationship (Fig. 41). Decreasing the stocking rate (i.e. more space for each animal to graze) results in a stretching of the pattern of relative vegetation distribution over time. This stretching means that degradation due to bush encroachment occurs later when fewer animals are put on a farm or more area is available per animal. Thus, the results show that an increase of livestock numbers on a farm leads to a degradation of range condition, i.e. an unfavourable mix of vegetation types in terms of grazing. This trend was e.g. also found by (Skarpe 1990; Díaz-Solis et al. 2003; Du Toit 2006). Our model results agree in pattern and trend with Weber and Jeltsch (2000) and Jeltsch et al. (1997a), who also found an increase in bush cover within 50 years of simulation for increasing stocking rates. We have overall a higher woody cover, especially for the last half of the simulation period, and a slightly too small effect of small changes in stocking rate in comparison with Jeltsch et al. (1997a). In the scenarios with heterogeneous precipitation, it can be seen that the palatable and especially the non-palatable perennial grasses are significantly more represented over the entire simulation period. Especially at the beginning of the simulation period, the perennial grasses can be present in high numbers for a longer time and in some cases (unpalatable grasses at 777 and 4440 cells/LSU) can even increase and be present in high numbers for a significantly longer time. However, when running simulations not only with grassers but using a grazer/browser mix we will be able to see that the (positive and stabilizing) effect on vegetation dynamics and the reduction of bush-encroachment is even stronger (see results 4.9.6 Browsing and compare with simulations by Szangolies et al. 2021).

Discussion: livestock condition --- The livestock condition indicates if the simulated group of animals found enough palatable biomass within their camps to get saturated. The stocking rate is constant over each simulation run and thus cannot be adapted, as it would usually be done in reality by famers in response to poor weather conditions and the associated declining veld condition and fodder scarcity. Though e.g. due to the economics of the livestock industry or lack of knowledge, unsustainably high stocking densities can actually be observed on real farms (Duraiappah and Perkins 1999; Hudak 1999). The livestock condition therefore also shows if the camps were unsustainably over-stocked. In reality, this can mean that livestock (or game animals that are sometimes not considered in the stocking rate) may die if no supplemental fodder is provided or the stocking rate is not reduced by the farmer (Tainton 1999; Du Toit 2006). Fynn and O'Connor (2000), however, found that it is also possible that even under high stocking rates and in dry years, non-degraded paddocks can balance out the fodder shortages on degraded camps. This would be an interesting scenario to test with a modified PioLaG landscape, as there is the option to set single camps to being already in various bush-encroachment stages. The results showed that the livestock condition decreases faster with increasing stocking rates. In some scenarios (e.g. 20 ha/LSU under heterogeneous precipitation) after reaching minimum livestock condition values, small spikes can be seen in the livestock condition with values less than 10. These spikes occur when the livestock is moved to a new camp. On the new camp that has been resting, grass did regrow so the livestock has some biomass to graze on which increases the livestock condition. The results further showed that in the heterogeneous precipitation scenarios the tipping point for an abrupt decline of livestock conditions was reached quicker in comparison with simulations with homogeneous precipitation *ceteris paribus*. This quicker decline is probably caused by the high proportion of bare soil especially at the beginning of the simulations. Since at many points in time a large part of the landscape consists only of bare soil, the biomass available as fodder for the livestock is greatly reduced. In addition, the overall relative abundance of palatable perennial grasses over the simulation period is smaller with spatially heterogeneous precipitation than with spatially homogeneous precipitation, thus providing less cells with potential fodder. The effects of over-stocking on the tipping points of livestock condition seem reasonable, and the model would additionally benefit from a more adaptive kind of management.

4.9.4 Homogeneous vs heterogeneous rainfall

I ran simulations with the default parametrization (see Tab C. 1 with default parametrization) with a spatially homogeneous precipitation distribution (for results see 4.9.1), but it is also possible to turn on a spatially heterogeneous precipitation distribution. This allows us to test the effect of the complex rainfall submodel, which is able to distribute the rainfall in form of clouds that randomly appear on the landscape. This cloud approach (Fig. 43) results in a very heterogeneous precipitation pattern where some cells receive a high rainfall (overlapping clouds) while others receive less or no water at all. Since precipitation is one of the main drivers of savanna vegetation dynamics, this unequal supply of water on the cells can have a major impact on vegetation dynamics. The temporal distribution of precipitation over the course of the simulation period is always heterogeneous as calculated by the Zucchini algorithm (see 4.8.1 Amount and temporal distribution of rainfall – Zucchini).

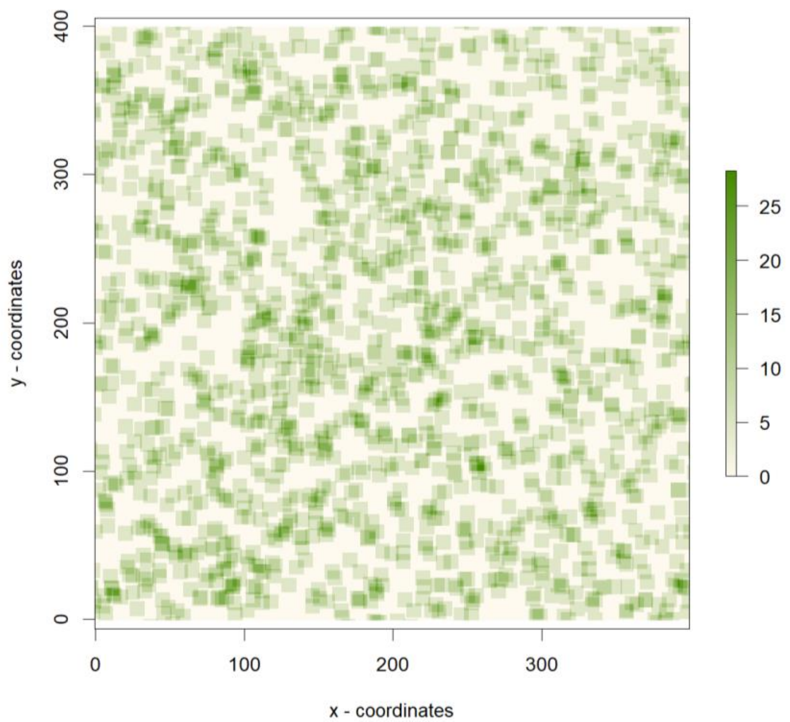


Fig. 43: Example of the spatially heterogeneous distribution of rainfall [mm/month] via clouds (year 3 month 12). Size of clouds (default = 10 x 10 cells ≈ 9 hectare) can be set in the parameter file (clima.x_cloud_size and clima.y_cloud_size).

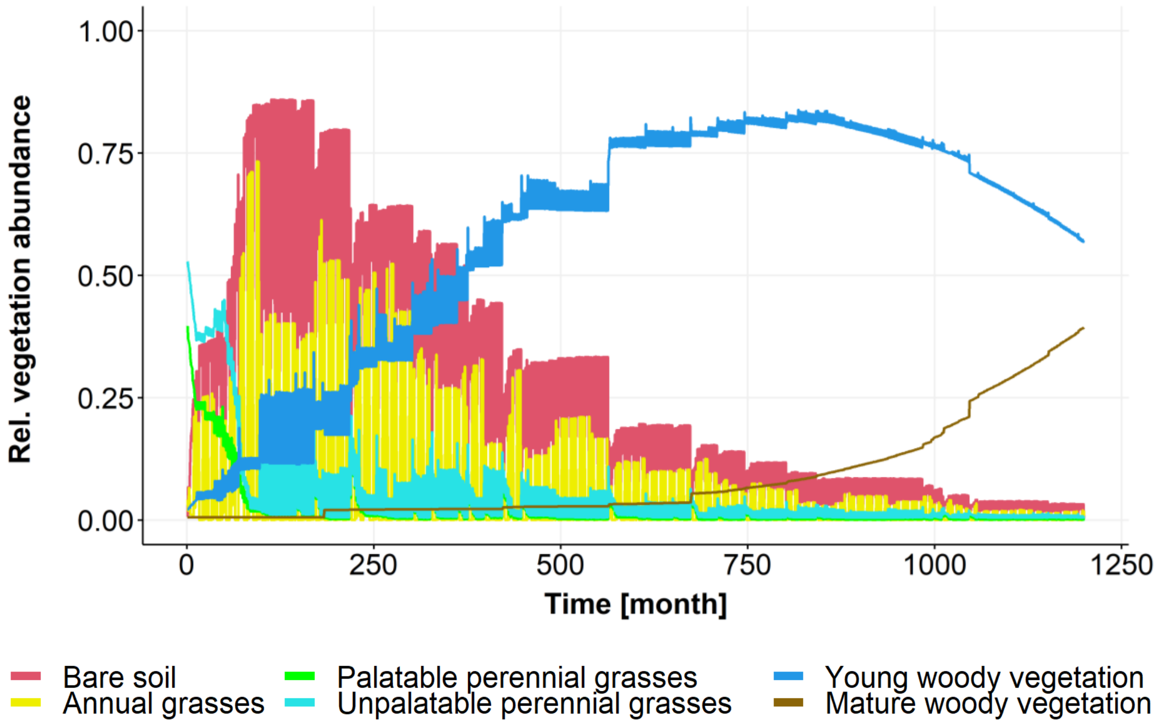


Fig. 44: Relative frequency of dominant vegetation types on the landscape over the 100-year simulation period with spatially heterogeneous precipitation. All images represent the state in February of the respective year.

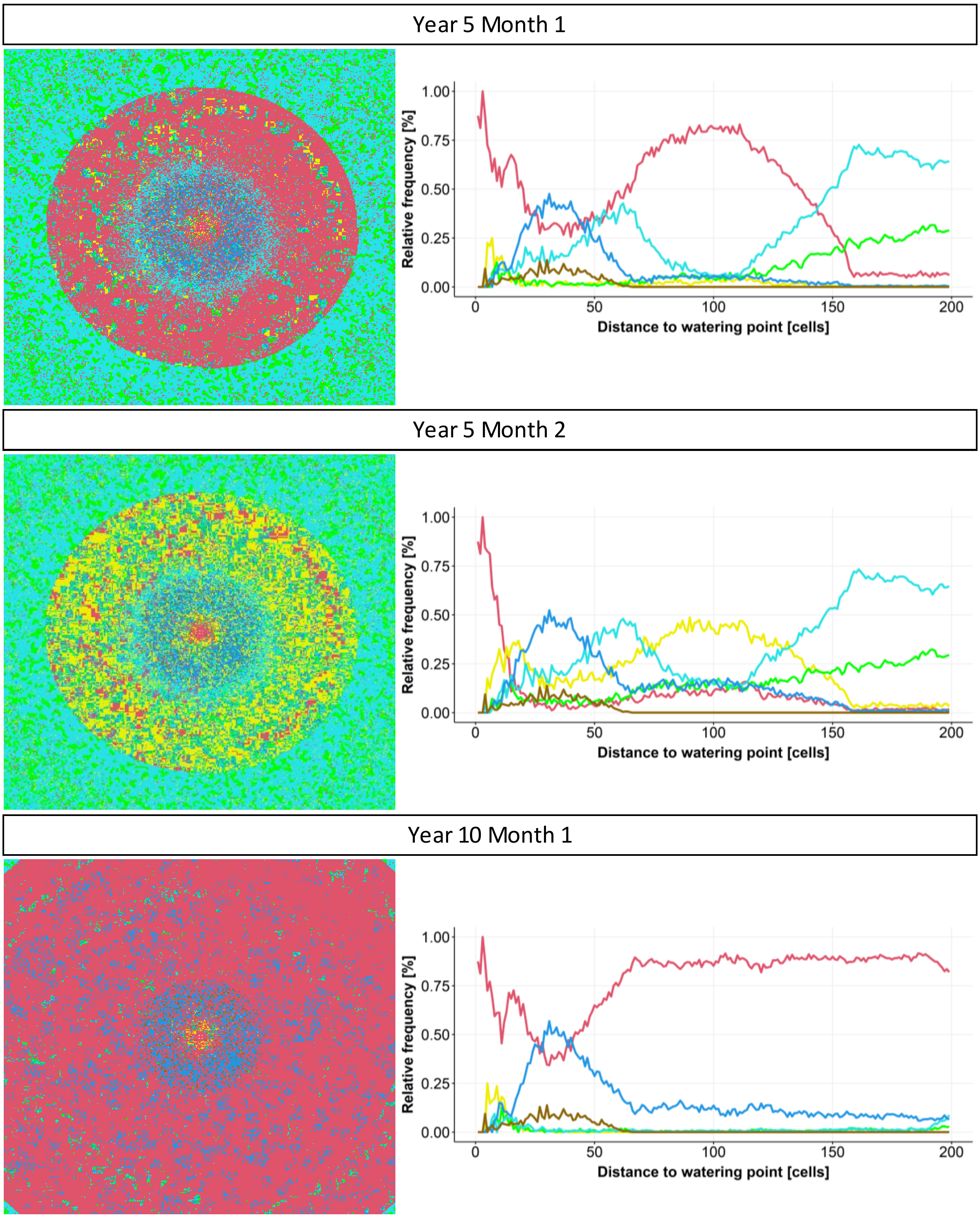
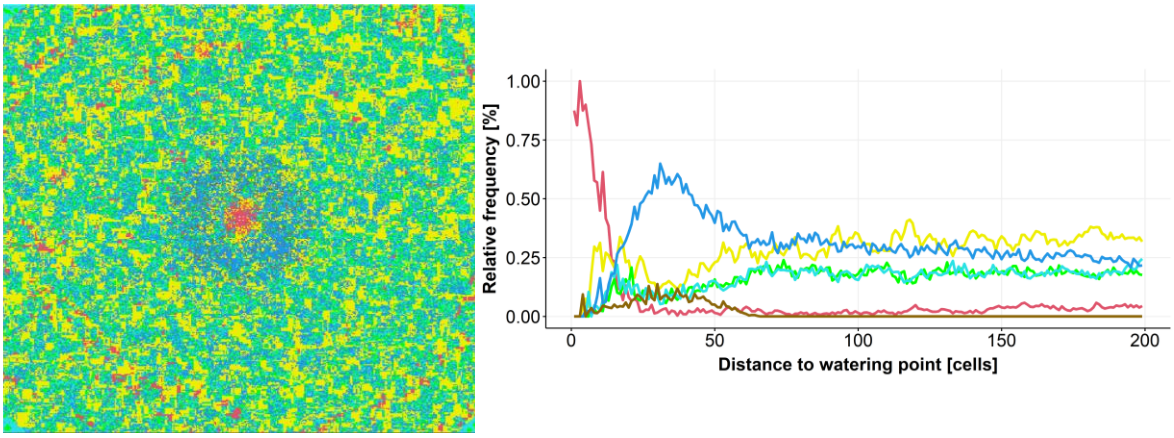
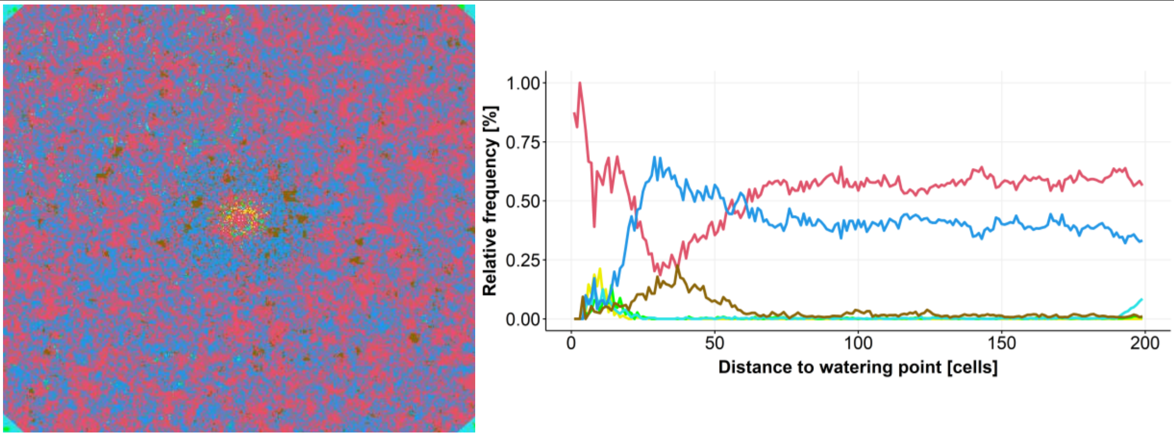


Fig. 45: Landscape maps of the simulated farm with the dominant vegetation type (Landscape 400x400 cells at 30x30 m resolution). The landscape contained a central watering point and four camps. Right: Relative frequency of dominant vegetation types with increasing distance to the watering point. All images represent the state in January or February of the respective year.

Year 10 Month 2



Year 30 Month 1



Year 30 Month 2

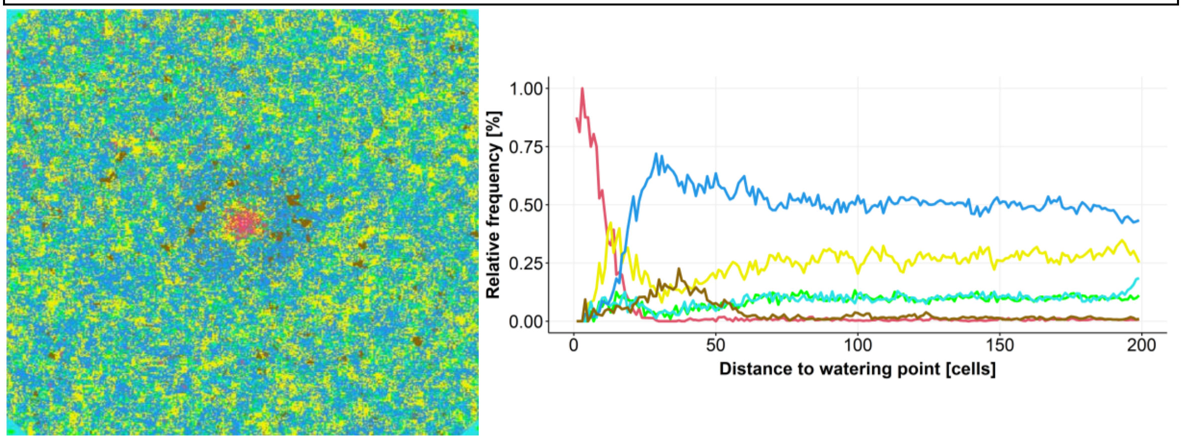


Fig. 45 continued: Landscape maps of the simulated farm with the dominant vegetation type (Landscape 400x400 cells at 30x30 m resolution). The landscape contained a central watering point and four camps. Right: Relative frequency of dominant vegetation types with increasing distance to the watering point. All images represent the state in January or February of the respective year.

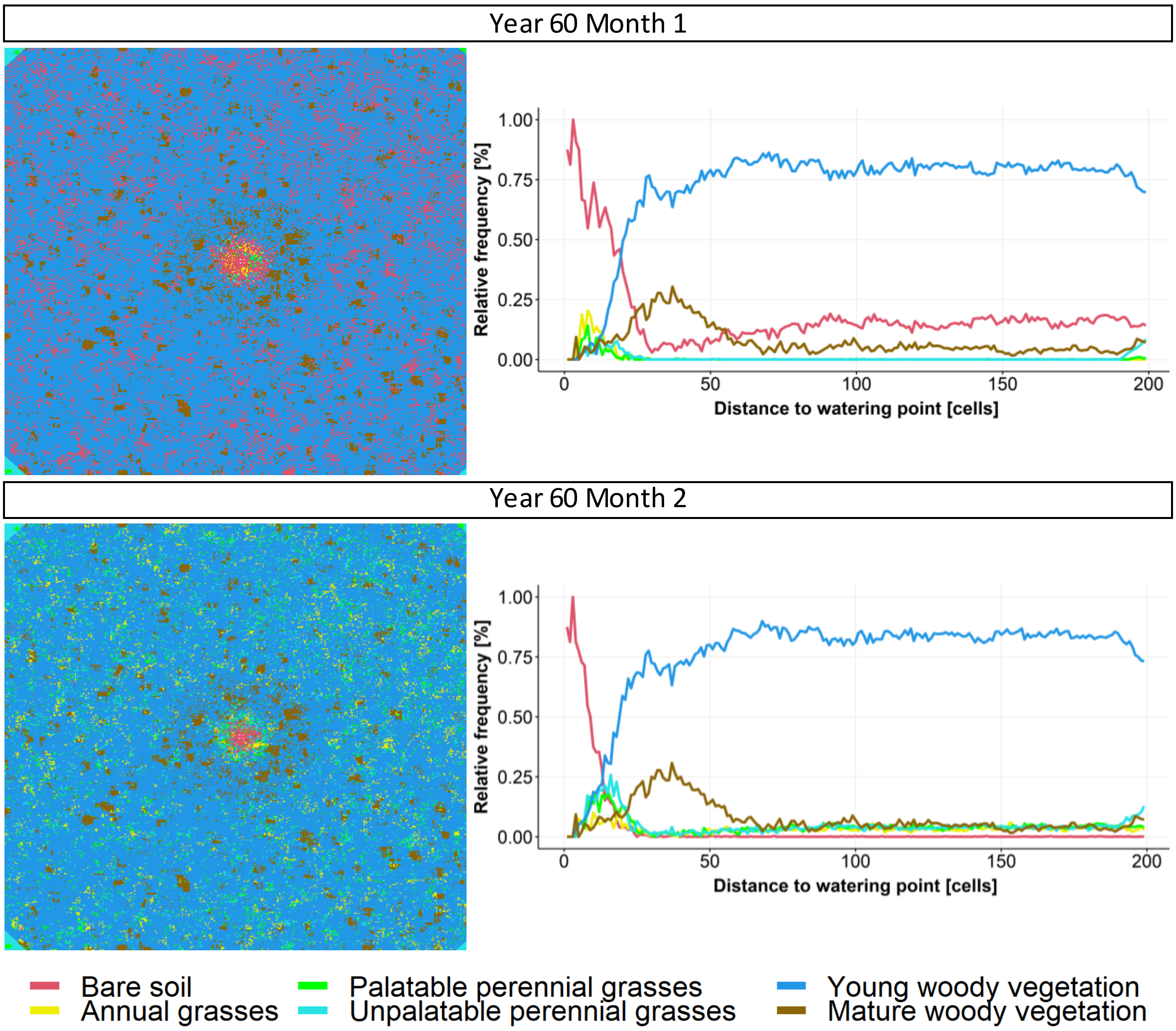


Fig. 45 continued: Left: Landscape maps of the simulated farm with the dominant vegetation type (Landscape 400x400 cells at 30x30 m resolution). The landscape contained a central watering point and four camps. Right: Relative frequency of dominant vegetation types with increasing distance to the watering point. All images represent the state in January or February of the respective year.

Results --- The simulations with heterogeneous precipitations showed very strong fluctuations, especially in the rel. abundance of bare soil and annual grasses (Fig. 44). Shortly after the start of the simulations, the palatable perennial grasses dropped from 40 % relative abundance gradually to 2 % in month 90. After this drop, the relative abundance started to fluctuate with maximum values of 13 % but with a decreasing trend so that the rel. abundance reached less than 2 % in month 720 and stayed this low for the rest of the simulation period. The unpalatable perennial grasses first started to decrease from 52 % to 36 % within the first two months, and then showed a short gradual increase up to 45 % just to drop again over the next three months to 2 % relative abundance. From there on, the pattern was similar to that of the palatable perennial grasses with decreasing fluctuations of relative abundance with peaks of up to 23 %. The young woody vegetation showed a strong, gradual increase with small fluctuations. The rel. abundance of the young woody vegetation peaked around month 840 with 84 %. From this point on, the relative abundance of the young woody vegetation decreases with fewer fluctuations to a value of 56 % at the end of the simulation period. The mature woody vegetation started to increase in month 180 from one to two percent and the relative abundance then showed more very small increases until, in month 670, an increase to 6 % occurred after which the rel. abundance increases slightly stronger up to 39 % at the end of the simulation period. Strongest fluctuations occurred in the abundance of bare soil and annual grasses. This pattern was caused by rapid (monthly or multi-month) switches between high relative abundance values of up to 86 % (bare soil, months 110 to 170) and 73 % (annual grasses, month 90) to low values of less than 2 %. The trend of both bare soil and annual grasses was decreasing after month 170 and 90 respectively and both vegetation types reached values below four percent in month 1050 for the rest of the simulation period. When looking at the landscape level, we can see already a quite heterogeneous landscape in **January of year 5** (Fig. 45; Year 5 Month 1). The centre around the watering point showed the typical trampling zone characteristics with mainly bare soil cells with few annual grass cells. Around this watering point at a distance between 15-60 cells, there was a zone with slightly raised abundance of mature woody vegetation (up to 14 %) and high young woody vegetation (48 %). This zone was overlapping with the elevated relative abundance of unpalatable perennial grasses between 20 to 80 cells distance from the watering point and a maximum value of 42 %. The unpalatable perennial grasses then dropped down to 6 % at a distance of 100 cells to then increase and become the most dominant vegetation type from 145 cells onward with a peak of almost 75 % at a distance and a slightly decreasing abundance down to 63 % at the edge of the landscape. The bare soil which creates a very strong donut-shaped pattern on the landscape map has, in addition to the very high peak in the sacrifice zone, another area (at a distance of 50-145 cells) in which it is very dominant with up to 82 % relative abundance. This spatial dominance of bare soil was temporally very variable and often lasted only one month after which other vegetation types became dominant again (Fig. 44). Already in the next month **February of year 5** (Fig. 45; Year 5 Month 2), we could see a similar pattern except for the fact that bare soil and annual grasses almost switched places in the 'donut-zone' (at a distance of 50-145 cells). The annual grasses were now the most dominant vegetation type between distances of 70 - 130 cells from the watering point while bare soil only reached values of up to 16 %. In **January of year 10**, the fluctuations of the dominance of bare soil had increased drastically Fig. 45; Year 10 Month 1). Except for a small area between distances of up to 30 cells from the watering points, annual and perennial grasses had a rel. abundance of less than 3 percent. The young and mature woody vegetation types had abundance peaks at 30 cells distance. Here, the young woody vegetation with a relative abundance of 56 % was more dominant than bare soil (34 %). However, except for this small area with a width of 10 cells, bare soil was the absolute most dominant vegetation type on the map with mostly values around 88 %. One month later, in **February of year 10** Fig. 45; Year 10 Month 2), the vegetation types originally standing at this site were back again, and showed a spatially very patchy and heterogeneous picture. In relative terms, on the landscape level, however, there was a very balanced, homogeneous distribution of vegetation types apart from bare soil dominance in the sacrifice zone and a peak of young woody vegetation at a distance of 30 cells with a relative abundance of 66 %. From a distance of 60 cells onward, the relative abundances of the vegetation types oscillate around 1 % (mature woody vegetation), 3 % (bare ground), 20 % (perennial grasses), 32 % (annual grasses), and 28 % (young woody vegetation, with a slight decrease towards the outer edges). In **January of year 30**, the pattern of relative abundance of vegetation types in relation to the distance to the watering point looked very similar to that in January of year 10 (Fig. 45; Year 30 Month 1). Only the abundance of bare soil after the sacrifice zone was smaller. There was a drop of bare soil to 19 % at a distance of 30 cells and then from a distance of 70 cells to the edge of the simulated landscape, the bare soil fluctuated around a relative abundance of 59 %. The woody vegetation types showed a higher relative abundance compared to January in year 10, with mature woody vegetation peaking at a distance of 36 cells with 23 % relative abundance while the young woody vegetation peaked at a distance of 29 cells with 69 % relative abundance and then only decreases a bit to settle at values around 40 for the rest of the simulation period. The landscape map of the dominant vegetation types showed a patchy pattern with some clusters of mature woody vegetation (Fig. 45; Year 30 Month 1, left). In **February of year 30**, the same phenomenon as in February of year 10 occurs and the vegetation that was at this side before the conditions were unfavourable and most cell turned to bare soil had returned and showed a fine patchy and heterogeneous picture (Fig. 45; Year 30 Month 1). In relative terms, on the landscape level, there was again a very balanced, homogeneous distribution of vegetation types. After the sacrifice zone and the surrounding disturbance zone dominated by bare soil and annual grasses, respectively, a donut at distances of 25 to 75 cells with an increase in young (max. 71 % rel. abundance) and mature (max. 23 %) was visible. From a distance of 76 cells onward, the relative abundances of the vegetation types oscillate around 2 % (mature woody vegetation), 1 % (bare ground), 10 % (perennial grasses), 27 % (annual grasses), and 49 % (young woody vegetation) with young woody vegetation showing a slight downward trend and annual grasses a slight upward trend. In **January of year 60**, most of the cells were dominated by young woody vegetation (Fig. 45; Year 60 Month 1). There were some bigger clusters of mature woody vegetation and smaller clusters of bare soil dispersed in the matrix of young woody vegetation. After the disturbances close to the centre, from a distance of 60 cells onward, the relative abundances of the vegetation types oscillated around 4 % (mature woody vegetation), 14 % (bare ground), 80 % (young woody vegetation) and annual and perennial grasses were below one percent. In **February of year 60,** the bare soil almost completely disappeared in the area outward of 30 cells from the centre (Fig. 45; Year 60 Month 2). Instead, this space was taken up by annual and perennial grasses (all around 4 %) and also the young woody vegetation showed an increased abundance in this area while the mature woody vegetation remained unchanged.

Discussion --- Rainfall in the (semi-) arid savannas of southern Africa is often very heterogeneous in space and time (Green 1969; Sharon 1981; Ward et al. 2004). The spatial and temporal overlapping of rainfall events in a patch-dynamic system is thought to be one of the main drivers of vegetation dynamics and possible causes of bush encroachment (Wiegand et al. 2006; Moustakas et al. 2009; Joubert et al. 2013). In order to increase the realism, Midessa uses an adaption of the SERGE rainfall generator (Eisinger and Wiegand 2008) to create patchy precipitation. The present results show that a heterogeneous precipitation led to a more heterogeneous spatial vegetation distribution with clusters of e.g. woody vegetation and the heterogeneous precipitation also slowed down the bush encroachment in comparison with the default scenario. It appears that the pattern of dominant vegetation over the course of the simulation period is a stretched version of the default scenario. While on average the rainfall may be the same, some cells will receive less or no rainfall while other cells receive a high amount of rainfall due to overlapping clouds, thus limiting the succession of vegetation types analogously (see Fig. 43 and also Fig. 26). Another interesting observation was that the camps or camp borders were not visible as they were in the scenario with homogeneous precipitation. This can be an indicator for the very strong effect of precipitation on small-scale vegetation processes even overshadowing (in a scenario with equally distributed rotational grazing) the effects that livestock has on the vegetation.

4.9.5 Camp rotation

Results 100-year overview --- In the open grazing system, also known as continuous grazing system, the farm was not subdivided into camps but instead all animals could move around freely on the farm. In the open grazing scenario, extreme bush encroachment occurred in a very short time (Fig. 46). After 40 months, young woody vegetation already dominated the landscape with 39% relative abundance and increased to 72% in month 100. After this mark, the relative proportion of young woody vegetation started to decrease and at the same time, the relative abundance of mature woody vegetation started to increase strongly. In a very short time, mature woody vegetation increased sharply from its initial value of about 4% at month 100 until it accounted for a full 98% of the landscape in month 325. This value still increased slightly until the end of the simulation runs to just below 100 %.

Landscape at certain points in time --- After only **5 years** (Fig. 47), large parts of the initially (Fig. 47; Initial conditions) grass dominated landscape were already covered by woody vegetation. The area up to 10 cells (≈ 300 meters) from the watering point was dominated by bare soil. The area at a distance of 20 to 46 cells as well as 54 to 163 cells from the watering point were dominated by mature and young woody vegetation with peaks at 53 % and 82 % relative frequency, respectively. Only few distances in between were dominated by unpalatable perennial grasses. The outer edges of the landscape still showed a high abundance of perennial grasses. The landscape map showed circles of different vegetation dominance that were homogeneous around the watering point.

In **year 10**, the woody dominance in the landscape extended even further. The sacrifice zone around the watering point was still dominated by bare soil. In the surrounding area (4 to 20 cells), a mix of palatable and unpalatable perennial grasses as well as annual grasses and both woody vegetation types was present. Distances from 15 to 196 cells were now mainly covered by woody vegetation with mature wood reaching a maximum relative abundance of 75 at a distance of 29 cells and young woody vegetation of 72 % at a distance of 142 cells. Toward the edges of the landscape, though interspersed with young woody vegetation, were unpalatable and palatable perennial grasses with a maximum of 39 % and 27 % relative abundance. After already **30 years**, almost the whole landscape was covered by mature woody vegetation (Fig. 47). After the bare soil dominated the sacrifice zone directly around the watering point, there was a 12 cells wide zone in which both perennial grasses (max. 16 %) as well as young (max. 36 %) and mature woody vegetation occurred. While the other vegetation types declined at 15-20 cells distance from the watering point, the mature vegetation rapidly increased to almost 100 % at a distance of 18 cells from the watering point. In addition, as can be seen on the landscape map, only in the very distant corners of the farm, the perennial grasses were still visible in higher abundances. At 60 years, the mixed zone in the centre, surrounding the sacrifice zone shrunk even further so that there was only an eight cells wide zone with perennial grasses and young woody vegetation. Mature woody vegetation however covered the landscape to 100 % already from 12 cells on onward. Again, only in the very corners were relicts of perennial grasses.

Discussion --- The magnitude of impact that livestock grazing (and browsing) has on the vegetation dynamics and specifically on the degradation of veld can be influenced by management decisions through altering the area (camp size) and time (grazing time, resting time) that the livestock is allowed to graze in a certain spot. In communal areas, large rangelands without or with only little camp infrastructure and open and continuous grazing are often predominant. In contrast, more actively managed farms often use a multi-camp (rotation) system that allows for a precise spatial and temporal allocation of livestock on the farm and thus a more sophisticated type of grazing management. The model shows that an open grazing system, where grasses do not get any time to rest and regrow but are instead continuously grazed, will likely lead to a quick degradation of the veld. These results are in line with studies in which the effect of grazing- and resting periods on the plant biomass and plant growth was researched (cf. Earl and Jones 1996; Tainton 1999; cf. Jacobo et al. 2006; Kgosikoma et al. 2013; Teague et al. 2013). Overgrazed cells can more likely become dominated by woody vegetation. This conversion shows a circular pattern that increases with time in size and distance from the watering point. While no or too little grazing can have a negative effect on the grass biomass growth rate, continuous grazing will have an even worse effect (Georgiadis et al. 1989; Skarpe 1991). The negative effect of non-grazing (no growth stimulation, and self-shading of grasses) was not implemented in the model, as it was not considered to be very important for the analysis of bush encroachment. Even more realistic results could be achieved if the grazing time can be chosen at shorter time spans less than a month, i.e. weekly resolution (Du Toit 2006; John Fair 2014), or if it could be also set in response to the available biomass on the camp. Also, during farmer interviews, some farmers mentioned that they let their livestock graze on a camp until a certain amount of the grass biomass (e.g. 60 %) was grazed and then move the livestock to the next camp.

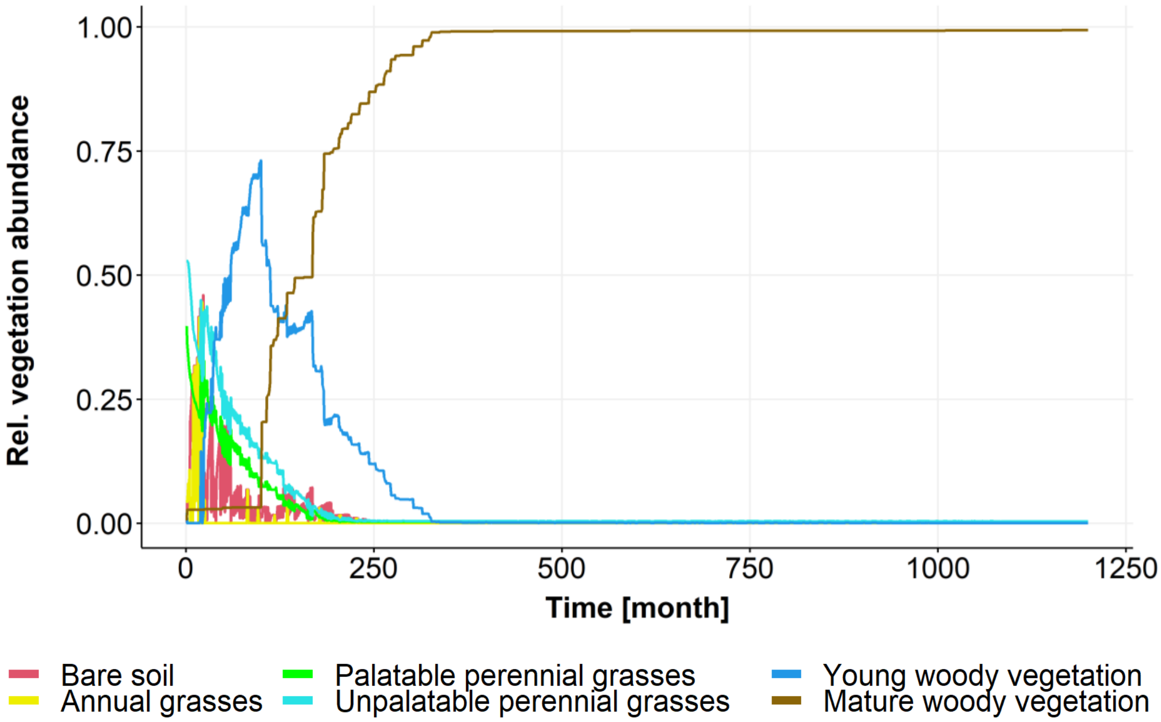


Fig. 46: Development of the relative abundance of vegetation types over the course of the simulation time (100 years) in an open grazing system with no camps.

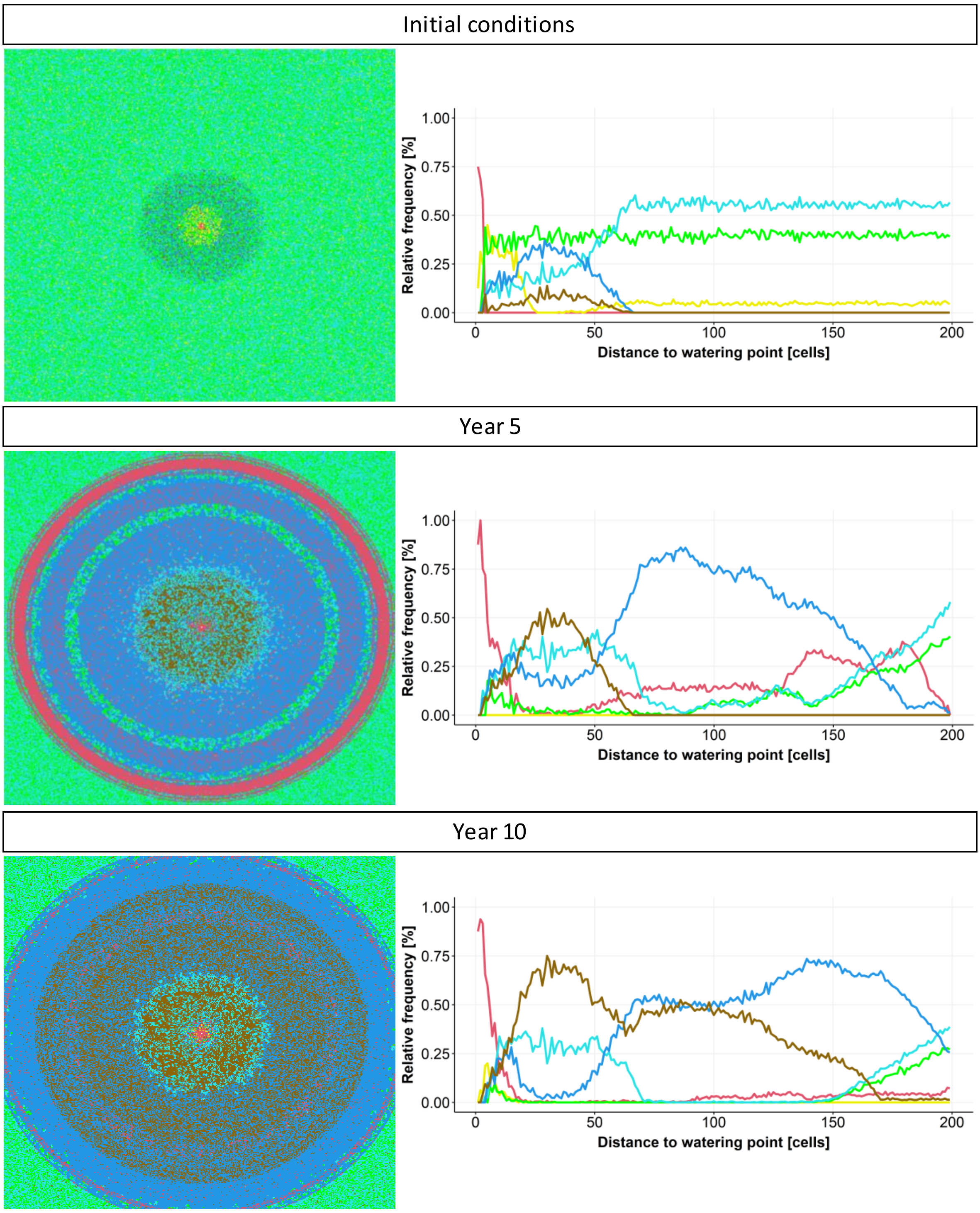


Fig. 47: Left: Landscape maps of the simulated farm with the dominant vegetation type (Landscape 400x400 cells at 30x30 m resolution). The landscape contained a central watering point and no camps or fences. Right: Relative frequency of dominant vegetation types with increasing distance to the watering point. All images represent the state in January of the respective year.

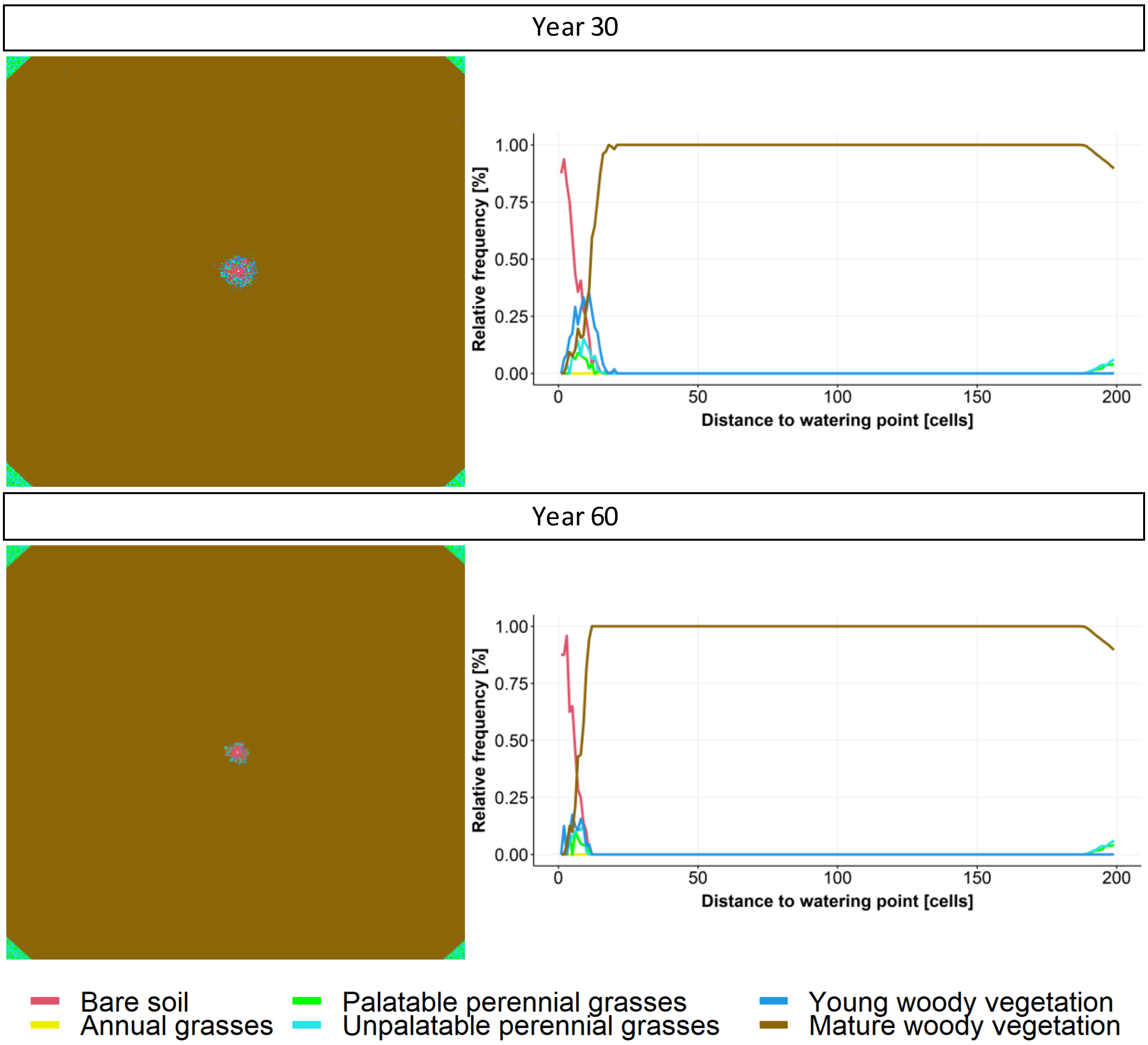


Fig. 47 continued: Left: Landscape maps of the simulated farm with the dominant vegetation type (Landscape 400x400 cells at 30x30 m resolution). The landscape contained a central watering point and no camps or fences. Right: Relative frequency of dominant vegetation types with increasing distance to the watering point. All images represent the state in January of the respective year.

4.9.6 Browsing

In this scenario, I used the default parametrization but turned on the browsing / mixed feeding (*animal.browse* = 1). This allowed the livestock to not only feed on the annual and palatable perennial grasses, but additionally on the young and mature woody vegetation. The farm consisted of four camps with a waterhole in the centre accessible from all camps.

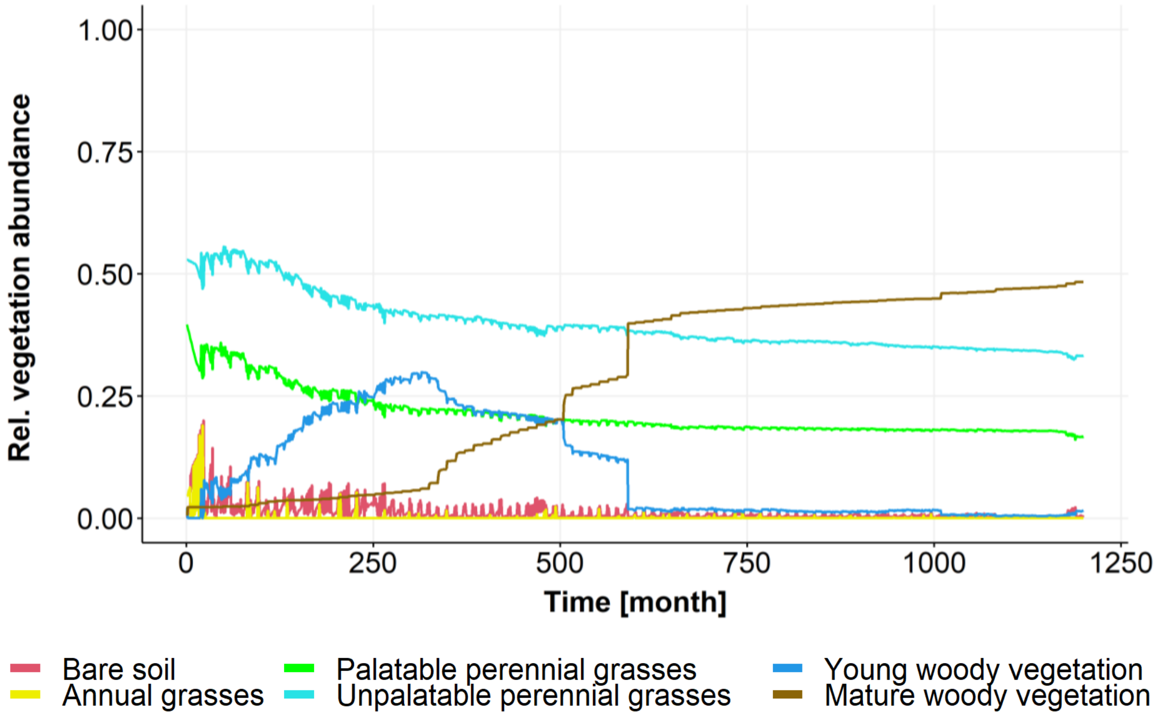


Fig. 48: Results of a scenario with browsers/mixed feeders. Relative Amount of different vegetation types on the landscape for 60 years (720 months) with default parametrization but activated browsing.

There was a tendency of slow bush encroachment with this parameterization (Fig. 48). Both woody vegetation types started with a relative abundance of less than 2 %. The young woody vegetation showed an increase of relative cell abundance up to 33 % in month 330 and then experienced a small drop down to 26 % as it was converted to mature woody vegetation. After this, the increase of woody vegetation was less steep. The young woody vegetation then showed another small drop at month 510 to 23 % followed by a big drop in month 600 down to 6 % where it remained until the end of the simulation period. The mature woody vegetation did not show a strong increase in the beginning and had a relative abundance of less than 4 % up to month 330 where it experienced the first increase to about 8-11 % until month 510. From there on, the development of the relative abundance of mature woody vegetation on the landscape was inverse to the young mature vegetation, i.e. when the young woody vegetation decreased, mature woody vegetation increased. Such an increase occurred in month 510 up to 19 % and then in month 600, there was a big jump up to 38 %. At the end of the simulation period, the woody vegetation covered almost 40 % of the landscape. Palatable and unpalatable grasses showed a constant slight decrease during the whole simulation period of 60 years. The unpalatable grasses started at a relative abundance of about 52 % and declined to about 34 % while the palatable grasses started with a relative abundance of about 40 % and declined to about 17 % at the end of the simulation period. While bare soil and the annual grasses reached high values in the beginning (up to 20 % in the first 30 months), after 80 months they did not reach more than 10 % of relative abundance each and their abundance kept dropping over the simulation period ending with less than 2 % relative abundance.

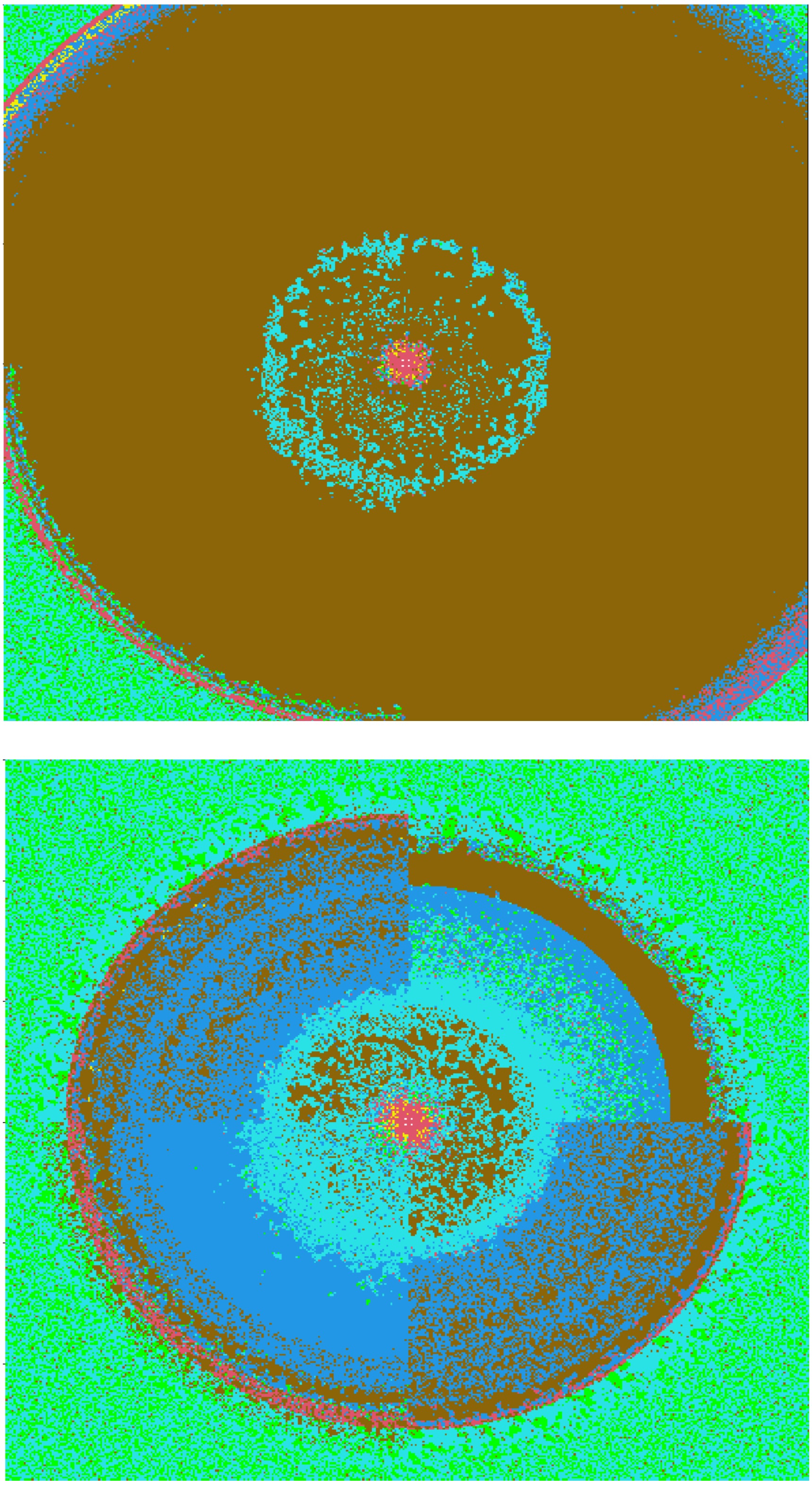


Fig. 49: Example of the dominant vegetation types on the farm in year 49 month 10. Top: Default scenario without browsers/mixed feeders. Bottom: Same point in time but with browsing turned on, *ceteris paribus*.

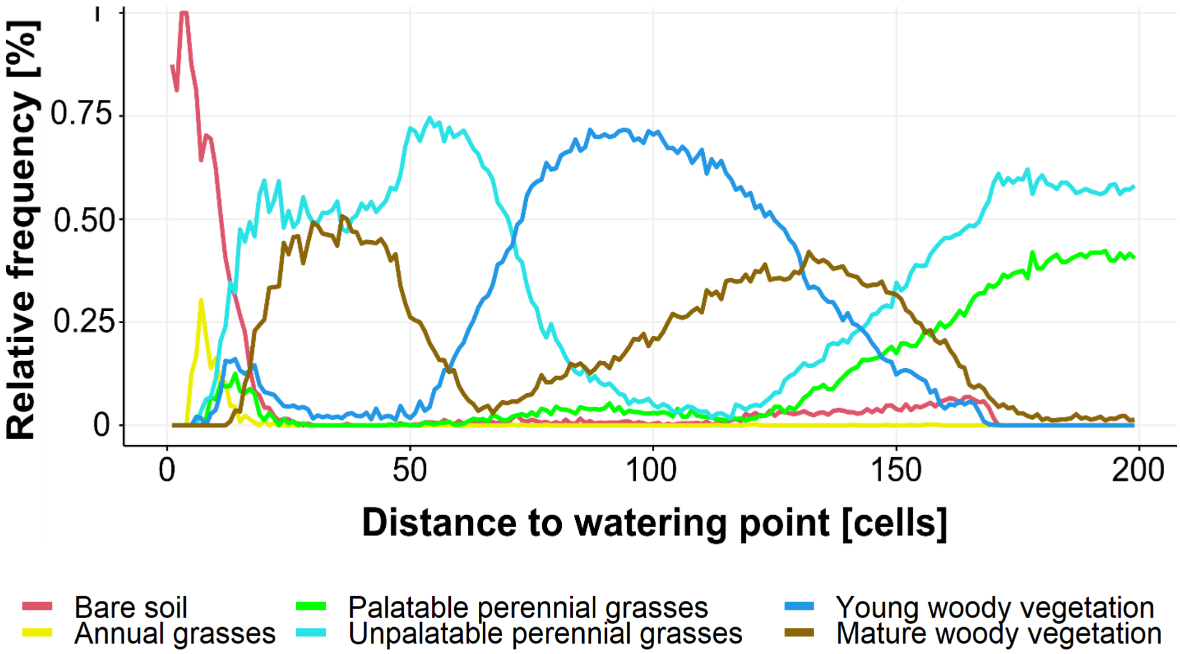


Fig. 50: Piosphere plot showing the relative frequency of dominant vegetation types in dependence of distance to the watering point on the farm in year 49 month 10.

The centre around the watering point was covered by cells with bare soil and annual grasses (Fig. 49, bottom). The cells with bare soil around the watering point were caused by trampling and defecation of the high animal density around the watering points. Also, the zone with annual grasses which had a width of about 3-12 cells (90-360 meters) was caused by the high frequency of animals on their way to the watering point. Because of the increase of the area in the circle, the frequency per cell was a bit less, thus allowing some annual pioneer grasses to establish in these sites. The next zone was dominated by unpalatable perennial grasses and patches of young woody vegetation. In this zone, the disturbance caused by the livestock was still quite frequent and being so close to the drinking resource, it was intensely grazed by the livestock. Next, was a zone with young and mature woody vegetation that was more or less pronounced, depending on the camp and the time in the year that it was used. There was an outer zone of bare soil caused by the current grazing activities. Livestock grazed in increasing (quarter of) circles thus creating distinct curves in the vegetation type patterns. The removal of grasses can lead to bare soil patches, which, over the next time steps and under the right conditions, can be conquered by other vegetation types. After this came the outer zone, the grazing reserve, which was up to now still mainly untouched by the livestock as they preferred the shortest distance between their water- and grazing source (Fig. 50).

In this scenario, the browsing was enabled which means that all cells, annual und palatable perennial grasses as well as young and mature woody vegetation were grazed/browsed. This simulates, for example, a farm with grazers like cattle in combination with (mainly) browsers (e.g. goats) or a game farm with a mix of grazers, browsers or mixed feeders. Such a mix of different animals increases productivity as they use the veld more efficiently and can also enhance sustainability as they reduce degradation (Bergström 1992; Shipley 1999). The strong effect of browsing becomes clear when the simulated landscape is compared to the default scenario without browsing, *ceteris paribus*. While under the absences of browsing, the woody vegetation covers most of the landscape, the scenario with browsing shows a lot less bush encroachment and more perennial grasses (Fig. 49). In addition, the woody vegetation consists to a high proportion of young woody vegetation while under the default scenario, almost all of the woody cells are mature woody vegetation. This is caused by the fact that the constant browsing and thus biomass reduction on young woody vegetation prevents or slows down reaching the biomass threshold to become an old woody vegetation cell.

4.9.7 Arboricide application

In this example, I ran the default parametrization but enabled the application of arboricides (*management.arboricideApplication* = 1) at a camp-based threshold of 50 % woody vegetation cells (*management.arboricideThreshold* = 0.5). Each camp that reached the 50 % threshold was treated with arboricides resulting in a conversion of 90 % of the cells dominated by woody vegetation to bare soil. Simulations were run for 60 years (Fig. 51).

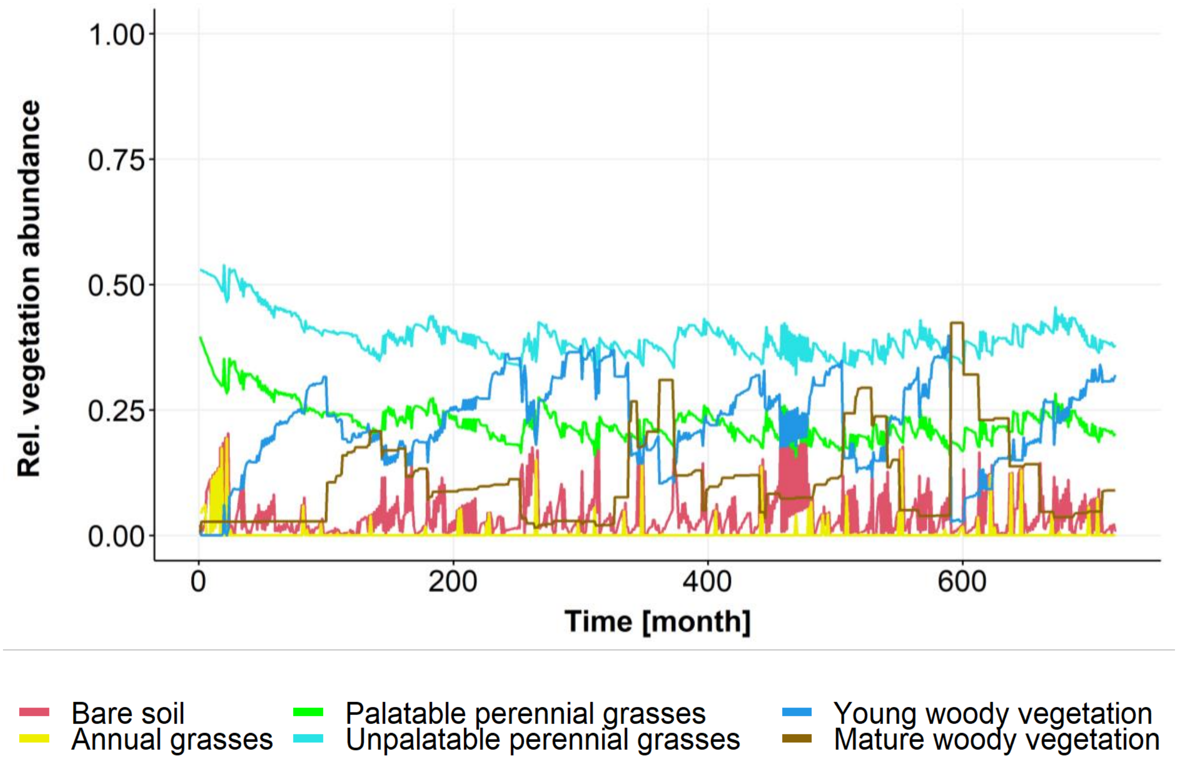


Fig. 51: Relative Amount of different vegetation types on the landscape for 60 years (720 months) with arboricide treatment at a threshold of 50 % woody vegetation per camp.

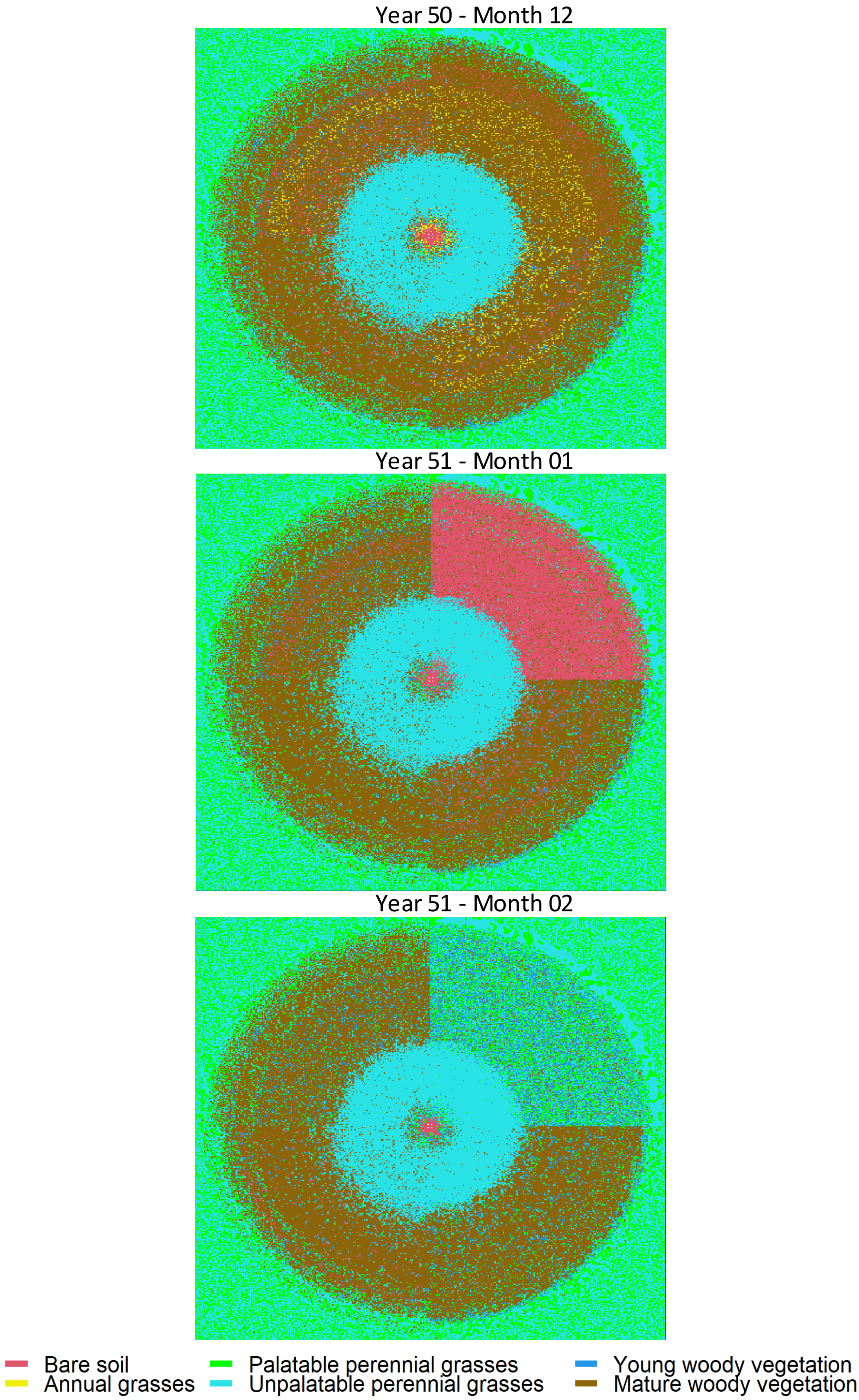


Fig. 52: Piosphere plot with watering point in the centre at year 50 month 12 (top), in this month the critical threshold of 50 % woody vegetation cells will be reached in the top right camp. In the following months (year 51, month 1, centre plot), 90 % of the woody vegetation cells on the upper right camp were converted to bare ground. Because the conditions in the next month were favourable (space and seeds available as well as sufficient soil moisture), perennial grasses and woody vegetation can establish in the top right camp (bottom).

Results --- In this scenario, the relative amount of palatable and unpalatable perennial grasses were quite constant over the whole simulation period with small fluctuations (Fig. 51). After a short initialization period, the palatable perennial grasses ranged between 15 - 28 % and the unpalatable grasses between 33 - 45 %. The young and mature woody vegetation showed an increase in relative abundance that was on average stopped at about 34 % and 30 % respectively and dropped to zero from where it then started to increase again. The mature woody vegetation stayed low after a drop down for several months, until enough biomass had accumulated on the young woody cells (on the treated camp) to allow them to convert to the mature woody vegetation type as well. The relative amount of bare soil and annual grasses remained quite low during the simulation extent and only showed big increases after arboricide treatments. The relative amount of annual grasses showed a similar pattern as bare ground but with a short delay. When the woody vegetation in year 50 month 12 (Fig. 52, top) reached the critical threshold of 50 % in the top right camp, the arboricide application was carried out. In the following month (year 51, month 1, Fig. 52, centre plot), 90 % of the woody vegetation cells on the upper right camp were converted to bare ground. Because the conditions in the next month (Fig. 52, bottom) were favourable (space and seeds available as well as sufficient soil moisture), perennial grasses and woody vegetation could now establish in the top right camp (right).

Discussion --- The use of arboricides with this camp-wise approach at a threshold of 50 % woody species will allow a more or less constant amount of palatable and unpalatable perennial grasses with small fluctuations. This approach is a good choice to create a long-term stable cover of grasses on the farm while also sustaining livestock during the whole simulation period. The quick succession after the use of arboricides from woody vegetation to bare ground to perennial grasses and young woody vegetation may be, depending on the chemicals used, a bit unrealistic as it happens quite fast. After the application of arboricides it can take several months (depending on rainfall to bring arboricides into the ground where they can be taken up by the tree) until the trees are dead and the cell becomes mainly bare soil with dead trees (Harmse et al. 2016). Depending on the amount of rainfall after this time, annual grasses will establish on the bare soil. Then, it may take some more months (or even up to eight years), also depending on rainfall patterns, soil moisture, soil type, but also on seed availability, for the next successional step, i.e. until a new perennial grass layer can become dominant (Donaldson and Kelk 1970; Smit 2004; Harmse et al. 2016). It is also unclear whether young woody vegetation will establish again right away on the cells treated with arboricides, as some of the chemicals will have a long-lasting effect and can stay active up to eight years in the soil and negatively influence tree growth (du Toit and Sekwadi 2012) while others (Haussmann et al. 2016) found evidence of instant regrowth of the encroaching species. However, on a larger scale over several decades, these details do not affect the simulation results negatively and have the benefit of saving runtime by simplifying the arboricide treatment process.

4.9.8 Complex landscapes

The previously shown simulations were run using realistic yet simple input landscapes. However, also complex landscapes with a variety of different camps, camp shapes and watering points (see also 3.6.2 Initialization: Farm setup) can be used as input for rangeland simulations with Midessa. These landscape data inputs can either be created with landscape generators such as PioLaG to have full control of all properties, or they can e.g. be created by classifying aerial or satellite images. In this section, I used a classified Landsat satellite image (Landsat-7 image courtesy of the U.S. Geological Survey) to show the kind of landscape complexity that can be included in the model. The landscape image was taken in 2005 close to Tseoge in the Molopo area. Bordering Botswana, the Molopo area is in the North West Province in South Africa. The climate in this area is semi-arid with a mean annual precipitation is 300 mm and a mean annual temperature of 19°C (Harmse et al. 2016). The image's total extend was 1240 columns by 1315 rows of 30 x 30 m cells. The image was then classified in vegetation types and additional information about camp borders and location of watering points was saved in separate files. Most Landsat satellite images have a spatial resolution of 30 x 30 meters which is a perfect fit as this is also the cell size in the Midessa model and the landscape images do not need rescaling. But also newer satellite images e.g. images taken by sentinel satellites from the Copernicus programme (Ludwig et al. 2019; Phiri et al. 2020) can be used if correctly classified and rescaled.

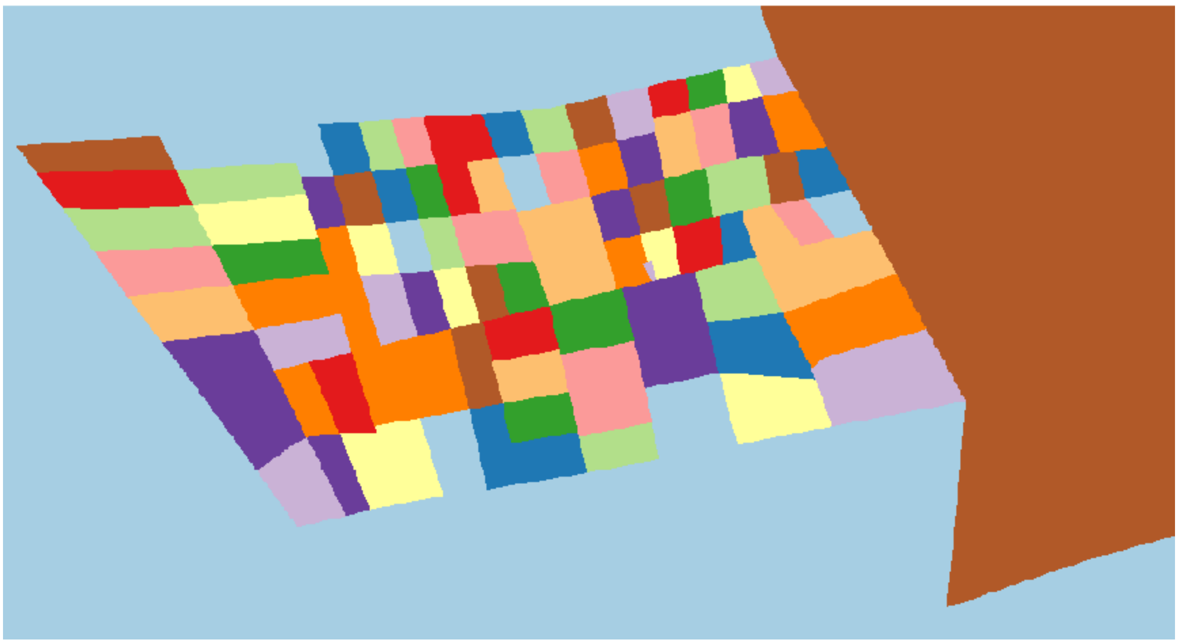


Fig. 53: Map with the location and boundaries of the different camps (different colours indicate different camps) on the classified image of the Tseoge area in the Molopo region in South Africa.

This landscape was a lot more complex than the default scenario as there were a total of 96 camps of different size and shape (Fig. 53). In addition, on the right side, there was a very large area that was not further subdivided. This big, connected area is typical for farms with continuous grazing such as game farms of communal farms as well as for nature conservation areas. The vegetation types were classified into bare soil, annual and perennial grasses as well as woody vegetation. The distinction between palatable and unpalatable perennials as well as young and mature woody species was not possible. It should, however, be possible to create more detailed maps with more recent approaches available (e.g. Gomariz-Castillo et al. 2017; Ludwig et al. 2019).

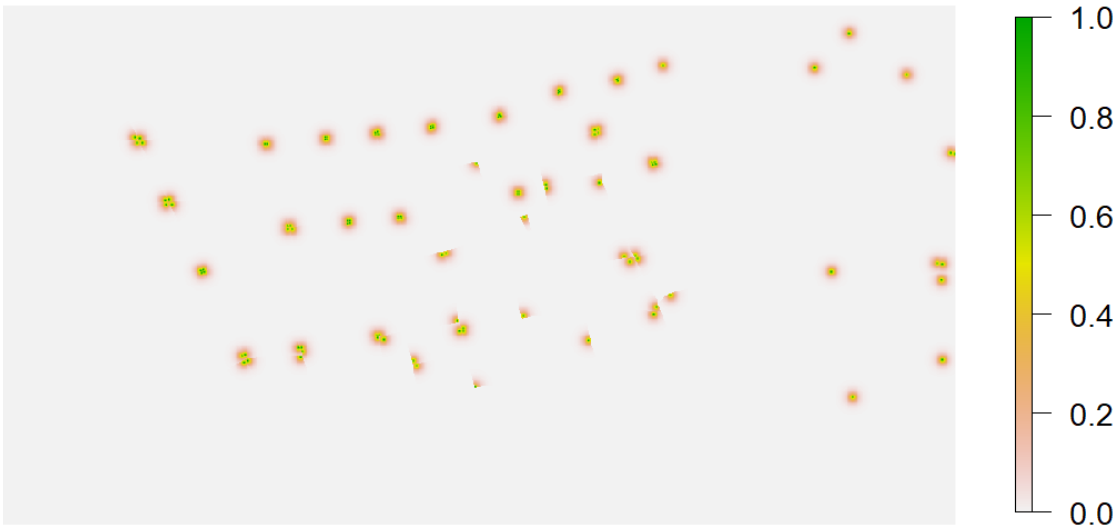


Fig. 54: Location of watering points in the Tseoge landscape with the immediate trampling zone around the watering points. Trampling intensity is represented by colour and ranges from very high trampling (green, 1) to no trampling (white, 0).

In total, there were about 44 watering points in the landscape (Fig. 54). Some watering points covered several close-by cells due to their position at the intersecting fences of neighbouring camps. This is often done to reduce the number of costly watering points by positioning them in a way that maximises the water supply of the surrounding camps.

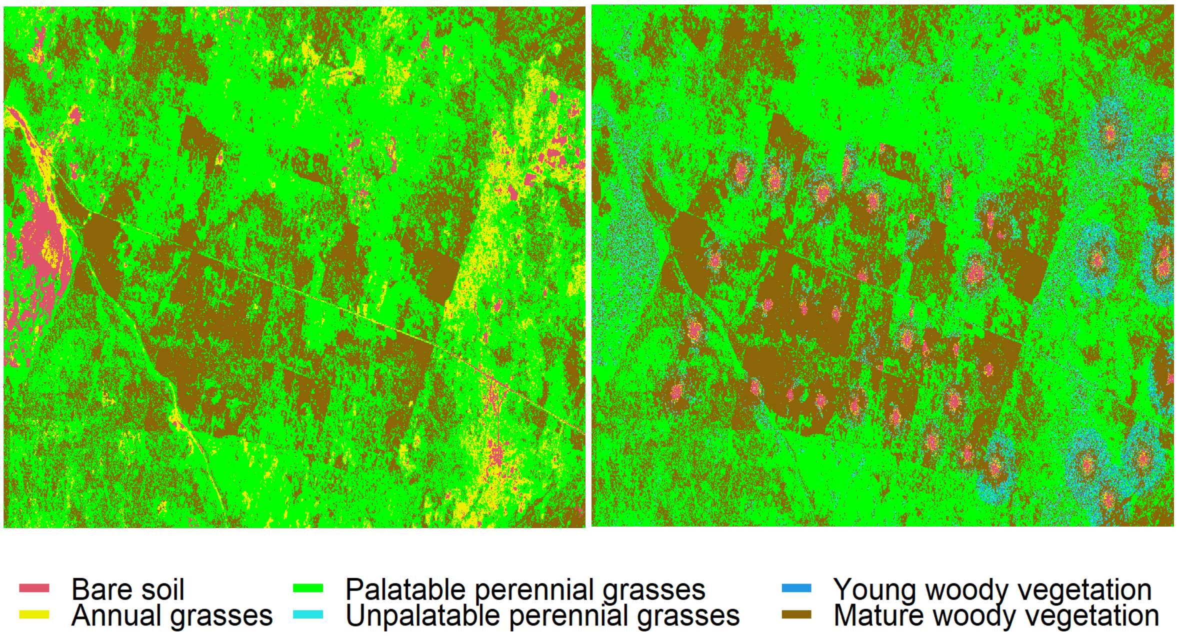


Fig. 55: Dominant vegetation types in the simulated landscape in the Tseoge area. Left: Initial vegetation condition based on classified satellite images at the start of the simulation. Right: Landscape after 50 years of simulation with default parametrization.

The simulations were run with default parametrization (Tab C. 1) for 50 years. Since a more refined classification was not possible from the satellite image, perennial grasses were defined as palatable perennial grasses and cells with woody vegetation were defined as mature woody vegetation. Several camp boundaries could be identified by the abrupt and linear change between vegetation types. Piosphere patterns (bare ground surrounded by a zone of annual grasses followed by a ring of woody vegetation surrounded by perennial grasses) were not clearly visible and can only be recognized to a small extent in some cases (Fig. 55, left). This was probably due to the spatial and spectral resolution of the image leading to difficulties in classifying and determining the dominant vegetation type for each cell, as there are usually always multiple vegetation types represented per cell. This deficient classification could be improved by using new GIS methods and higher resolution satellite imagery, as well as by considering different times of the year.

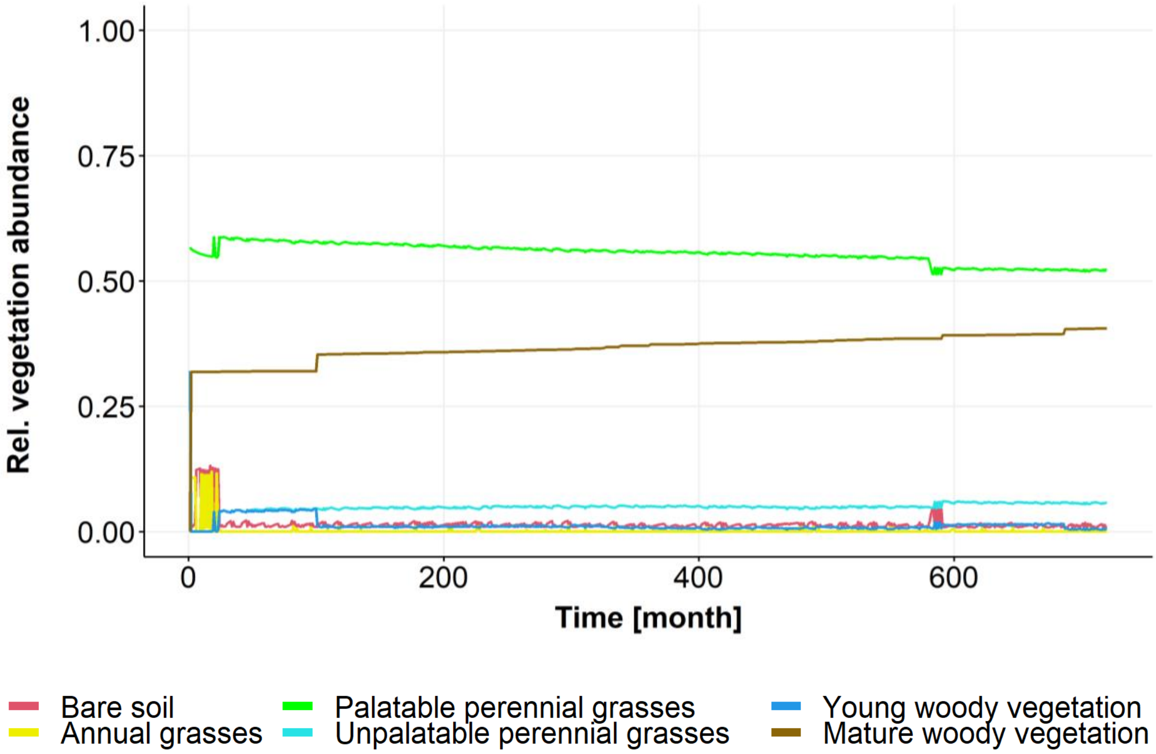


Fig. 56: Dynamics of dominant vegetation types on the Tseoge landscape during the 60 year simulation period.

Results --- At the beginning of the simulation, the most abundant vegetation type was palatable perennial grass with a relative abundance of 56% (Fig. 56). After short fluctuations after the start, the palatable perennial grasses started to slowly but steadily decrease from month 30 onwards. They dropped from 58 % rel. abundance in month 30 to 52 % at the end of the simulation period in month 720 (60 years). Around month 600, there was a steeper drop of 4 %; otherwise, there was a steady decrease with the usual intra-annual fluctuations. The second most common vegetation type was the mature woody vegetation type. This vegetation type started with 31 % relative abundance and slowly increased with a few steps to 40 % at the end of the simulation period (month 720). The unpalatable perennial grasses started at a very low rel. abundance but then showed a 4 % increase in month 30. This level was kept until month 600 where the rel. abundance increased to 6 % until the rest of the simulation period. The increase in month 600 coincided with a rainfall peak (cf. Fig. 36). The young woody vegetation type started with a very low rel. abundance and then had a short 80-months period where its cells occurred with a higher, about 4 % relative abundance. Otherwise, the relative abundance was at very low values below 2 % for the rest of the simulation period. The bare soil started with a relative abundance of 12 % at the beginning of the simulations until it dropped in month 28 to low values between 1 % and 3 %. The relative abundance fluctuated in this range until the one-year shift seen in all vegetation types in month 600. At this shift, the abundance of cells dominated by bare soil reached a value of 5 % but dropped thereafter again to values between 1 % and 3 % until the end of the simulation period. The annual grasses initially followed the pattern of the bare soil, but after 30 months, they were at very low relative abundances of less than 2 %. After 50 years of simulation, the landscape looked different in several ways than it did when the simulations began. A clear pattern that was visible then were the so-called sacrifice zones around the watering points marked by bare ground. These bare ground patches were surrounded by annual grasses and a mix of young woody vegetation and unpalatable perennial grasses as it was typical for piospheres (Thrash and Derry 1999). One fact that was particularly noticeable was that the piospheres in the right, very large camp were considerably larger than in the rest of the landscape. Furthermore, larger areas that were originally covered by bare ground or annual grasses were then covered by perennial grasses or young woody vegetation. Especially in the centre of the initial map, there were many small patches of palatable perennial grasses surrounded by many woody vegetation cells. After 50 years however, a large portion of these green cells had disappeared and there were then mainly large patches of mature woody vegetation.

Discussion --- The Tseoge landscape that was obtained through classification of satellite images could be used in the Midessa rangeland model with ease. The already strongly bush encroached Tseoge landscape experienced still more bush encroachment, while the relative amount of palatable perennial grasses slowly decreased. Especially large piosphere patterns formed in the big camp on the right around several watering points. This was possible by the unconstructed space that was surrounding the watering points allowing the livestock to freely choose the distance for the trade-off between walking further to get to (better/more) palatable grass and walking not as far to be close to the water resource. If the livestock was fenced in a small camp however, the grazing gradient abruptly stopped and the full piosphere pattern was not visible but instead ended at the fence line. If the farm is not properly stocked and the camps not properly rotated, the intense grazing in the fenced area will be very high and likely lead to bush encroachment. Additionally, small perennial grass patches in a matrix of woody vegetation can also simply be overgrown by woody vegetation through spatial spread, as seen in the simulation results. There are, however, some uncertainties connected with the use of remotely sensed data. The user cannot be sure if all the watering points were recorded correctly and that the access to all the watering points is in fact possible. The user can only dependent on the fact that everything is really correct with the data and everything was recorded properly if there is no time/funding for supplementary follow-up investigations. Still, there could also be other factors that were not considered during compilation of the landscape input, which, however, might affect the real situation making it thus more difficult to compare reality with the simulated results, for example, an open gate in a fence, specific soil properties affecting classification, etc.

The Midessa model can easily be used for large and complex landscapes simply by exchanging the input data. No special adaptions are necessary; only the different layers (vegetation type, position of watering points, location and boundaries of camps and farms) are required. The model can thus also be used for classified aerial images of real landscapes as long as information about dominant vegetation type, farm- and camp infrastructure and watering point position can be calculated/classified or are otherwise available. However, it needs to be kept in mind that certain properties of e.g. soil properties, actual species composition, land surface, chemical treatment history, nutrients, etc. are usually not registered by aerial and satellite images. Thus, the simulated landscape and the results after simulation can deviate from the actual conditions on that site. This must be considered when running and interpreting simulation results. The uncertainty can be reduced by more detailed (in terms of spatial, temporal, or spectral resolution) satellite imagery, additional ground truthing and by including data from e.g. questionnaires about site history.

4.10 Sensitivity analysis

To test the behaviour of the different parameters of the model, I conducted a sensitivity analysis. In particular, I used a revised version of the Morris's elementary effects screening (Campolongo et al. 2007) to test selected parameters (called 'factor' in Campolongo et al. 2007) and their impact on the model results and interaction effects (Morris 1991; Thiele et al. 2014). As central output variables of the Midessa model, I used the relative abundance of bare ground, annual grasses, unpalatable and palatable perennial grasses, as well as young and mature woody vegetation. But also, the amounts of dead and alive biomass, and their SD within the landscape as well as the livestock condition were of importance as indicators of vegetation dynamics and thus included as output variable in the Morris screening. A combination matrix of all selected test parameters (1300 combinations in total) was drawn and to keep runtime of the sensitivity analysis reasonable, only a selection of parameters was chosen. As input parameters of interest, I varied the water dependency of the livestock, fire frequency, grazing time on each camp, stocking density, mortality of woody vegetation, MAP, fire biomass threshold, seed base probability, transition biomass from young to mature woody, number of neighbours for spatial transition, and the fodder demand per LSU. All parameters were automatically varied within a realistic parameter space. A problem for the sensitivity analysis is the non-equilibrium of the vegetation types over the course of the simulation time. The tendency towards a very bush encroached landscape over shorter or longer time periods makes an analysis of the effects of input parameters more challenging. Depending on the phase of the simulation period, the different input parameters can have a different effect on the vegetation patterns at that moment. However, looking at the effects on shorter time frames should be of greater interest and leads to plausible results. Therefore, I have chosen to analyse the effect in the 30th year, because in most scenarios, all vegetation types were still represented at that time. The results are the average of all twelve months in the 30th year. Simulations were run with spatially homogeneous and spatially heterogeneous precipitation. In the results of the Morris screening, μ is the overall effect (first-order effect) of a parameter on the respective output. The direction of the effect is indicated by either positive or negative values of μ. μ* denotes the absolute value of μ. The higher the value of μ*, the stronger the effect. Another output of the Morris screening is the SD of the elementary effects (σ) for each parameter. Elementary effects that vary a lot (high σ) indicate that other parameters also have an effect on the output variable, i.e. there is an interaction between parameters but this may also be due to non-linearity (Menberg et al. 2016). The ratio between σ/μ* can be roughly grouped into response classes and I have added lines (at a ratio of 0.1, 0.5, and 1) to the plots to visualize the group borders. A σ/μ* ratio ≤ 0.1 indicates (almost) linear responses of output values to changes in the input parameter. A σ/μ* ratio between 0.1 and 0.5 indicates a monotonic behaviour and a ratio between 0.5 to 1 points towards an almost monotonic response. Whereas a σ/μ* ratio > 1 indicates large interaction effects and/or a non-linear behaviour.

Results and Discussion --- The results of the Morris screening were mostly as expected and consistent with results from the literature, as well as from expert knowledge and farmer interviews. The results showed very well which input parameters have a positive or negative influence on the considered output variables and whether these effects are linear or non-linear. The latter is an indication of interaction effects with other parameters (Saltelli et al. 2002). Overall, the parameters that had an effect on the observed output variables showed a lot of interaction which can be expected for such a complex system.

4.10.1 Spatially homogeneous precipitation - first-order effects

In the analysis for the homogeneous precipitation scenarios (Fig. 57), the most influential parameter for the abundance of **bare soil** was the <u>mean annual precipitation</u>. The strong negative effect on the abundance of bare soil with increasing precipitation is realistic because under high rainfall scenarios bare soil cells can quickly be repopulated by annual- and perennial grasses as well as young woody vegetation. Another influencing parameter with a not as strong negative effect was the <u>stocking density</u>. When the hectare per LSU is increased, there will be less animals on the farm and thus less trampling will occur which usually leads to bare ground. In addition, the total grazing will be less and with that, the chance that a cell with palatable perennial grasses gets overgrazed and develops poor vegetation condition, which would make it susceptible to competitors (spatial transition). Another influencing parameter with a slight positive effect was the <u>mortality of woody vegetation</u> any "death" of a vegetation type will lead to a conversion of that cell to bare soil before it can then be overgrown again by another vegetation type. All <u>other chosen</u>

input parameters also showed to a lesser extent slightly positive or negative effects on the abundance of bare soil on the landscape.

The effect of the different input parameters on the **annual grasses** was similar to that on the bare ground. Highest effect had stocking density and mean annual precipitation (strongly negative effect). All other input parameters had a smaller either slightly positive or negative effect on the annual grasses in the landscape. This output seems reasonable. It makes sense that it is similar to that of bare ground as the annuals are usually the next successional step after bare soil since seeds are always available and omnipresent, and the soil moisture demands are low.

For the **palatable and unpalatable perennial grasses**, the most influential parameter with a positive effect is the stocking density. When the hectare per LSU is increased, there will be less animals on the farm and thus the effects on palatable perennial grasses through grazing and trampling will be smaller allowing the grasses to grow a lot of biomass and thus giving them the chance to outcompete neighbours and distribute seeds in the landscape. The strong positive effect of a decreased number of animals on the unpalatable perennial grasses, however, seems a bit off and the reasons are not obvious at first glance. One reason could be that by promoting palatable perennials, the balance between the three competing vegetation types (perennial grasses and young woody vegetation) is better, so that the unpalatable grasses have a better chance to persist in the landscape in contrast to a scenario where the palatable perennial grasses are diminished and the young woody vegetation can increase its dominance by e.g. spatial transition, i.e. outcompeting neighbours through higher numbers. Additionally, the before mentioned effects on bare soil and annual grasses should be considered; these cells can now be overgrown also by unpalatable perennial grasses. Though the general trend can be explained, I would have expected that the positive effect on palatable perennial grasses would have been stronger than on unpalatable perennial grasses. The positive effects of the mean annual precipitation and the mortality of woody vegetation seem natural, as does the negative effect of the water dependency. Higher values of the negative water dependency reflect that the livestock is less depending on water and will more likely graze further away from the watering point in the centre. Thus, the negative impact through grazing and trampling on the farm is spatially larger when water dependency values are high. Browsing is positive for both perennial grass types because, on the one hand, it partly spares the palatable perennial grasses, since the livestock can also satisfy the feeding needs with young woody vegetation. On the other hand, the unpalatable perennial grasses are also benefited because their competitor, the young woody vegetation, is put at a competitive disadvantage by the reduction of the woody biomass.

The effects on the **young woody vegetation** are a bit counter-intuitive. It is unclear why the stocking density has a stronger effect than the mortality of woody vegetation. Maybe this positive effect is indirectly caused by the fact that already many young woody vegetation cells became mature woody cells so that the cause-and-effect relationships are not clearly visible anymore. This again is a problem of looking at only one year during the fluctuating course of the simulations. Averaging over longer time periods considering the thresholds for the conversion to mature woody vegetation might change the effect of the stocking density. The negative and second strongest effect of the mortality of woody vegetation was clear and as expected. The mean annual precipitation as parameter with the third strongest effects also showed an unexpected behaviour. With increasing precipitation, the amount of woody vegetation should, in reality, increase in the landscape (Scholes et al. 2002; Sankaran et al. 2005); however, the Morris screening suggested a strongly negative effect. This again could be explained by the fact that the increased precipitation leads to a better growth of young woody vegetation thus allowing it to turn quicker into mature woody vegetation, thus overall reducing the current abundance of only young woody vegetation. Important parameters were also, as expected, the transition threshold from young to mature woody vegetation, which has a very strong positive effect as cells can sustain longer in the 'young' state before becoming mature woody vegetation cells. Another important parameter with a strong negative impact on the young woody vegetation was naturally, the browsing.

When looking at the **mature woody vegetation**, the before mentioned unexpected behaviours were not visible anymore, suggesting that indeed, the conversion from young to mature woody vegetation negatively affected the output of the Morris screening and is likely the reason for the e.g. opposite effect of MAP. As expected, the parameter stocking density showed a strong negative effect on the abundance of mature woody vegetation. A reduction of livestock and thus (over-) grazing leads to a decline of bush encroachment. Overgrazing in savannas is hypothesised to be one crucial factor leading to bush-encroachment (Smet and Ward 2005; Britz and Ward 2007). The mortality of woody vegetation showed to have a slightly negative effect on the abundance of mature woody vegetation which is reasonable, but it might be beneficial to increase this effect in future model versions to counteract the strong trend towards bush encroachment during most simulation scenarios. The mean annual precipitation affected the abundance of mature woody vegetation as expected, such that higher MAP led to a higher overall woody vegetation cover (Sankaran et al. 2005). The other parameters and their effects also seem reasonable. One interesting fact is that the effect of the transition threshold from young to mature woody vegetation was stronger and more negative than the effect of browsing. This should be taken as an incentive to re-examine the parameterization of this parameter for the different species compositions of mature woody vegetation types for the different areas in southern Africa in detail in order to optimize estimates for this parameter and thus reduce uncertainties in the model.

The most influential parameter for the mean amount of **dead biomass** was the stocking density with a slight positive effect, which is likely being caused by the fact that less grass biomass is taken up by the livestock and therefore, remaining dead grass biomass can accumulate. However, also the decrease of bare soil and annual grasses that are connected to less livestock on the farm can be a reason for the slight positive effect as these cells are then taken up by perennial grasses which can store more (dead) biomass than bare soil and annual grasses, or they can be overgrown by young woody vegetation which, especially when it turns into mature woody vegetation, has a very high dead vegetation (wood) storage capacity. The second most influential parameter with a positive effect on the amount of dead biomass was the mortality of woody vegetation, which clearly makes sense. Most positive effects came from the parameters fodder demand per LSU and the fire frequency. The complex interactions in the model do not allow an easy conclusion on the rationale for this behaviour. However, it is probably because increased fodder demand weakens and reduces the palatable grasses, allowing more woody vegetation to become established, which, once mature, can store significantly more dead biomass per cell than any other vegetation type. The reasoning for a positive effect of increased fire frequency on biomass is not quite so straightforward. However, the model rules for fire spread are such that only young, but not mature woody vegetation cells can be ignited. Thus, once woody vegetation becomes mature, it is safe from the fire and can accumulate a lot of dead biomass, whereas young woody vegetati on and grasses lose all their green and dead biomass. Due to the loss of biomass, the grasses are again more prone to be spatially overgrown by woody biomass or to lose a cell to woody vegetation by chance during the temporal vegetation dynamics. This approach is especially useful for arid and semi-arid savannas, where the necessary biomass amount is rarely reached to get a fire strong and hot enough to completely burn even mature woody vegetation. However, this should be adapted in the course of the upgrade to the advanced fire submodel (Limberger et al. 2020) so that under certain circumstances (beneficial weather conditions and sufficient combustible biomass that produce particularly hot, strong fires), mature woody vegetation is also decimated by fire. The most negative effect on the mean amount of dead biomass had the transition biomass threshold for mature woody vegetation because of similar reasons as discussed before. When the threshold for mature woody vegetation increases, it will take longer for the cell to turn from young to mature woody. Since young woody vegetation and the biomass on these cells is more susceptible to external influences (fire, browsing, drought and competition), it is more likely that dead biomass is lost compared to a situation where young woody vegetation cells turn quickly into mature woody vegetation cells and are thus better secured against the loss of biomass.

The **green biomass** was very positively influenced by the mean annual precipitation. As soil moisture is the key variable for biomass growth, this effect is expected. The mean annual precipitation is also the biggest driver of spatial heterogeneity **(SD) of green biomass**. This can be explained by the strongly stimulated growth of biomass of mature woody vegetation with higher precipitation, but the simultaneous non-growth on the cells with bare soil and a reduced and strongly restricted growth of annual grasses. These processes lead to a highly diverse landscape in terms of green biomass. The strongest negative effect on the green biomass have the parameters stocking density and fodder demand per LSU. The effect of the stocking density on the amount of green biomass is rather complex and also shows the highest interaction effects. Palatable perennial grasses can compete and survive better when they are not weakened by grazing. Thus, these cells cannot be taken over (easily) by woody vegetation. As mentioned before, mature woody vegetation can accumulate significantly more biomass (600 kg per cell) than perennial grasses (270 kg per cell). Thus, a lower number of mature woody vegetation cells can have a negative effect on the total green biomass considered. The effect of the parameter fodder demand on green biomass is likely explained by the fact that simply more biomass gets removed quicker from the palatable grass cells and woody vegetation cells (if browsing is enabled) leading to a generally lower amount of biomass in the system.

The stocking density is the parameter with the strongest (positive) effect on the **livestock condition**, which is as expected since less animals will have more fodder to share amongst them, as a lot of animals will. The effects of the other parameters also seem reasonable: Mean annual precipitation has a positive effect on biomass (fodder) growth. A more water independent animal (increased values of water dependency) can graze larger areas and focus on areas that are further away yet hold more fodder. Browsing allows the mixed-feeder a wider choice of fodder and the separation into browsers and grazers reduces the competition for fodder. A higher fire biomass threshold (necessary biomass on a cell that will allow a fire to start) will reduce the number of fires and thus save palatable biomass from burning so that it can be grazed by the livestock. No effect on the livestock condition was registered from the parameters camp grazing time, number of neighbours for spatial transition, and seed base probability. The fact that the camp grazing time has no effect might seem unreasonable at first, but during the simulations, it was mostly just a very short period in which the livestock condition decreased tremendously thus this again can be an effect of the non-equilibrium of abundance of vegetation types over the course of the simulations. The management decision of camp grazing time is difficult to parameterize as it depends, in reality, on many factors such as grass type, remaining biomass, expected rainfall, etc. and also, many different strategies are used by the farmer. Thus, it is beneficial that the grazing time does not affect the livestock condition strongly. The fact whether a rotational grazing system or open grazing is in place is, however, a very different story and was not tested during this sensitivity analysis, but strong evidence for a big influence were observed when comparing scenarios of the two different grazing systems (see chapter 4.9.5). Negative effects were registered from the following parameters: The fodder demand per LSU showed slight negative effects as expected because there will be less fodder available in total when all animals need more fodder to get saturated. The threshold of biomass for a transition from young to mature woody vegetation showed a negative effect as can be expected since it will take out the woody vegetation from competition with the perennial grasses thus reducing the chance of cells turning to palatable grasses again. The mortality of woody vegetation unexpectedly showed a negative effect on the livestock condition, which could again be due to temporal fluctuations over the course of the simulation extent since a negative connection between this parameter and the output seems implausible. Fire frequency shows a strong negative effect on livestock condition as fire reduces the available biomass on the veld and thus the amount of available fodder that is directly connected to the livestock condition.

4.10.2 Spatially homogeneous precipitation - interaction effects

The interaction effects of most tested parameters is high for almost all observed output values (Fig. 58). All parameters that influence the abundance of bare soil show σ/μ^* ratios ≥ 1 indicating non-linear and/or non-monotonic effects. The same applies to all parameters of the outputs annual grasses, young and mature woody vegetation, as well as mean and SD of dead and alive biomass and livestock condition. Only for the abundance of palatable and unpalatable grasses there are two parameters that do not have a σ/μ^* ratio ≥ 1. That is the fodder demand per LSU, which is still almost non-monotonic, and is surely interacting with e.g. stocking rate and will likely have a non-linear effect once grazing resources are exhausted and the regrowth of grass biomass gets more important. The other parameter that does not show high interaction effects has a σ/μ^* ratio > 0.5 and is the fact whether browsing occurs additionally to grazing thus representing a livestock mix or a herd of mixed-feeders. The monotonic effect of browsing can be explained by the simple fact that the model currently only has a switch to turn browsing on or off. It would be interesting to test browsing not as a Boolean on/off option but instead on a gradual scale from no browsing/pure grazing over mixed feeding to pure browsing/no grazing to actually see the behaviour and effect of different mixes of grazers and browsers.

The high number of parameters with interaction effects highlights the complexity of the savanna system and emphasizes that vegetation dynamics in the landscape are influenced to varying degrees by different, interacting factors depending on the initial condition, environmental conditions, management settings, and settings of other parameters.

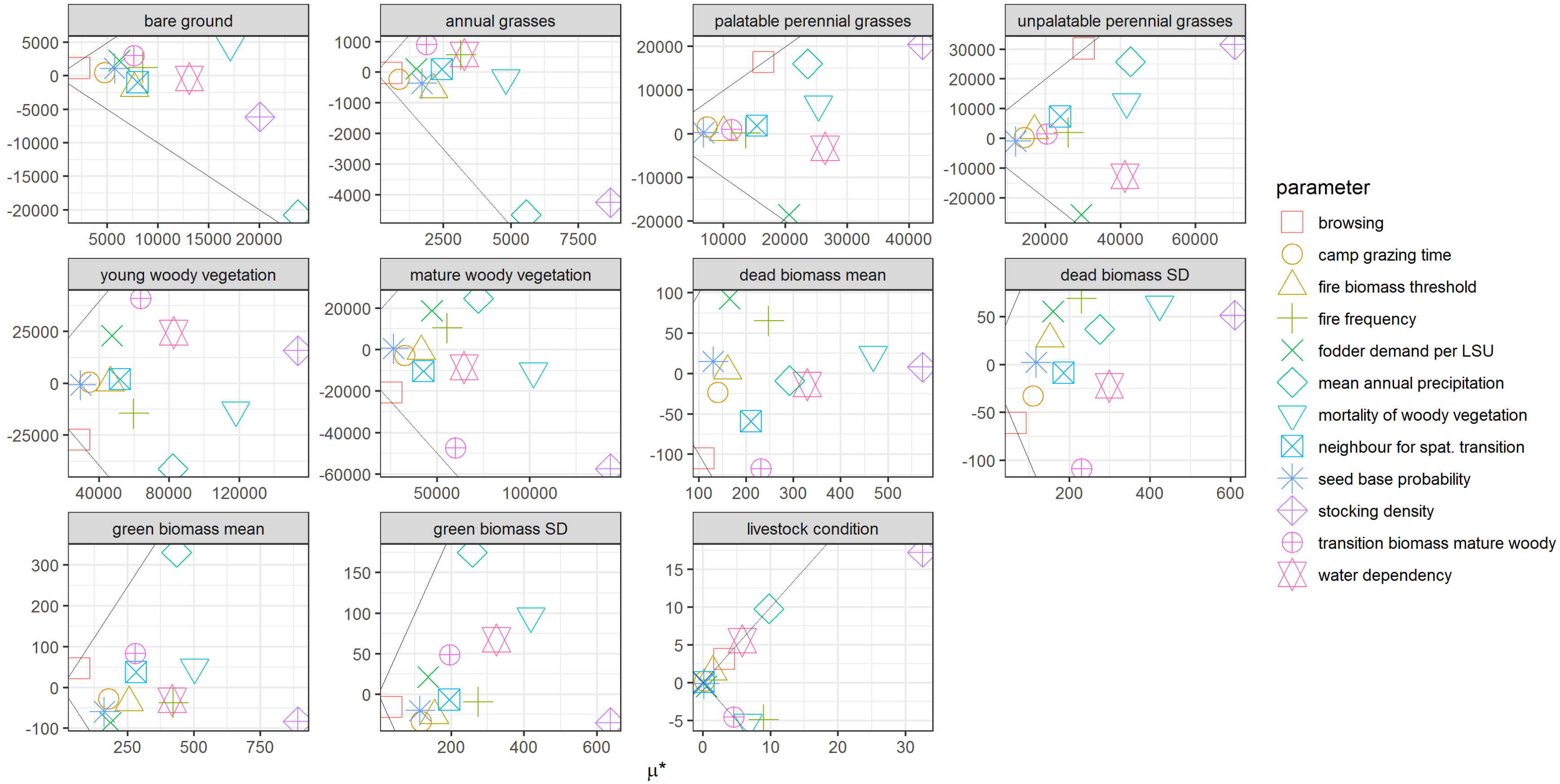


Fig. 57: Results of the sensitivity analysis for simulations with <u>spatially homogeneous precipitation</u> illustrating the absolute mean values (μ*) on the x-axis and real mean values (μ) on the y-axis of the elementary effects which show the magnitude and direction of the first-order effect of the twelve input parameters. Screening was done with 1300 parameter combinations and was performed for the 30th simulation year.

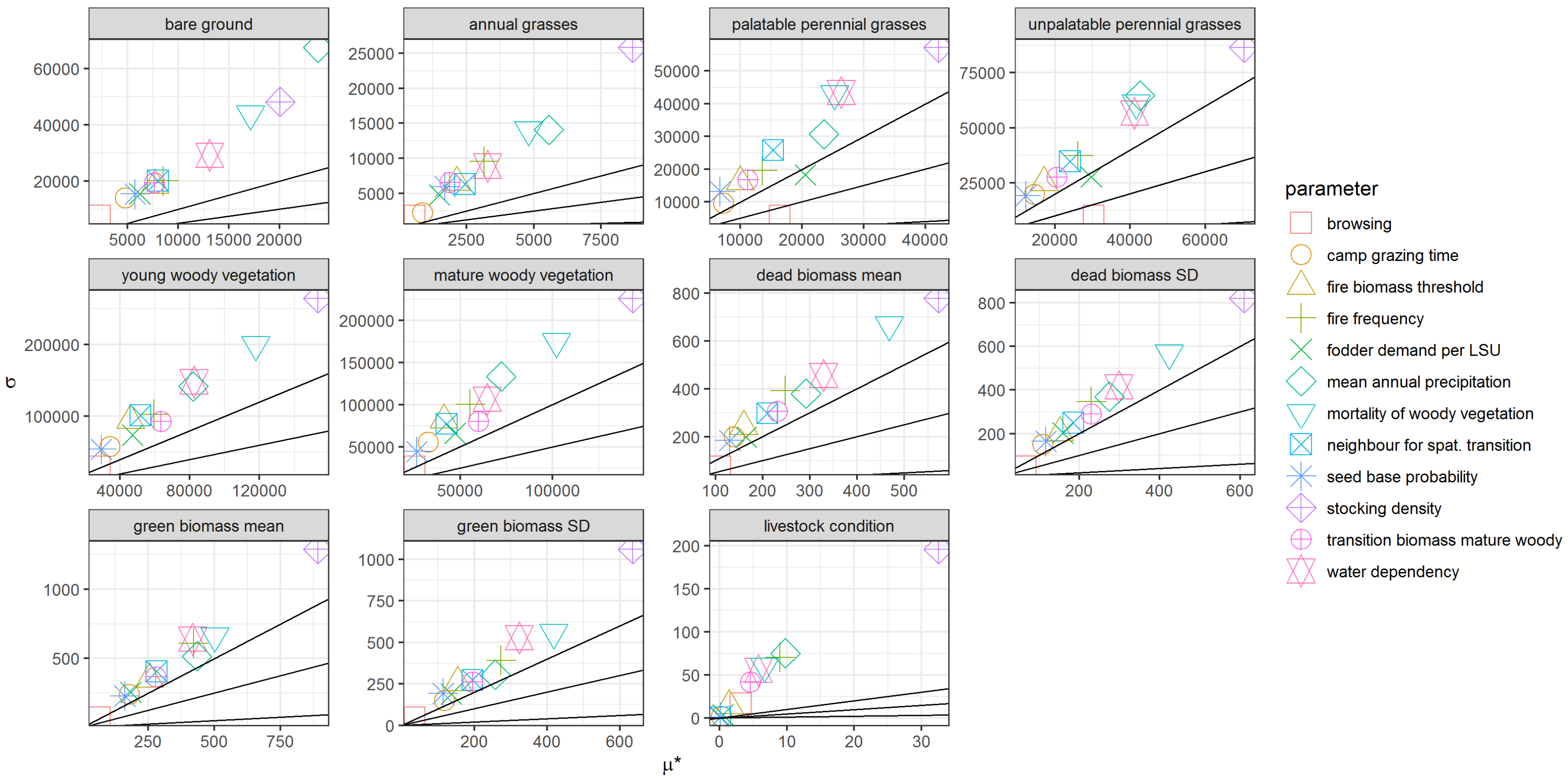


Fig. 58: Absolute mean values (μ*) on the x-axis and the standard deviation of the elementary effects (σ) for each parameter on the y-axis show the interaction of the input parameters i.e. the second-order effects for simulations with spatially homogeneous precipitation. The auxiliary lines show the ratios of σ/μ* = 1, 0.5, and 0.1.

4.10.3 Spatially heterogeneous precipitation - first-order effects

When running the Morris screening on a **heterogeneous precipitation** scenario, the effects of the input parameters was quite different (Fig. 59 and Fig. 60). With spatially heterogeneous precipitation, especially the fodder demand, stocking density and number of neighbours of the same vegetation type that lead to a conversion of the central cell played a major role. Especially the now higher importance of the latter was as expected because the spatial distribution of vegetation types over the landscape is very heterogeneous and thus events where the spatial transition rules lead to a change of vegetation types occur more often resulting in a stronger effect on the overall vegetation dynamics.

For **bare ground** and **annual grasses,** the most influential parameters were a <u>high fodder demand per LSU</u> (positive effects), <u>high stocking densities</u> (negative effects) and the parameter <u>browsing</u> (positive effects). An increase in fodder demand will lead to more grazing and thus to less biomass on perennial grass cells which can result in the degradation to bare ground. Bare ground can then quickly and easily be overgrown by annual grasses. The stocking density has exactly the opposite effect. More available hectare per LSU will lead to less grazing per area and thus to less stress on palatable perennial grasses and less conversion to bare ground. The positive effect of browsing on bare ground and annual grasses can be explained by the fact that now not only perennial grasses can be overgrazed leading to a degradation to bare soil, but also young woody vegetation biomass will be decreased by the livestock thus endangering in total more cells to degrade to bare soil. Two other parameters that had an impact on bare ground and annual grasses, which is on average almost neutral, were the <u>camp grazing time</u> and the number of <u>neighbours for spatial transition</u>. Depending on other parameters such as stocking density and fodder demand or other palatable grass biomass influencing parameters, the parameter camp grazing can have negative or positive effects. But likely the effect of a variation of grazing time spend on a camp is not as strong as the difference between an open grazing and a rotation system in general. For the direction of effect by the number of neighbours of the same vegetation type that are necessary for a spatial transition (see Tab. 9) it largely depends on the overall situation and patchiness on the camp, on patch sizes and fluctuations of vegetation type (see landscape maps Fig. 45; year 30 month 1 and year 30 month 2).

For the **perennial grasses,** the effect of <u>stocking density</u> and <u>fodder demand per LSU</u> were reversed. This is logical because less grazing (more hectare per LSU) will reduce stress on the grasses and not reduce the grass biomass as much, allowing the perennial grasses to compete again woody vegetation (spatial transition). In addition, if grass is overgrazed and dies, the bare soil will be randomly assigned either a perennial grass or woody vegetation which overall reduces perennial grass abundance over time if more perennial grass cells then woody vegetation cells die and get overgrown randomly. I would have expected that browsing has a positive effect on the perennial grasses for similar reasons, but the results of the Morris screening do not support this. Instead, they did not show any effect for added browsing functionality. This might be caused again by the one-year time period that is being analysed and the possibility that this parameter is simply not yet relevant under the conditions at that time.

The main parameters that influence the rel. abundance of **young woody vegetation** were as expected the transition biomass to mature woody and browsing. When the threshold for successional change is increased, the young woody vegetation cells will automatically stay longer in their state before becoming mature woody vegetation cells.

The same applies in reverse for the **mature woody vegetation**, which increases the earlier young woody vegetation cell reach the threshold. The other important influence parameter with a strong negative effect on young woody vegetation was browsing. This is because browsing effectively reduces the woody biomass. Young woody vegetation cells then succumb more quickly in competition with perennial grasses. Thus, overall browsing can reduce the relative number of young woody cells. Another parameter with a slightly negative effect on young woody vegetation was the number of neighbours required for spatial conversion. By increasing the number of necessary neighbours and thus making the conditions for overgrowth of other vegetation type cells more difficult, the spread and establishment potential of the young woody vegetation is reduced. In the case of mature woody vegetation, only the parameter browsing has an additional (negative) effect. This can be explained by the fact that this parameter has a particularly strong effect on young woody vegetation and thus only fewer cells become mature woody vegetation after a longer time.

The **mean and SD of the dead biomass** was strongly affected by the parameter browsing as well because when young woody cells get browsed their biomass will not or only after a longer time reach the threshold to become mature woody vegetation. Once this succession occurred the woody vegetation is save from browsing and can start to accumulate dead biomass. Additionally, this effect is increased because mature woody vegetation can store higher amounts of biomass (600 kg per cell) than e.g. perennial grasses (270 kg per cell).

The **mean and SD of the green biomass** were influenced very positively by the parameter browsing. One might expect at first that activating browsing would overall decrease the green biomass. This, however, is not the case as there are no browsers added but instead the existing livestock is replaced by a combination of grazers/browsers or by mixed feeders that have the same biomass demand. Thus, the browsing will take the unilateral pressure off palatable perennial grasses and lead to a more balanced ratio between the woody vegetation and the perennial grasses and also the biomass will be more balanced between these vegetation types. A higher biomass (which is interpreted as good vegetation condition) will likely result in less degradation of the woody vegetation or perennial grass cells to bare soil (compare chapter 4.8.6 Vegetation Transition and Tab. 9). On the landscape level, the lower occurrence of degradation will lead to less bare soil (no biomass) or annual (little biomass) but more perennial or woody cells (both more biomass), so overall to an increase of green biomass. Another very strong negative parameter for the mean and SD of green biomass was the threshold of transition biomass. As mentioned before, a delay of the succession of young woody to mature woody vegetation also means a delay in storage capacity for biomass.

The **livestock condition** was most strongly (negatively) effected by the fodder demand per LSU. When the biomass demand increases and the biomass resources are limited, it is only a natural consequence that livestock condition will decrease. Stocking density, however, had the opposite effect. When the number of hectare per LSU is increased, the grazing pressure decreases so that more biomass per LSU becomes available. Water dependency and grazing time had small and slightly positive effects on the livestock condition. As mentioned before, when the livestock is less dependent on water, (increased values of water dependency) it can graze larger areas and focus on areas that are further away and may still have higher biomass resources. The camp grazing time on the other hand allows grasses on the rested camps to regrow, thus the longer livestock grazes on a camp, the more time do other camps have to regrow their grass. If the livestock is then moved to a new camp, the initial round of grazing will be more beneficial for the livestock condition because more grass biomass regrew on that camp. This effect however, has to be viewed with caution as it is based on the assumption that the livestock can still survive at lowest livestock conditions. In reality most likely the livestock would die.

Overall, there are less parameters in the heterogeneous precipitation scenarios that show a strong influence on the vegetation abundance, biomass and livestock dynamics compared to simulations with a spatially homogeneous precipitation. This can be explained by the temporal vegetation dynamics of the simulations with spatially heterogeneous precipitation that is in year 30 at a state where e.g. seeds are still widely available (seed base probability) or where the biomass of flammable vegetation types are high enough to reach realistic fire biomass thresholds that could have a big impact on the vegetation. These parameters do not yet play a crucial role but could become relevant when looking at larger time frames.

4.10.4 Spatially heterogeneous precipitation - interaction effects

All of the before mentioned parameters that had strong effects on the observed output also showed interaction effects (Fig. 60). For the output of **bare ground**, **annual grasses**, and the

perennial grasses, the fodder demand per LSU, stocking density, camp grazing time, number of neighbours for spatial transition, and the water dependency showed in most cases a σ/μ* ratio ≥ 1 indicating large interaction effects and/or a non-linear behaviour.

For the **mean and SD of green and dead biomass,** additionally the biomass threshold for transition from young to mature woody showed large interaction effect. This is as expected because when cells can sooner become mature woody vegetation cells they can accumulate a lot more biomass.

For both the relative abundance of both **young and mature woody vegetation**, especially the transition biomass to mature woody showed very high impacts and the biggest interaction effects. For the **young woody vegetation**, the parameter browsing showed a very high monotonic effect (σ/μ* ratio < 0.5) but as mentioned before the implementation of a gradual mix of grazers and browsers may lead to a more detailed insight into the behaviour of this interesting management option. The effect of browsing on the relative abundance of **mature woody vegetation** was characterized by high interaction effects.

For the **livestock condition**, the fire frequency, stocking density, number of neighbours for spatial transition, the water dependency as well as the camp grazing time showed strong non-linear, non-monotonic effects. This seems reasonable as fire frequency is the chance for a fire to start but it depends on many other factors as well if the fire will become very strong to spread and potentially kill the vegetation around it. The other interactions are all logical as well, because the stocking density, water dependency, and camp grazing time will interactively affect the tempo-spatial distribution of livestock on the farm and thus the pattern and amount of available biomass that is needed to sustain a good livestock condition. The number of neighbours for spatial transition, however, does not affect the livestock distribution directly but again influences in combination with other factors, the spatial distribution of vegetation types.

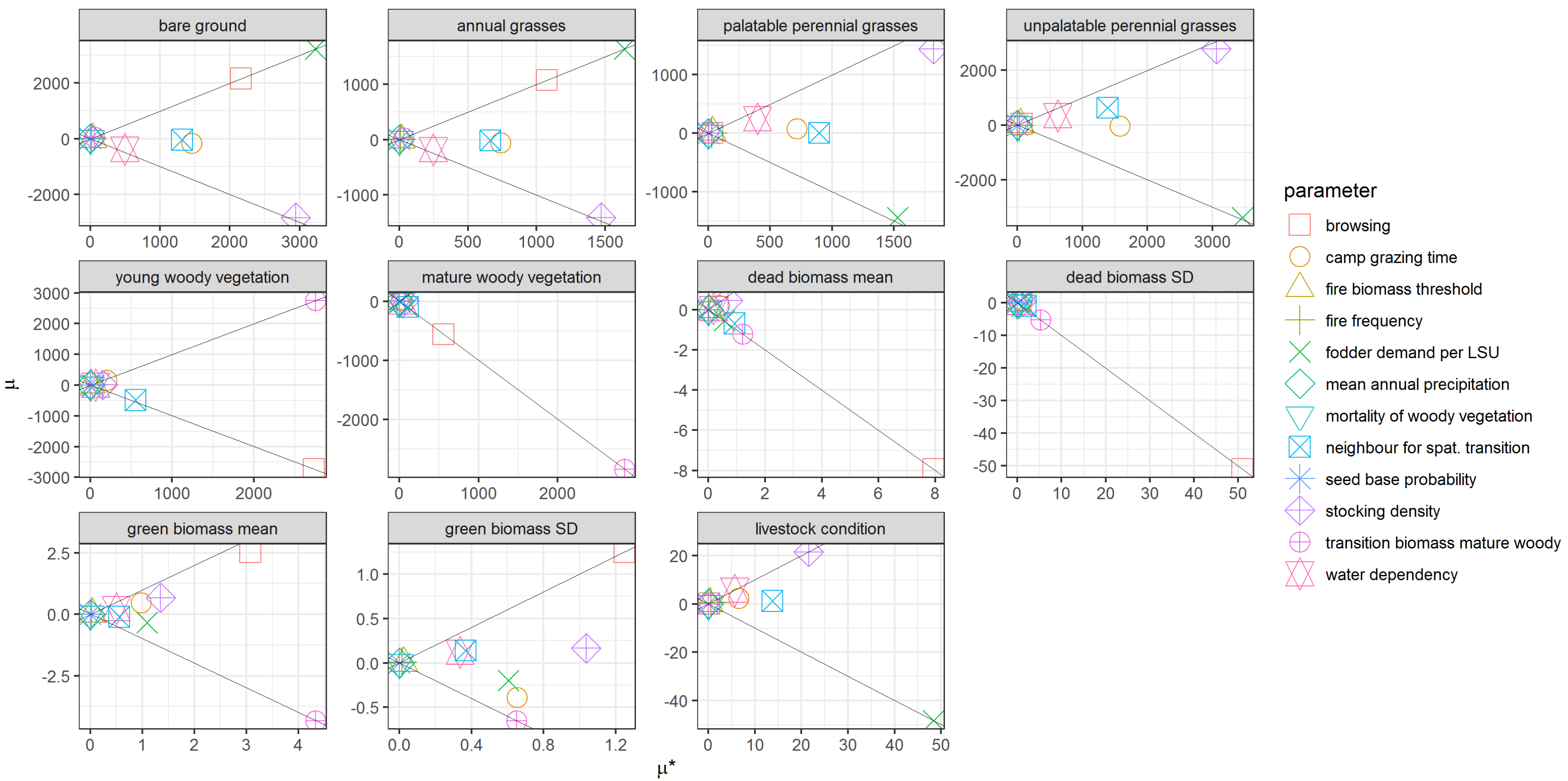


Fig. 59: Results of the Morris screening for simulations with <u>spatially heterogeneous precipitation</u> testing the effects and interactions in year 30 for simulations with heterogeneous precipitation patterns. The absolute mean values (μ*) on the x-axis and real mean values (μ) on the y-axis of the elementary effects show the magnitude and direction of the first-order effect of the twelve input parameters.

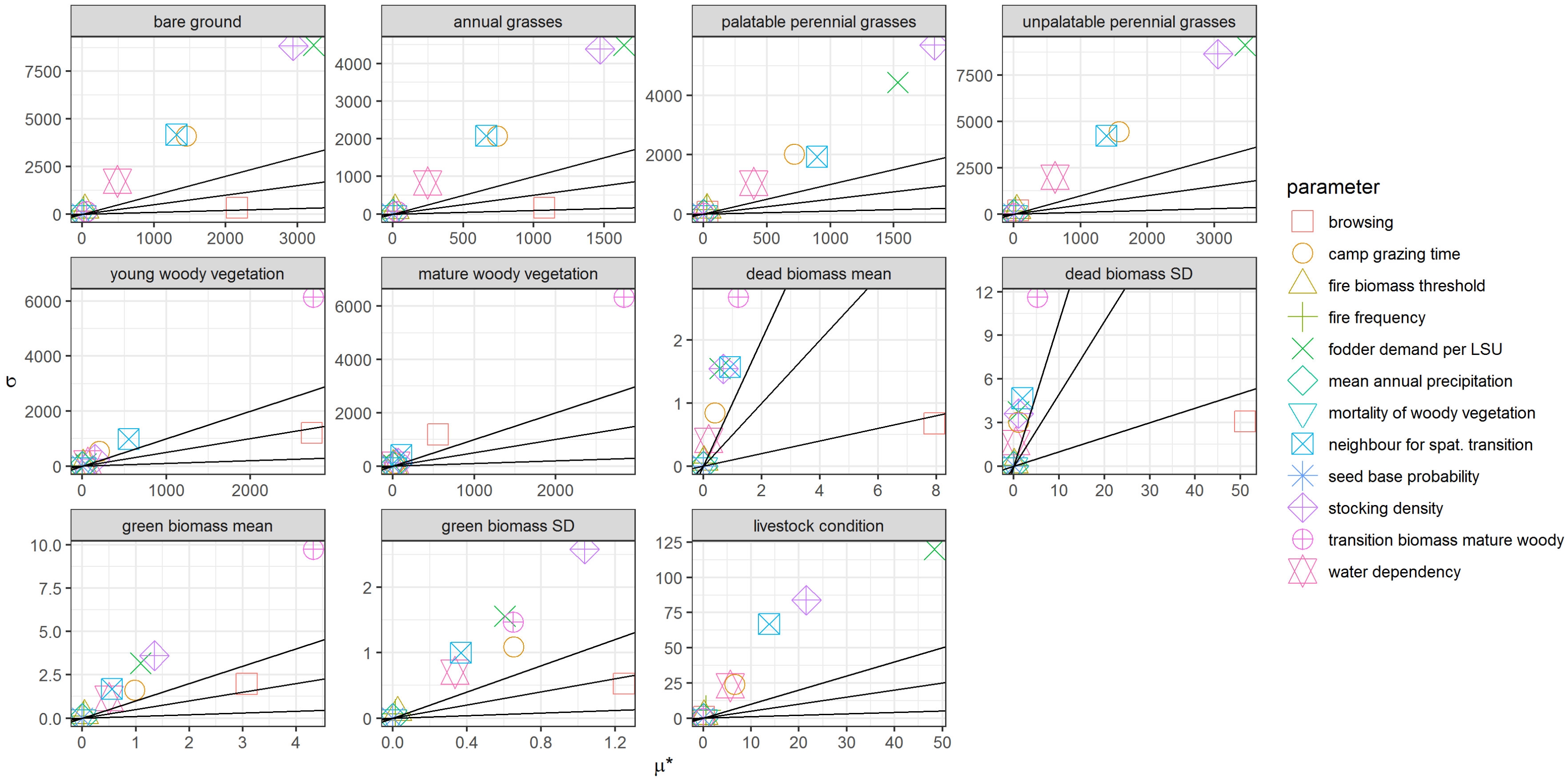


Fig. 60: Absolute mean values (μ*) on the x-axis and the standard deviation of the elementary effects (σ) for each parameter on the y-axis show the interaction of the input parameters i.e. the second-order effects for simulations with <u>spatially heterogeneous precipitation.</u> The auxiliary lines show the ratios of σ/μ = 1, 0.5, and 0.1.

4.11 Limitations and future extensions

To improve the model even further, optimize its predictability and make it more realistic some functions and processes could be improved and additional functionality could be added. In the following, I will describe some extensions for the model that could be of benefit for future model versions.

Climate change

The global climate change also affects flora and fauna in savannas and will likely have an increasing impact on savanna dynamics in the future (Lohmann et al. 2012; Hoffman et al. 2019; IPCC 2021). This is why it may be beneficial to model climate change in greater detail in the Midessa rangeland model the see the effect on the complex vegetation dynamics. Currently all aspects of climate change climate change can be simulated in Midessa either directly by adapting temperature and rainfall parameters or indirectly by e.g. adapting production parameters as response to CO_2 increase. Other approaches to integrate climate change and its effect on the vegetation dynamics focus in greater detail or with a different implementation of processes and factors that are influenced by climate change. Some focus on **seasonality** (Howden et al. 1999; Gao and Reynolds 2003; Shafran-Nathan et al. 2013) and i**ntra-annual variations** (Gao and Reynolds 2003; Tietjen et al. 2009, 2010; Lohmann et al. 2012; Shafran-Nathan et al. 2013) and many also on changed **CO2 levels** (Parton et al. 1995; Howden et al. 1999; Bond et al. 2003; Gao and Reynolds 2003; Christensen et al. 2004; Scheiter and Higgins 2009; Tietjen et al. 2010; Lohmann et al. 2012; Moncrieff et al. 2016) and **temperature** (Parton et al. 1995; Christensen et al. 2004; Tietjen et al. 2009, 2010; Lohmann et al. 2012; Shafran-Nathan et al. 2013) as well as **inter-annual variation** (Howden et al. 1999; Williams and Albertson 2006; Tews et al. 2006; Lohmann et al. 2012; Shafran-Nathan et al. 2013; Jakoby et al. 2014; Martin et al. 2014; Golodets et al. 2015)**.** All of the before mentioned approaches except the one by Bond et al. (2003) include changes in **MAP** as the most important factor for vegetation dynamics (Köchy et al. 2008). These are promising approaches that would be interesting to also explore with Midessa.

Improved Arboricide application

Currently the application of arboricides is simply implemented by reducing the amount of woody vegetation in a camp. Being one of the major management options to fight bush encroachment (Smit et al. 1999; Harmse et al. 2016) with the quickest response on the vegetation dynamics in the savanna system, a greater detail and more management options would be a benefit for the model. To make the model more realistic and adjustable it would be interesting to include the differentiation between manual- and airplane application as well as the need for a second treatment followed by a long period of inability for woody species to grow on the treated camp.

This can be especially helpful when looking at the economic sustainability of the rangeland management system and for farmers who have to do a cost/benefit/risk analysis for the high-cost arboricide treatments to see if it's worth the investment (Lukomska et al. 2014). With monetary investment, drastic changes can be made to alter the species composition in favour of the grass society.

Atmospheric CO_2 levels

The difference in the chemical photosynthetic processes between C3 and C4 plants might be another competition factor (Diaz and Cabido 1997; Ward 2005; Kgope et al. 2009). With climate change an increase of atmospheric CO_2 is predicted (IPCC 2021). Trees and shrubs in savannas mainly use the C3 carbon fixation as metabolic pathway for photosynthesis, while grasses are usually associated with the C4 group. With increasing CO_2 levels, the photosynthesis can be done with a better water-use-efficiency by C4 plants compared to C3 plants (Morgan et al. 2004; Conradi 2018). In the model this could be implemented by introducing a CO_2 variable that directly influences biomass production, e.g. similar to the seasonal temperature implementation (see chapter 4.8.3 Temperature). It should be possible to allow CO_2 levels to increase at different rates during the simulation period.

Soil depth and type

The soil submodel is implemented in a very basic way in the rangeland model. To make the model more adaptable to different countries and to a great variety of sites it would be helpful to specify different soils and the according parametrization that the user can chose from. It would also be interesting to introduce different soil depth and model different soil horizons separately. Ground water in deep soils is not accessible by grasses and can give an extra advantage to deep-rooting trees/shrubs. In shallow soils, this advantage for the woody vegetation does not exist and there is a strong competition in the upper, shallow soil layer. The addition of soil depth and expansion of the soil type in the model could provide further insight to the effects of varying soil depths on the possible depth of root penetration and water balance as well as on the resulting competitive (dis-) advantages between woody vegetation and grasses. A first step could be to introduce a soil texture map like in the PioLaG landscape generator to automatically define the clay content based on location/GPS coordinates or giving the option to make it directly user defined

Seed production

In order to take the effects of drought periods and high rainfall years more strongly into account, an adjusted **seed production** for woody vegetation based on precipitation or soil moisture could be implemented (see e.g. Milton 1995).

Erosion

In sandy dune areas with little vegetation cover and in sloped areas (even with hard top soils, see gully erosion in 1.1 *Soil properties*) erosion can occur. For these areas, it would be interesting to extent the model by introducing wind speed and -direction to simulate wind erosion as well as slope for water driven erosion both in combination with a biomass threshold representing the lack of vegetation cover.

Fire intensity and spread patterns

As **fire** is an important factor that has the potential to counteract bush encroachment (Scholes and Archer 1997) it would be a great asset for the model to simulate fire and its effect on vegetation and bush encroachment dynamics in greater detail and more realistically. This can be quite easily done by replacing the basic fire submodel in Midessa with the sophisticated Savanna Fire Model (SaFiM) developed by Limberger (2018; Limberger et al. 2020). This has the benefits that wind direction and intensity are considered as well as rel. humidity, slope, and air temperature. This leads to a more detailed prediction of fire spread patterns and the effects on the vegetation. Another interesting addition, especially for more humid savannas, could be the management options of creating firebreaks and doing prescribed burnings.

Browsing

When *animal.browse* is set to true i.e. browsing is added, actually all cells disregarding of vegetation type are browsed/grazed. This means that the livestock on the veld is a mixed feeder or a combination of grazers and browsers. It would be interesting to actually give a percentage of browser/grazer mix to be able to test different scenarios with adding browsers such as goats to cattle or combining different game to see what affect it has on e.g. bush encroachment.

4.12 Overall discussion of simulation results

The aim of developing Midessa was to create a rangeland model with the purpose of recreating and understanding the processes and interactions that are important for vegetation dynamics in southern African savannas, as well as the disturbances and factors that lead to bush encroachment. The model concept, default parameter settings and management options were discussed with farmers and researchers early on during the development of the model to ensure that the farmers' requirements and concerns were implemented correctly. By this, we ensured that theoretical-scientific aspects as well as practically oriented factors and options were taken into account.

The results of the default parametrization show temporal and spatial vegetation dynamic trends as expected from farmer interviews and discussion with rangeland experts for a not sustainably managed farm that is experiencing bush encroachment. However, the abundance of woody vegetation in the model is sometimes even exceeding values that were measured in reality for similar mean annual precipitation values. This is likely due to the spatial resolution of the model in combination with the approach that there is always only one dominant vegetation type per cell and the other non-dominant vegetation types on that cell are neglected and do not appear in the total relative abundance of vegetation types in the overall landscape statistics. Being able to use artificial, yet realistic input maps from the piosphere landscape generator PioLaG, avoids a long initial settling phase at the beginning of the simulations. Management options that influenced bush encroachment and vegetation dynamics the most during the simulations were (1) the application of arboricides, (2) the selection of a livestock (or game) mix of grazers and browsers, or mixed-feeders, and (3) a decrease of the stocking rate. The model shows clear thresholds for an abrupt decline of livestock condition. These thresholds are lower for simulations with spatially heterogeneous precipitation than for those with spatially homogeneous precipitation. Simulations with a higher mean annual precipitation reached the threshold for the decline of livestock condition later than scenarios with less precipitation. When it comes to the stocking rate the threshold for the abrupt decline of livestock condition is reached sooner, the more livestock is present on the farm. All these cause-and-effect relationships are reasonable and consistent with the information gained during the farmer interviews. However the model could be further improved by extending some functions and introducing new factors to the model as well as by improving the knowledge about realistic parameter ranges e.g. by field experiments or time-series analysis of remote sensing data.

To conclude, the Midessa rangeland model is working as expected. Midessa is a spatially-explicit, process-oriented rangeland model and thus easy to adapt and rescale to different systems and areas with different species. The option to use the model with idealized landscapes but also with classified real landscape input for theoretical and applied exploration of savanna dynamics makes Midessa a universally applicable research and decision support tool. The model is user-friendly and easy to parameterize via the parameter file. Midessa depicts the important factors and processes determining the vegetation dynamics in southern African savannas. All cause-and-effect relationships are reasonable and consistent with information obtained from the farmer interviews and literature. Thus, it is a useful tool to understand savanna dynamics and to explore the impact of different management options and environmental factors on vegetation dynamics. Our model helps to find sustainable management strategies, which are important to ensure livelihood of farmers and food supply.

5 Concluding discussion and outlook

This thesis aimed to identify the processes and factors that are potentially most influential for vegetation dynamics in South African savannas. Additionally, the aim was to improve the understanding of savanna vegetation dynamics with the help of modelling and to recognize those processes and factors that need to be further explored, e.g. by field-based research, and modelled in greater detail to further improve modelling and, ultimately, management of savanna rangelands. This was done by interviewing farmers, scientists and other stakeholders in South Africa and then using this information to create and adapt two simulation models that aid to identify the most important processes for vegetation dynamics and their trends. The first model developed was the Piosphere Landscape Generator (PioLaG). PioLaG can create realistic, user-defined, site-specific input landscape maps with information on vegetation distribution and farm infrastructure. The second model was the rule- and grid-based, spatially explicit, process-oriented rangeland model Midessa, which was based on the Molopo simulation model. Midessa allows using simple or complex landscapes as input data to run complex rangeland simulations considering many interacting spatio-temporal processes and factors and their effect on the vegetation dynamics of savannas for short and long time periods.

5.1 Key environmental and management factors of vegetation dynamics in southern African savannas as identified by farmer interviews

The farmer interviews, participatory observations, and discussions with scientists proved to be very helpful to gain an understanding of the common practices of South African farmers in livestock and pasture management as well as to get insider information from different systems and management approaches. This information allowed us to concentrate on the potentially most important features and processes to create a successful rangeland simulation model. We could find out which factors are considered most important for management decisions, which details farmers pay particular attention to, how they respond to the various changes and extremes in the system, how they deal with uncertainties and risks that are present in a rangeland system, and which setscrews of rangeland management the farmers typically use. Their main goal was either to maximize economic revenues, to improve and sustain veld quality, or to ensure sustainable livelihoods, or a combination of these interests. Factors that the farmers considered important for vegetation dynamics and often mentioned during interviews were the type of grazing system (rotational/open grazing), the application of arboricide and other measures to fight bush encroachment, the setting of the stocking rate with respect to the carrying capacity of the farm, and the various backup plans for droughts. In some cases, opinions and management approaches differed greatly. Therefore, in order to allow adaptation in the model, most parameters are read from the adaptable parameter file instead of defining them in the program code. This way, maximum adaptation possibilities for the different regions and management approaches are given. During the farmer interviews, it was pointed out that as soon as money is available, many farmers use this to buy and apply arboricides. This effectively combats bush encroachment on the fields and should be reflected in the model. The farmers emphasized that the type of grazing system is very important and that rotation systems are very diverse in their spatial as well as temporal setup. In addition, the type of livestock/game kept on the farm and the adaption strategies for drought years differed quite substantially between the farmers. Most of the wishes of the farmers could be implemented, especially in the creation of the landscape generator, which was designed to be easy to use and to load data in the background based on GPS coordinates automatically. The Midessa rangeland model has also been supplemented and optimized to meet the wishes of the farmers, e.g. by giving the option of arboricide application.

5.2 Crucial features, processes, and data for modelling southern African savanna vegetation dynamics

The piosphere landscape generator PioLaG was developed in order to have a simple representation of the savanna system and to project the effects of the individual model factors on the vegetation dynamics and the landscape patterns. Its output landscapes are an important data input for sophisticated grazing models, as they can thus start under realistic initial conditions and require no or only a very short settling phase. The resulting piosphere patterns are also an indicator of pasture condition and can give indications of overuse, and poorly adjusted management options. Thus, already by itself PioLaG aids in understanding the cause-and-effect relationship of different environmental and management factors and their impact on the trends of vegetation dynamics. PioLaG allows for testing different management scenarios and settings in a fast and simple way without the need for complex parametrization and time intensive temporal development dynamics.

The farmer interviews and workshops with scientists underlined that to better understand and realistically represent the effects of different environmental conditions and options for actions and management on vegetation dynamics, a sophisticated pasture simulation model geared towards farmer decisions is beneficial. The creation of the Midessa rangeland model aims at mapping (1) the processes that are important for vegetation dynamics in savannas and also (2) the disturbances and factors that lead to bush encroachment and thus allows exploring different parameter combinations, especially management options. Through this approach, the rangeland model can contribute as an important decision support tool to ensure the livelihood of farmers and to feed people sustainably in the long term. The Molopo simulation model of Hanß (2013) for the Molopo region was updated, improved and extended, resulting in the rule- and grid-based spatially explicit Midessa rangeland model. The model was completely rewritten and overall enhanced to improve clarity, workflow and runtime. Updates such as adapted seasonality parameters, improvements such as the sequence and timing of temporal transition rules and extensions such as the arboricide submodel led to an improvement of the model making it more realistic and user-friendly. The final model is user-friendly and the individual processes react realistically to changes in the parameterization so that the effects of different management options as well as changing environmental conditions could be tested. While under current default settings, a clear trend to bush encroachment is visible as it is on many farms in southern Africa, the model would benefit from more data gained through field experiments, especially focusing on succession and competition parameters of the different vegetation types.

The simulations with the Midessa model showed that using a heterogeneous precipitation pattern has a major impact on simulation results. Heterogeneous precipitation led to a more realistic clustering of vegetation types, an overall more heterogeneous distribution of vegetation types as well as a slower development of bush encroachment. These results indicate that this approach should be investigated and possibly adapted further in terms of realistic cloud sizes and heterogeneity of cloud sizes over the simulated landscape. The Midessa results further showed that also browsing and the application of arboricides have a major impact on the vegetation dynamics and especially on the advancement of bush encroachment. Browsing on a farm is often connected to uncertainties because some farmers were not sure how many and what type of wild game was on their farm thus affecting the vegetation dynamics either favouring (grazers) or slowing down (browsers) bush encroachment. Browsers are already commonly found on some farms in the form of goats or on wild game farms; however, they could be used more actively and in a more targeted manner to counteract bush encroachment. Introducing and testing different ratios of a grazer/browser mix on the simulated farms seems to be a promising approach for a non-chemical management tool against bush encroachment. The chemical treatment with arboricides against bush encroachment is one of the most commonly applied management options if necessary funding is available. This anti-bush agent is ideal because it can be applied in a very targeted manner in terms of time and space and usually achieves a high effect in killing woody vegetation. It can also be applied in different forms and thus be adapted to the respective situation on the camp. Furthermore, different products with different active ingredients and properties are available. The model results showed the strong effect of arboricides and different application thresholds can already be tested with the model. An extension of these application options, especially in the context of environmental parameters (rainfall patterns after application influencing efficacy and temporal dynamics) and temporal application decisions (repeated treatments for a reliable and long-lasting destruction of woody vegetation) could be of great interest especially for practically oriented farmers. Fire can play an important role in areas with higher precipitation and thus higher available amounts of biomass as fuel. If fire is suppressed by management or overgrazing, the natural system dynamics are fundamentally disturbed and counter-measures should be put in place to ensure long-term economically and ecologically sustainable livestock farming. The use of several camps and a rotation grazing system instead of an open grazing system has a strong decreasing effect on bush encroachment, as it is closer to a more natural grazing regime with a low stocking rate but high local grazing pressure. Results of Morris's elementary effects screening emphasize the effect of higher mean annual precipitation, and higher livestock numbers on the vegetation dynamic as catalyst of bush encroachment. While more hectares per LSU, the introduction of browsers, higher precipitation and a higher woody mortality favour the beneficial perennial grasses in the simulations. As can be seen from the Morris screening of elementary effects, interaction effects between input parameters are pervasive in the model. This makes it difficult to examine and parameterize the individual processes separately. For example, the temporal vegetation succession is highly sensitive and it is difficult to observe and quantify this (e.g. temporal transition probabilities between vegetation types) precisely in nature and therefore also difficult to implement it exactly in the model.

5.3 General conclusions

The developed rangeland model Midessa helps to further deepen knowledge about savanna dynamics and processes. Various simulation scenarios with different environmental conditions and management actions were run and key processes and influential factors for the vegetation dynamics of South African savannas identified. The scenarios showed that arboricide application, browsing, and the type of grazing system are the most influential farm management factors for changing long-time vegetation patterns. The implementation of precipitation and its coupled processes within the model had major environmental effects on the vegetation dynamics. A site-specific landscape input map with detailed information of all necessary influential factors for the vegetation dynamic proved to be beneficial for working with rangeland models. If patterns occur in reality that cannot be explained with the simulated processes, other factors that were not considered might be the cause. Thus, it should be kept in mind that it can be better to use idealized landscapes to make a general prediction instead of simulating complex landscapes and situations that cannot fully be covered by the model, so that results might deviate from reality. The PioLaG landscape generator is ideal to create these idealized yet realistic landscapes. The results from this thesis showed the complexity of vegetation dynamics in southern African savannas as well as the challenges to implement realistic behaviour, and point to further avenues for advancing savanna-modelling research. Model complexity could always be increased to replicate certain processes even more realistically and in greater detail. However, this can quickly become too complex and can exceed the available computing capacity, and it also can introduce unnecessary sources of error into the model. A simplified approach is consequently often better. Therefore, a model should be as simple as possible and only as complex as absolutely necessary. Despite the complexity of savanna ecosystems, this dissertation has shown that the interactions between environmental factors and management decisions as well as the resulting effects on the vegetation dynamics of southern African savannas can be recreated and better understood with a rangeland simulation model.

5.4 Outlook

Knowledge about savannas is constantly evolving and all interrelationships are not yet fully understood. It is important to investigate the underlying processes further in order to assess the impact of our actions and to reduce negative effects on the environment. For this purpose, models are of great importance because they allow us to break down complex systems into small units and to look at and test them individually. This enables us to examine and better understand the various effects in the overall structure of the influencing factors.

Midessa was implemented in a way that makes it easy to (a) adapt the model to improve its performance with regard to special research questions in southern African savannas, but also to (b) extend the model to different new scenarios and locations. The same goes for PioLaG, which can also easily be adapted and parameterized to produce a wide range of different landscapes that will serve as input data for Midessa and thus reduces the problem of data limitations and parameter unavailability. In section 4.11 *Limitations and future extensions*, I presented a set of adaptations and extensions that could greatly benefit the model and would be interesting to model in future studies. Additionally, more data on vegetation succession and probabilities in vegetation dynamics, gained e.g. through field experiments would be an asset to the model.

The problem of bush encroachment will be an ongoing challenge and it will require more work in the future to fully understand its dynamics and find natural, sustainable counteractive management measures. The effects of climate change especially changes in precipitation patterns may exacerbate the advance of bush-encroachment in future decades. Thus, there is a strong need for the farmers to find reliable and cost-effective alternatives to fight bush encroachment through adapted management. PioLaG and Midessa serve as useful tools to lay the groundwork for finding solutions now and for future generations to come.

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Supplementary material

A Supplementary material for chapter 2

Results from scientists' workshop and questionnaire

Questionnaire part 1 - landscape generator & user inputs:

Questions were discussed in three groups and all answers were collected below. Names were anonymized.

1. **Are the vegetation-type compositions different depending on veld quality AND on location? How can we best distinguish between the regions? Is it sufficient to concentrate on precipitation or do we need to consider also topography and soil parameters?**

Yes, precipitation, soil type, vegetation type, topography
Consider all parameters and maybe more e.g. land-use, climate (precipitation, temperature), soil, topography

2. **What is the relative abundance of plant functional types in an <u>arid savanna (e.g.: Mier)</u>:**

Depends on animal composition; categories across savannas problematic, Stick to PFGs
The values will differ depending whether you are on a game farm or on a cattle farm

	Bare soil	Annual grasses	Unpalatable perennial grasses	Palatable perennial grasses	Young woodys	Woodys
Climax Veld	20	10	45	15	10 (together)	
Subclimax Veld	25					
Disturbed Veld	10	80	1	1	80	

What is the relative abundance of plant functional types in a <u>semi-arid savanna (e.g.: North-West)</u>:

	Bare soil	Annual grasses	Unpalatable perennial grasses	Palatable perennial grasses	Young woodys	Woodys
Climax Veld	3	10	20	10		85
Subclimax Veld						
Disturbed Veld	30	8	1	1		60

What is the relative abundance of plant functional types in a <u>mesic savanna (e.g.: KwaZulu - Natal)</u>:

	Bare soil	Annual grasses	Unpalatable perennial grasses	Palatable perennial grasses	Young woodys	Woodys
Climax Veld	0	3	30	40	7	20
Subclimax Veld	5	10	40	20	10	15
Disturbed Veld	15	15	40	5	15	10

Rather choose the categories: Good, moderate, poor veld
Or maybe "early successional" and "late successional" species

3. **Is it okay to select the desired simulation area with GPS coordinates or is there a better way?**

Yes, GPS coordinates are sufficient
Yes

4. Is the variable "animal condition" important: Is it just an informative output about livestock health or do they also eat less when their condition is bad?

Yes, animals eat less when in poorer condition.
Animal condition is important and is a symptom of veld degradation

5. What is important user input?

We have so far: Farm size and location, number of camps and waterholes, stocking density and animal type, vegetation composition, number of bush encroached camps, simulation time, and rotational system

Woody plant density in three classes: Not encroached (below 1000TE pro hectare); Moderate (1500 TE / ha); Severely (more than 2000 TE pro ha)
Change "rotational system" to "grazing system"; add "historical use of farm"
A wild game farm is a continuous grazing system. --> So rather talk about a grazing system than about rotational grazing

Vegetation structure (because we only distinguish between young wood any woody, it would be good a sort of average height), fire history (important), management history (important), age of grasses (unused grasses die relative quickly), distribution of small woodys vs. few large woodys

6. Which are the most common rotational systems in the three different regions? Please specify! How many camps, camp size, grazing time, resting time, percentage of grass eaten before moved to next camp, etc.…

Arid: 6 camps, 200ha camp size, 50 % of biomass removed, 2 weeks (more or less)
Semi-arid: 6 camps, 150-200ha camp size, 50 % of biomass removed, 2 weeks
Hard to say; get information from local extension officers; think about whether you want to include systems with holistic range management
Grazing system Mier and Northwest province: fewer camps and bigger
KwaZulu-Natal: more camps and smaller

7. How do farmers decide how many camps to set in a grazing system?

Animal management requirements; funding; higher production = smaller camps
Ask farmers
Depends on existing infrastructure and costs

8. What are the most common forms of camp arrangement? Are the two farm layouts that we have okay like that or do we need something else? Is the pie layout so uncommon that we can maybe even leave it out?

Fine as it is.
Four camp system on average; leave out pie system
The more complex the environment, the fencing will be according to the landscape units

9. Is it common to have more than one waterhole in a single camp?

Not common
No, one waterhole per camp
Number of watering points is not an issue in KwaZulu Natal; but it is in more arid systems; and it can differ also on the same properties
--> When you have two waterholes per camp, the utilization of the camp is better, but you hardly see it anywhere

10. Are there different camp sizes for different seasons? And are there maybe backup camps for a drought period?

No, already implemented into grazing system
No, no backup for drought

Yes, always, but depending on grazing system and area

11. Is the vegetation composition different under sustainable rotational grazing compared to under sustainable continuous grazing: which one has more advantages?

Yes, sustainable grazing management
Yes, rotational grazing better
Stocking density is more important than rotational vs non-rotational (Regan + Turner 1992)

12. Does it make sense/will there be a difference in modelling 4- vs. 8-camp systems?

8 camps will be more desirable than four camps
No, 8 camps system uncommon
Own model derivation of biomass much more reliable; everyone has their own model
If you are looking at the biomass, you should base it on literature values, but on the data delivered by e.g. *anonymized*, because they will show much more reliable data about whether 4 and 8 camps systems are really different

- ➔ There is a big difference between the using types of the land, e.g. cattle vs wild game. In the northwest there are huge areas under game farm
- ➔ Cattle systems nowadays will have more 4 camp systems than 8 camp systems.
- ➔ The time of rest for the camps that are not grazed is the most important. In *anonymized* areas, most people use a 6 camp system, so that the camps have a little bit more time to rest

13. Is the grazing capacity map from 1993 still valid and can it be used or is there better data available?

2016 grazing map
Not 1993, use latest published maps; ask *anonymized* for newest map
1993 is the only one available

14. What would be a good source with high resolution for soil layer depth?

Agricultural Research council
No soil depth maps?
For Northern Cape, ask *anonymized*

15. How big are the woody clusters in the bush-encroached areas and should they be equally distributed?

More evenly distributed
In arid areas more evenly distributed; high rainfall areas: bush clumps more common
Less in KZN; topography plays a role; recruitment bottlenecks

16. Is it always "the more camps the better for plant recovery", or is there a threshold where an increase in number of camps no longer makes a difference?

Generally more camps = more time for veld recovery = resulting in better veld condition; a threshold will exist where it doesn’t have an effect anymore
There is a threshold with no more benefit with more camps
In the end it does not really matter whether there are 6 or 8 camps, important is the grazing frequency, if I always send the cattle quickly to a new camp, the camps will have enough time to rest

17. In the landscape generator, the piosphere pattern depicts grazing intensity. The grazing-capacity : stocking-rate ratio affects the outcome. Do these grazing categories make sense? If not, how would you adjust it?

Stocking situation	Grazing-capacity (ha/LSU) / Stocking-rate (ha/LSU)
Under-stocked	< 1
Recommended	1 <= r <= 1.5
Over-stocked	1.5 <= r <= 2.5
Severely-overstocked	r >= 2.5

<1 – understocked
=1 – recommended
1.5 – overstocked
2 – severely overstocked

Change “recommended” to 1 (not 1.5)

Terminology, refer to Trollope (Trollope and Bosch 1990)

Recommended should be less, then the grazing capacity, it should always be below 1 e.g.: recommended = 0.75 -0.9 and understocked: <0.75

Questionnaire part 2 - vegetation dynamics in space and time - savanna model:

Arboricide submodel

1. Is it always the camps with the highest percentage of woodys that are treated first?

Yes
Yes
Depends on the rate of treatment

2. How big of an area is usually treated with arboricides? And is this within one or several camps?

Funding is the biggest factor; severity of encroachment; above 2000TE/ha (aeroplane control); below 2000 TE/ha (manual control)

Depends on funds and on the method of application
Whole camp per treatment +/- 1000ha in west and +/-200ha in the east. Depends on tree species.

3. How will the available biomass change after treatment?

Initial dramatic increase in grass production and slower increase in woody biomass (follow up treatment necessary)
Woody biomass decreases; grass biomass would increase with sufficient rainfall
Arid areas – Annual + low percentage perennial species
Mesic areas – perennial species
KZN: It will be faster than in areas of lower rainfall

4. What is the temporal vegetation development (e.g.: Bare soil, annual grasses…) after treatment?

Bare soil --> annual grasses --> perennial grasses (in arid areas it may stop at the stage of annual grasses)
Annuals generally first, no direct way

5. After arboricide treatment, the cell is set back to bare soil and has to become annual grass first before it can become perennial grass. Is this reasonable or should there be a direct way to e.g. palatable perennial? How quick would such a switch be and how much biomass would be on the cell compared to the woody biomass before.

Yes
Two years increase in grass biomass, slow decrease in dead woody biomass
It's not logical that from bare soil its directly first annual grass and then perennial grass.. under some circumstances it might also be directly perennial grass.

6. When does the treatment have to be repeated?

Three years, method can change (you can use first airplane and the second time manual control)
5-10 years
It must be very soon because there we have due to the higher rainfall a quicker recovery of woody species than in the arid areas (e.g. *A. tortilis*, *A. nilotica*, *D. cinerea*)

7. How common are "gullivers" in our study area?

Very common
Not common
Very common in the moisture areas (*A. karoo* and *A. siberiana* tend to form seedling banks)

- ➔ It's a more recent terminology. It's not a sapling. We might need a definition of gullivers and sapling.

8. How common is re-seeding? Is it an important option for the model?

Common, depending on land-use and funding; need to protect the seeded area to ensure establishment
Not common; if applied, only with low success
In wet areas it is not uncommon
--> You cannot really buy seeds… you have to cut your own grass and then get it from there

9. For how long do arboricides affect germination of young woodys?
Tebuthiron – 15 months to three years
Access – no restriction (Pychloram)
Metasulfuron – 2 years?
The soil type is very important
Depends on chemical used, usually 10 years

10. Is it a good (and commonly used) idea to use goats to counteract bush encroachment?
Needs high management
Is a good idea; "stock theft" is a problem with small stock; predation; fencing needs to be in good condition; ticks and "foot rot" (is a hoof infection commonly found in sheep, goats, and cattle) in mesic savannas
In the kalahari, the growing period is not long enough and the goats start competing for grass; It is not commonly done; but from a scientific point of view a good idea.

Climate change submodel

11. Ways to implement climate change could be based on intra-annual and inter-annual variation of rainfall, changing MAP, CO2 levels and the temperature. Is this sufficient? What else needs consideration?
Yes it is sufficient; No, it is not, Evapotranspiration, Black frost

Frost, frost causes dieback of woody plant, it's not so important for grasses but we have to ask *anonymized* whether he can provide data on frost as well

Soil submodel

12. What are the key soil parameters that we have to consider at the minimum?
Texture, depth and nutrient content
Clay content, soil moisture, soil organic matter, soil temperature, soil depth
Clay percentage and texture (you can deviate most things from the texture); Soil erosion could be important, in Mier; wind erosion and water erosion in KwaZulu-Natal

13. Is it sufficient to model the topsoil level only?
Yes
No, not sufficient, should focus on deeper soils also
Rather than considering two layers, one should consider the depth of the topsoil, topsoil is defined as the A-horizon

14. Which parameters are the most important over the IDESSA gradient and how do they change?
Vegetation Transition

15. "Whenever a transition occurs, all entities in a cell (e.g. vigor, biomass, soil moisture) stay the same, only the vegetation type changes." Is this a reasonable simplification?
No
No, Bare soil = no biomass; Annuals = low biomass; subclimax grass = moderate biomass; climax = high biomass

No, it's over simplification

16. „If the veld is managed sustainably, there will be little to no vegetation transition." --> Is this reasonable?

Yes, it is
Agree, except for climate change scenario
Depends on initial condition; a poor condition should transform to a better state over

17. Germination needs: Seeds, Space and SoilMoisture
Annual Grasses need a min 30 % Soil moisture to germinate --> Is this reasonable?
Perennials + young woodys need min 50 % soil moisture to germinate --> Is this reasonable?

Yes, but hard scaled seeds need scarification (woody seeds);
Possibly but follow-up rain needed for survival of seedlings
Contact *anonymized*
Not sure; What exactly is meant with „germination"? How long must the 30 % soil humidity persist? How long can a sandy Kalahari-soil keep the soil moisture at 30 %? Some seeds need to go through various swelling and shrinking stages to be able to germinate.

18. For annual grass to survive the first month, there has to be a soil moisture content of 30 % for at least 20 days --> Is this reasonable?

Yes
Contact *anonymized*
No disagreement, but ...

19. For perennials and young woodys to survive the first month, there has to be a soil moisture content of 50 % for at least 30 days --> Is this reasonable?

Yes
Contact *anonymized*
No disagreement, but...

General

20. What are interesting and useful output variables for the farmer?

Economic viability; What to use – method; What to kill what to leave – density/species; Impacts on biodiversity
Short term prediction would improve rangeland management; long-term predictions would improve economic viability and productivity
How biomass translates into animal production

21. Are there any updates on the farm-shapefile available?

No, don't know
Contact *anonymized*
No

22. How big are the "clouds" that distribute rainfall over the landscape? How patchy is rain?

Variable
Frontal = Wide area; thundershowers = patchy rain as low as 500m
Ask *anonymized*

Questionnaire fire module for the MIDESSA savanna simulation model

Questions were discussed in three groups and all answers were collected below. Names were anonymized.

1. How long does it take to burn 1 ha of savanna and under which conditions?

1) High windy condition
Wind speed 10 km/h
Temp 25°C
Humidity less than 25 %
Time 14 seconds for 1 hectare
Against the wind 100 minutes for 1 hectare
Flanking fire: 25 seconds
No wind – 100 minutes for 1 hectare
2) Provided there is sufficient fuel, Wind speed and season (fuel moisture) – very fast (head fire)
3) Equation: Wind!
KZN 0.5ha in 0.5 hours in June (dry)
Woody debris gliming
Duration is different for wildfires and managed fires

2. Which temporal and spatial resolution is relevant for simulating realistic fire patterns?

1) 30m; daily
2) Temporal – Minimum of 1 Minute
Spatial – 30x30m; should include total area to be burnt
3) ./.

3. Among the savanna types considered along the IDESSA gradient, what would be the simplest approach to adapt the fire model to the different regions and what are the main differences relevant for fire dynamics?

1) Different across gradient:
Biomass (Grasses)
Fuel load recovery after fire
Rainfall
Topography
Use of pre-scribed fire
2) Arid – adequate biomass fuel available very sporadically long intervals between fires. Less commonly used by managers.
Wet (KZN) more biomass fuel, more frequent fires, more commonly used for management
3) Litter, humidity, fuel load, bush control by fire more common by mesic areas

4. What is the minimum fuel load (kg/ha) required for a fire to spread?

1) 2000kg/ha
2) 2000kg/ha
3) 2 ton/ha

5. What is the minimum fuel load (kg/ha) required for a fire to be effective in killing woody species? (e.g. 4.500 kg/ha DMP in the semi-arid Molopo savanna)

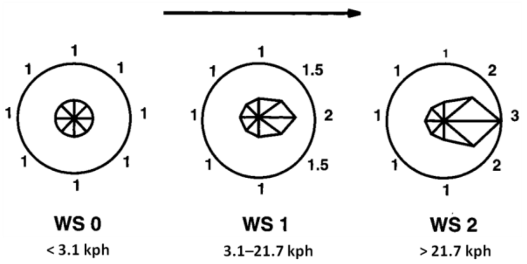
1) 4000+ kg/ha
2) Fire generally does not kill trees. Causes top-kill i.e. changes the structure! Established trees: > 4000kg/ha. Young saplings 2000kg/ha.
3) Fire intensity, not fuel load alone, depends on species

6. Fire spread into woody vegetation patches: what proportion of alive biomass and dead biomass (stem) is burned of young woodies (size class susceptible to fire)?

1) < 6mm in diameter – Fire fuel
30 % live material removed
Stem biomass very little removed

2) Young woodies generally don't have dead biomass. If fire is hot enough it can cause 100 % top-kill. Will coppice again from collar region.
3) Depends…

7. How can better estimates for the weights of wind velocity be acquired than by Hargrove et al. (2000)?



1) We can't do it better.
2) Possible source – Domingos Viegas, Portugal + Frank Albini, USA
Burning Moribund grass < 10km/h
Bush control – wind speed 12-15km/h
>15km/h: risk too high
3) ./.

8. Is slope a relevant parameter to include?
1) Yes, very important.
2) Yes
3) Yes, (upslope rapid)

9. Is there a basic difference between wildfires in conservation areas and managed rangeland systems?
1) Burning under conditions similar to pre-scribed burn then will leave to burn out – For both systems
--> The recovery of veld would differ as rangeland manager will be able to remove the livestock, which will not be possible in conservation areas.
2) Yes Controlled vs minimal control
3) Depends on fuel continuity (function of foraging behaviour)

10. Are you aware of any sources providing sufficient reference for answers to some of above-mentioned questions?
Anonymized

B Supplementary material for chapter 3

B.1 Piosphere patterns in classified aerial images

Classification of aerial images

To be able to classify the simulated model results and verify the approximation to the real world, we compared PioLaG outputs with piosphere patterns quantified on aerial images of real savanna landscapes. The aerial images were provided by the National Geo-Spatial Information (NGI) South Africa, covering the whole Molopo region. The images were taken during the dry season in July 2013 and have a resolution of 0.5 m, which allowed for the visual detection of 10 obvious animal concentration points (watering points, kraals). These points served as the centre for a 3 x 3 km aerial image tile. For these tiles, the Visible Vegetation Index [*VVI*, Eq. 1; (PHL 2015)] was calculated from the available RGB bands to enhance vegetation characteristics.

$$VVI = \left[\left(1 - \left|\frac{red - 30}{red + 30}\right|\right)\left(1 - \left|\frac{green - 50}{green + 50}\right|\right)\left(1 - \left|\frac{blue - 1}{blue + 1}\right|\right)\right] \tag{18}$$

Land cover classes were then determined in an unsupervised classification approach. A k-means algorithm, implemented in R (R Core Team 2018) was applied to cluster each of the tiles based on their RGB bands and VVI. The number of classes was determined by the comparison of the sum of squares within the separate cluster to the total sum of squares for different amounts of clusters. The identified optimal number of clusters was four. Hence, the images were clustered into four classes, which were then assigned to the corresponding land cover class on the basis of the *VVI*. The visual interpretation and comparison with the aerial image let to the interpretation of these four classes as *bare ground* (low *VVI*), *herbaceous vegetation* (two classes, medium *VVI*) and *woody vegetation* (high *VVI*). However, due to the constraints of limited image bands (RGB) and the difficult spatial patterning of vegetation (no larger connected patches but rather inter-mixed and clustered vegetation with no clear boundaries) providing no indication for a reasonable distinction of herbaceous vegetation types, we decided to combine the two corresponding classes.

Site selection and calculation of piosphere patterns

We identified a total of 31 watering points [or similar structures with clear signs of regular animal concentration and radial vegetation patterns (piospheres)] in the portion of the Molopo region for which we had aerial-image coverage. This selection was carried out visually with the aid of RGB satellite images in QGIS (version 2.18.9; with the open layers plugin: google satellite). The vegetation patterns and corresponding distribution of land-cover classes were quantified on the classified aerial images (see above) using R version 3.4.4 (R Core Team 2018). First, we created 10-m buffer donuts up to 1000 m around each watering point and determined the relative frequency of the dominant vegetation types (land cover classes) for each distance donut. The distance of 1000 m corresponded to local camp sizes as measured on the images. In a second step, we plotted the mean frequency of the three different vegetation types against the distance from the watering point (herbivore-use intensity gradient) in reference (1) to all 31 watering points (piospheres) and (2) to three configurations of vegetation differing in the proportion of woody vegetation (trees and shrubs). Chosen thresholds for woody vegetation within the 1000-m buffer zone were: low (≤ 17 % woody vegetation; n = 15), medium (> 17 % and ≤ 25 % woody vegetation; n = 11) and high (> 20 %; n = 5). Contrary to grasses and forbs, the abundance pattern of established woody vegetation is relatively stable over time, at least in the short- to medium term. It also determines the competitive environment for the herbaceous layer. Hence, the additional distinction of savanna vegetation configurations allowed us to contrast different real-world scenarios that not only represent snapshots in time.

Results of classified aerial image analysis

Piospheres with an overall low proportion of woody vegetation (Fig. OR1.1A) were characterized by much bare soil along the whole 1000-m gradient from the watering point. However, there was clear indication of a sacrifice zone with a steadily increasing proportion of herbaceous vegetation, which levelled-off at about 38 % at a distance of 250 m. In piospheres with a medium proportion of woody vegetation (Fig. OR1.1B), herbaceous vegetation became already dominant after 130 m from the watering point and bare soil dropped below 38 %. In contrast, piospheres with a relatively high proportion of woody vegetation (Fig. OR1.1C) displayed the shortest sacrifice zone with an almost abrupt drop of bare soil within the first 100 meters to values between 10 % and 20 % and a sharp increase of herbaceous vegetation to nearly 50 %. These proportions remained quite constant along the gradients. Averaged over all 31 piospheres (Fig. OR1.1D), the basic vegetation pattern described a moderate increase of herbaceous vegetation at the expense of bare ground with no indication of a zone of denser woody vegetation along the gradients.

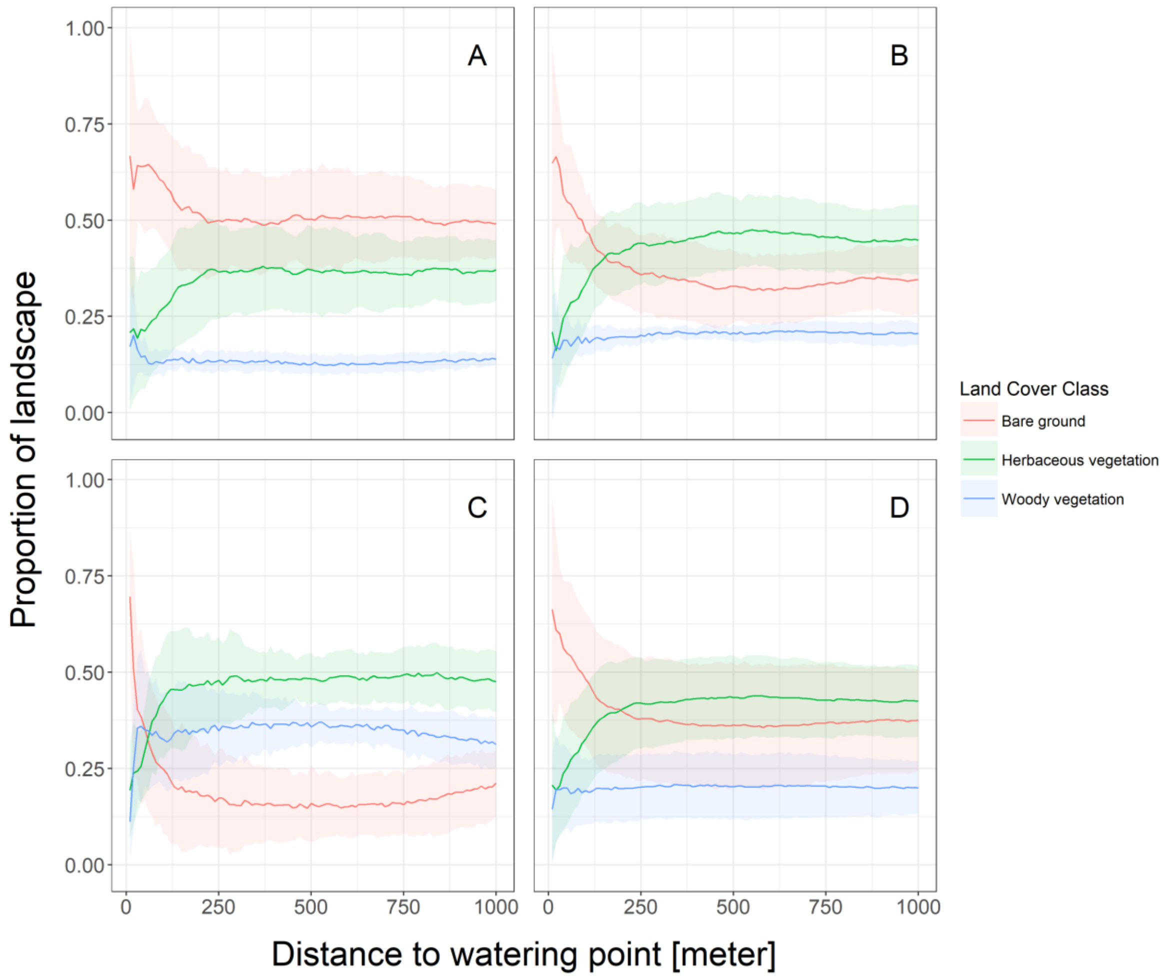


Fig. B. 1: Distribution of land cover classes around watering points identified on aerial images of the Molopo savanna in South Africa. A total of 31 piospheres were subdivided into vegetation configurations with (A) low (≤ 17 %, n = 15), (B) medium (>17 % and ≤ 25 %, n = 11) and (C) high (> 25 %, n = 5) proportions of woody vegetation (trees and shrubs) as a relatively constant variable. (D) Piosphere plot with the proportional vegetation types averaged over all 31 watering points.

Similarities between aerial images and generated landscapes

The piospheres recreated with the piosphere landscape generator (PioLaG) were much more complex but their basic vegetation patterns were comparable to the patterns quantified on the aerial images. Similarities include the sacrifice zone of varying width and dominated by bare soil in close vicinity to the watering point, as well as the constant increase of herbaceous vegetation thereafter. This is especially true when combining the response of annual-, palatable perennial-and unpalatable perennial grasses in PioLaG, which could not be differentiated on the aerial images. However, in the simulated landscape, all scenarios included a rather humped-shaped distribution of cells dominated by woody vegetation, while in the aerial images the proportion of woody vegetation remained relatively stable along the whole gradient beyond the sacrifice zone. This is in sharp contrast to savanna piosphere patterns described in scientific literature (compare main text). However, as bush thickening is widespread in the Molopo area (and consequently corresponding patterns also visible on aerial images), the rather open savannas detected could result from active interventions like bush control, which is commonly conducted in the area to restore a productive grass layer (Harmse et al. 2016). In this respect, our identification of 31 piospheres may also be biased towards clearly visible watering points, because such located in denser stands of woody vegetation are more likely overlooked. Another problem with the aerial images is that they are not representative for the full potential of vegetation. Accordingly, insufficient and patchy rainfall, a fire event or high grazing pressure preceding the date of the images may have accounted for the observed relatively high proportion of bare ground also beyond the sacrifice zones, a pattern not displayed by PioLaG as well (at least under the chosen simulation settings). It is therefore that for additional verification of the PioLaG piospheres in reference to real-world scenarios, further site-specific assessments and analyses would be necessary that allow to consider the local management history (e.g. with respect to stocking rates, resting periods or bush control measures) and other disturbances (e.g. fire events, rainfall patterns or drought periods).

References

Harmse CJ, Kellner K, Dreber N (2016) Restoring productive rangelands: A comparative assessment of selective and non-selective chemical bush control in a semi-arid Kalahari savanna. J Arid Environ 135:39–49. doi: 10.1016/j.jaridenv.2016.08.009

PHL (2015) Visible Vegetation Index (VVI) - Technical report. University of Puerto Rico at Arecibo. http://phl.upr.edu/projects/visible-vegetation-index-vvi

R Core Team (2018) R: A language and environment for statistical computing

B.2 Input data used for PioLaG

Tab. B. 1: Classification of stocking situation on farm and associated parameters.

Stocking rate class	Stocking ratio	Stocking factor (Parameter that affects slope of HUI curve)
Under-stocked	($x < 0.9$)	1.5
Optimally-stocked	($0.9 < x \leq 1.0$)	1
Over-stocked	($1.0 < x \leq 1.5$)	0.9
Severely over-stocked	($1.5 < x$)	0.8

Tab. B. 2: Classification of clay percentage and associated parameter values.

Clay percentage class	Clay percentage	Parameter *(soilBushFactor)*
Low	($x < 30$ %)	0.8
Medium	(30 % $\leq x < 50$ %)	0.7
High	($x \geq 50$ %)	0.6

Tab. B. 3: Classification of severity of bush thickening in outer piosphere and associated parameter values.

Severity of bush thickening	Parameter *(severityOfBushEncroachment)*
Low	0.33
Medium	0.5
High	1

B.3 Example of two common types of spatial camp arrangements in the Molopo region of South Africa

The examples clearly show straight fence lines with a central watering point (or similar animal concentration point). Tracks along the fences and the area directly surrounding the watering points appear bright as a result of dominant bare soil.

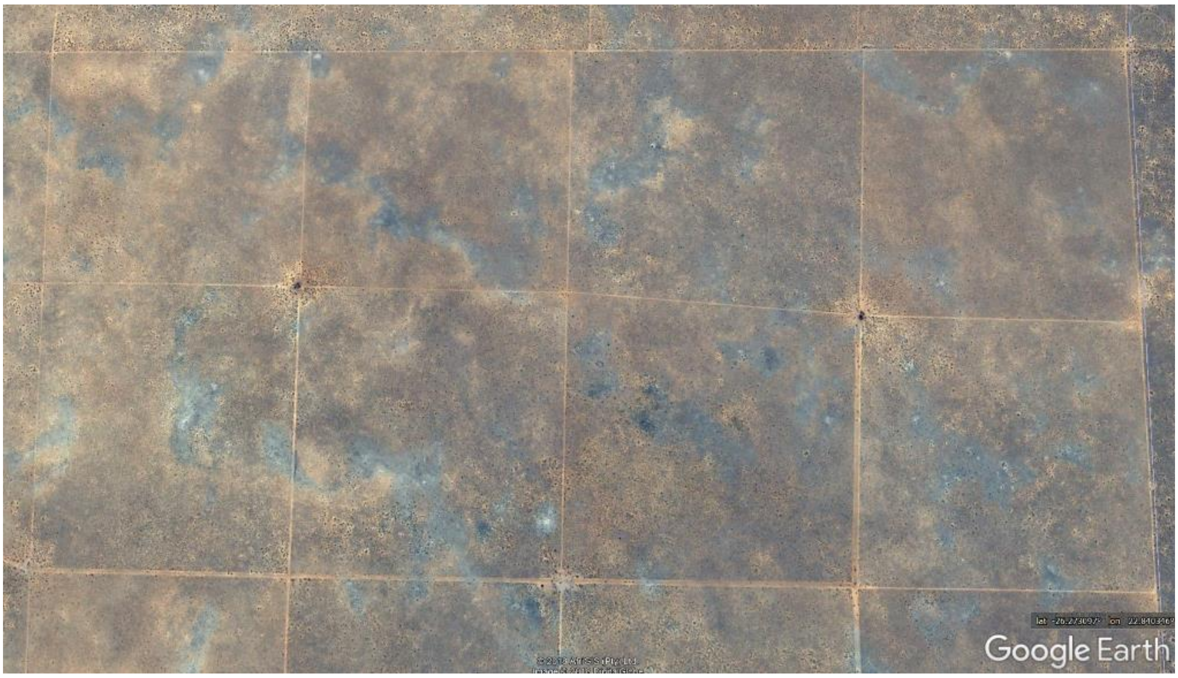


Fig. B. 2: Square camp arrangement (26°16'16.2"S 22°50'21.6"E; google earth).

Fig. B. 3: Wagon wheel shaped camp arrangement (25°41'31.54812"S 23°20'26.69604"E; google maps).

B.4 Additional generated landscape scenarios

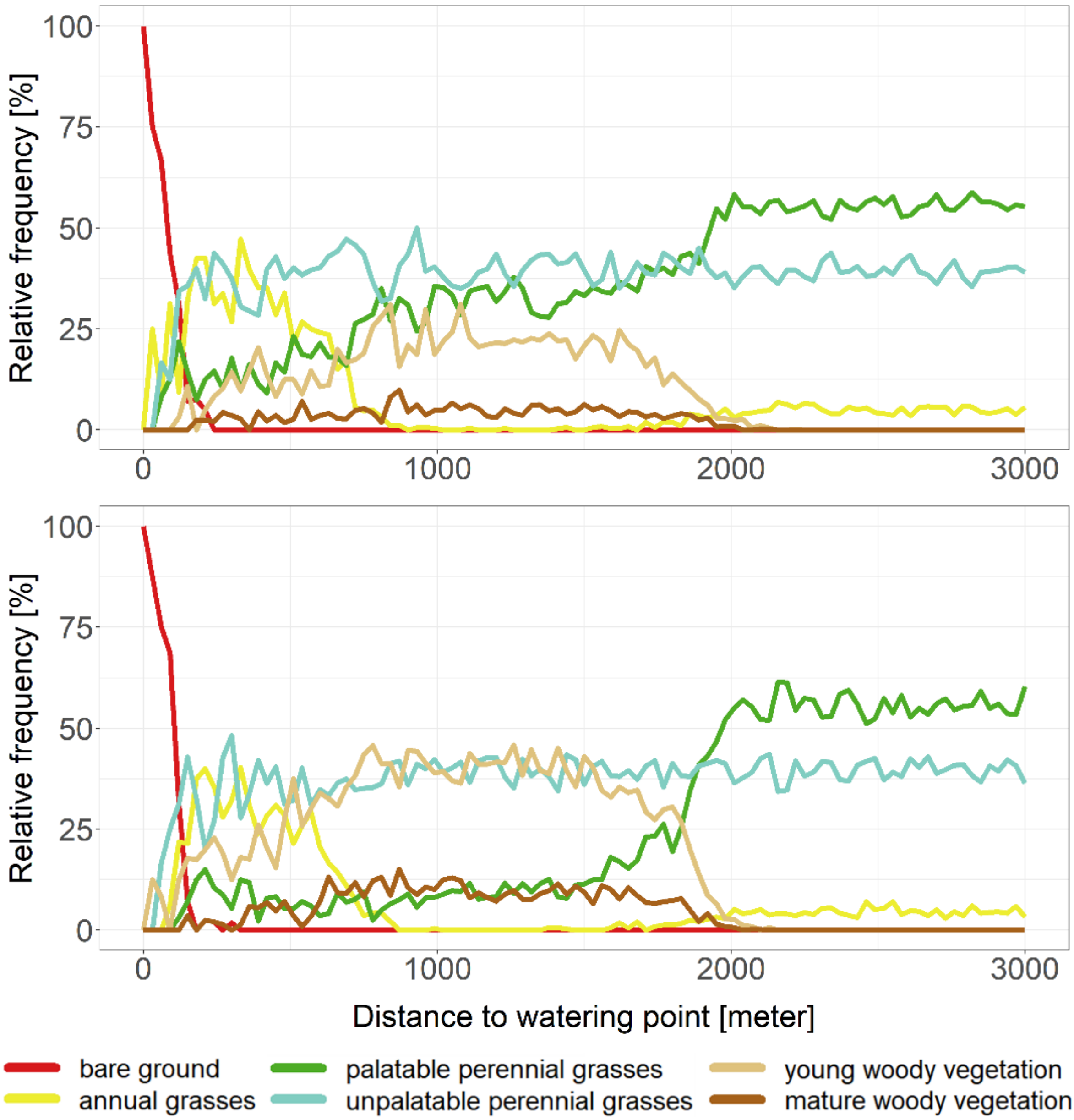


Fig. B. 4: Piosphere graphs of a scenario with low mean annual precipitation (124mm) and low clay content (5 %) in the soil (top) and with high mean annual precipitation (490mm) and a high clay content (27 %) in the soil (bottom).

Tab. B. 4: Model parameterization in Fig. B. 4/top.

Longitude (x)	23	**bush-thickened camps**	0
Latitude (y)	-26	**severity of thickening**	NA
MAP	124 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	On
stocking rate	13 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	2 cols; 2 rows
stocking ratio	0.92 = optimally stocked	**no. of watering points**	1
		clay content	0.05

Tab. B. 5 Model parameterization in Fig. B. 4/bottom.

Longitude (x)	23	**bush-thickened camps**	0
Latitude (y)	-26	**severity of thickening**	NA
MAP	490 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	On
stocking rate	13 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	2 cols; 2 rows
stocking ratio	0.92 = optimally stocked	**no of watering points**	1
		clay content	0.27

B.5 Parameterization (parameter settings) for the analysed scenarios in Fig. 16 to 20 (main text)

Tab. B. 6: Model parameterization in Fig. 16

Longitude (x)	23	**bush-thickened camps**	0
Latitude (y)	-26	**severity of thickening**	NA
MAP	405 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	On
stocking rate	13 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	2 cols; 2 rows
stocking ratio	0.92 = optimally stocked	**no. of watering points**	1
		clay content	0.03

Tab. B. 7: Model parameterization in Fig. 17a.

Longitude (x)	23	**bush-thickened camps**	0
Latitude (y)	-26	**severity of thickening**	NA
MAP	405 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	On
stocking rate	20 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	2 cols; 2 rows
stocking ratio	0.6 = understocked	**no. of watering points**	1
		clay content	0.03

Tab. B. 8: Model parameterization in Fig. 17b.

Longitude (x)	23	**bush-thickened camps**	0
Latitude (y)	-26	**severity of thickening**	NA
MAP	405 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	On
stocking rate	13 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	2 cols; 2 rows
stocking ratio	0.92 = optimally stocked	**no. of watering points**	1
		clay content	0.03

Tab. B. 9: Model parameterization in Fig. 17c.

Longitude (x)	23	**bush-thickened camps**	0
Latitude (y)	-26	**severity of thickening**	NA
MAP	405 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	On
stocking rate	6 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	2 cols; 2 rows
stocking ratio	2,0 = severely overstocked	**no. of watering points**	1
		clay content	0.03

Tab. B. 10: Model parameterization in Fig. 18a.

Longitude (x)	28.64	**bush-thickened camps**	0
Latitude (y)	-25.05	**severity of thickening**	NA
MAP	490 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	On
stocking rate	13 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	2 cols; 2 rows
stocking ratio	0.92 = optimally stocked	**no. of watering points**	1
		clay content	0.05

Tab. B. 11: Model parameterization in Fig. 18b.

Longitude (x)	21	**bush-thickened camps**	0
Latitude (y)	-30	**severity of thickening**	NA
MAP	124 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	On
stocking rate	13 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	2 cols; 2 rows
stocking ratio	0.92 = optimally stocked	**no. of watering points**	1
		clay content	0.27

Tab. B. 12: Model parameterization in Fig. 19.

Longitude (x)	23	**bush-thickened camps**	0
Latitude (y)	-26	**severity of thickening**	NA
MAP	405 mm	**rotational grazing**	OFF
Farm size	14400 ha		
stocking rate	6 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	1 cols; 1 rows
stocking ratio	2 =severely overstocked	**no. of watering points**	1
		clay content	0.03

Tab. B. 13: Model parameterization in Fig. 20.

Longitude (x)	23	**bush-thickened camps**	6
Latitude (y)	-26	**severity of thickening**	high
MAP	405 mm	**rotational grazing**	On
Farm size	14400 ha	**auto-setup-mode**	Off
stocking rate	13 ha/LSU	**camp layout**	rectangular
grazing capacity	12 ha/LSU	**camp layout**	4 cols; 4 rows
stocking ratio	0.92 = optimally stocked	**no of watering points**	4
		clay content	0.03

C Supplementary material for chapter 4

C.1 Default parametrization for the Midessa rangeland model

Tab C. 1: Example parameter file with default parametrization for the Midessa rangeland model.

```
#####################################################################
# Parameter file
#####################################################################

//Number of years in the simulation:
dim_landscape.n_years 60 // number of years // Simulation runtime

dim_landscape.firefreq 5  //relative number of cells ignited per 100,000 ha and month (1ha ==
11,11 cells)
dim_landscape.fire_bm 270  //(grass) fuel load needed to start a fire (3t/ha == 270 kg / cell)

seedForRandomNumbers 111 // choose -1 to set system time as seed to get 'random' results
outputMode 2 // 1=only last year, all output files // 2=all years, only vegType // 3=all years, all
files

* Clima and Soil begin *********************************************
// Soil properties
porosity 0.373          // dimensionless, soil porosity
evapotrans_max 8.0 // mm maximum evapo-transpiration
s_fc 0.442              // soil field capacity
soildepth 100           // depth of active soil for germination in mm

//spatial distribution of rain
heterogeneousRain 0  // 1=heterogeneous rain, 0=homogeneous rain

// Parameters for the clima.zucchini-Model from http://134.76.173.220
// All Parameters are available on the data DVD
// Mean:        282      mm/year MAP
// Std.Dev.:    88

AMWW0 -1.12
AMDW1 1.26
AMMU2 8.28
PHDW1 27.47
AMWW1 0.32
AMDW2 0.35
PHDW2 100.52
AMWW2 0.15
AMMU0 104.95
PHWW1 34.19
PHMU1 42.58
AMDW0 -3.15
AMMU1 24.07
PHWW2 63.47
PHMU2 61.22
```

```
CV	1.1

// Temperature index (seasonality) (Expert guess by K.Kellner)
clima.temperature_index0 0.9	// JAN
clima.temperature_index1 0.8	// FEB
clima.temperature_index2 0.6	// MAR
clima.temperature_index3 0.45	// APR
clima.temperature_index4 0.25	// MAY
clima.temperature_index5 0.1	// JUN
clima.temperature_index6 0	// JUL
clima.temperature_index7 0	// AUG
clima.temperature_index8 0.2	// SEP
clima.temperature_index9 0.75	// OCT
clima.temperature_index10 0.95	// NOV
clima.temperature_index11 1	// DEC

clima.x_cloud_size 10 // Cloud size in cells
clima.y_cloud_size 10

clima.begin_winter 4 // MAY - End of growing season
clima.end_winter 8   // SEP - Start of growing season
*************************************************************

* Vegetation begin ***********************************************
[BARE].palatability 0.0	// sand cannot be eaten (though this is only the dominant type and there might be grasses present)
 [ANNUAL].palatability 0.9	// only dead annual biomass is palatable
[P_PER].palatability 0.9
[U_PER].palatability 0.1
[Y_WOODY].palatability 0.9  // affects only browsers and only green biomass (zero for non-browsers)
[WOODY].palatability 0.9	// affects only browsers and only green biomass (zero for non-browsers)

[BARE].class_veg_cond[HIGH] 1.0
[BARE].class_veg_cond[MEDIUM] 1.0
[ANNUAL].class_veg_cond[HIGH] 1.0
[ANNUAL].class_veg_cond[MEDIUM] 1.0
[P_PER].class_veg_cond[HIGH] 0.435	// Classification border for COND; percent of max capacity (1.0 == 100 %)
[P_PER].class_veg_cond[MEDIUM] 0.273
[U_PER].class_veg_cond[HIGH] 0.435
[U_PER].class_veg_cond[MEDIUM] 0.273
[Y_WOODY].class_veg_cond[HIGH] 1.0
[Y_WOODY].class_veg_cond[MEDIUM] 1.0
[WOODY].class_veg_cond[HIGH] 1.0
[WOODY].class_veg_cond[MEDIUM] 1.0

[BARE].memory[HIGH] 0.0
[BARE].memory[MEDIUM] 0.0
[BARE].memory[LOW] 0.0
[ANNUAL].memory[HIGH] 0.1
```

```
[ANNUAL].memory[MEDIUM] 0.1
[ANNUAL].memory[LOW] 0.1
[P_PER].memory[HIGH] 0.95 // based on Wiegand et al. 2004
[P_PER].memory[MEDIUM] 0.4
[P_PER].memory[LOW] 0.1
[U_PER].memory[HIGH] 0.95
[U_PER].memory[MEDIUM] 0.4
[U_PER].memory[LOW] 0.1
[Y_WOODY].memory[HIGH] 0.1
[Y_WOODY].memory[MEDIUM] 0.1
[Y_WOODY].memory[LOW] 0.1
[WOODY].memory[HIGH] 0.1
[WOODY].memory[MEDIUM] 0.1
[WOODY].memory[LOW] 0.1

[BARE].basalcover[HIGH] 0.0
[BARE].basalcover[MEDIUM] 0.0
[BARE].basalcover[LOW] 0.0
[ANNUAL].basalcover[HIGH] 0.031
[ANNUAL].basalcover[MEDIUM] 0.031
[ANNUAL].basalcover[LOW] 0.031
[P_PER].basalcover[HIGH] 0.086 // unit basal cover (in percent)
[P_PER].basalcover[MEDIUM] 0.065
[P_PER].basalcover[LOW] 0.031
[U_PER].basalcover[HIGH] 0.086
[U_PER].basalcover[MEDIUM] 0.065
[U_PER].basalcover[LOW] 0.031
[Y_WOODY].basalcover[HIGH] 0.031
[Y_WOODY].basalcover[MEDIUM] 0.031
[Y_WOODY].basalcover[LOW] 0.031
[WOODY].basalcover[HIGH] 0.031
[WOODY].basalcover[MEDIUM] 0.031
[WOODY].basalcover[LOW] 0.031

[BARE].intercept[HIGH] 0.0
[BARE].intercept[MEDIUM] 0.0
[BARE].intercept[LOW] 0.0
[ANNUAL].intercept[HIGH] 41
[ANNUAL].intercept[MEDIUM] 41
[ANNUAL].intercept[LOW] 41
[P_PER].intercept[HIGH] -26
[P_PER].intercept[MEDIUM] 19
[P_PER].intercept[LOW] 41
[U_PER].intercept[HIGH] -26
[U_PER].intercept[MEDIUM] 19
[U_PER].intercept[LOW] 41
[Y_WOODY].intercept[HIGH] 41
[Y_WOODY].intercept[MEDIUM] 41
[Y_WOODY].intercept[LOW] 41
[WOODY].intercept[HIGH] 41
[WOODY].intercept[MEDIUM] 41
[WOODY].intercept[LOW] 41
```

```
[BARE].slope[HIGH] 0.0
[BARE].slope[MEDIUM] 0.0
[BARE].slope[LOW] 0.0
[ANNUAL].slope[HIGH] 0.48
[ANNUAL].slope[MEDIUM] 0.48
[ANNUAL].slope[LOW] 0.48
[P_PER].slope[HIGH] 1.67
[P_PER].slope[MEDIUM] 0.62
[P_PER].slope[LOW] 0.48
[U_PER].slope[HIGH] 1.67
[U_PER].slope[MEDIUM] 0.62
[U_PER].slope[LOW] 0.48
[Y_WOODY].slope[HIGH] 0.48
[Y_WOODY].slope[MEDIUM] 0.48
[Y_WOODY].slope[LOW] 0.48
[WOODY].slope[HIGH] 0.48
[WOODY].slope[MEDIUM] 0.48
[WOODY].slope[LOW] 0.48

[P_PER].seed_mortality 0.3 // Annual decay rate of seeds (i.e. of the seed index [0-1])
[U_PER].seed_mortality 0.3
[Y_WOODY].seed_mortality 0.3 // for young and mature woody

[ANNUAL].mortality_green_biomass 1.0 // Variation/variability of mortality (SD)
[P_PER].mortality_green_biomass 0.35
[U_PER].mortality_green_biomass 0.35
[Y_WOODY].mortality_green_biomass 0.35
[WOODY].mortality_green_biomass 0.35

[ANNUAL].var_mortality_green_biomass 0.0
[P_PER].var_mortality_green_biomass 0.1
[U_PER].var_mortality_green_biomass 0.1
[Y_WOODY].var_mortality_green_biomass 0.1
[WOODY].var_mortality_green_biomass 0.1

[ANNUAL].decay_dead_biomass 0.35 // decay rate of dead biomass
[P_PER].decay_dead_biomass 0.35
[U_PER].decay_dead_biomass 0.35
[Y_WOODY].decay_dead_biomass 0.0
[WOODY].decay_dead_biomass 0.0

[ANNUAL].var_decay_dead_biomass 0.10
[P_PER].var_decay_dead_biomass 0.10
[U_PER].var_decay_dead_biomass 0.10
[Y_WOODY].var_decay_dead_biomass 0.10
[WOODY].var_decay_dead_biomass 0.10

s_c 0.35 // soil moisture threshold below which plants close stomata

// Seed dispersal
seed_base_prob 0.1 // Basic probability that a long-range seed distribution occurs
```

```
// ratio: sum P_PER + U_PER + Y_WOODY should be 1
[P_PER].seed_ratio 0.6 // Specific dispersal probability for long-distance dispersal
[U_PER].seed_ratio 0.3
[Y_WOODY].seed_ratio 0.1 // for young and mature woody
interception 1 mm

[BARE].min_biomass 0
[ANNUAL].min_biomass 9
[P_PER].min_biomass 9
[U_PER].min_biomass 9
[Y_WOODY].min_biomass 9
[WOODY].min_biomass 9

// Max carrying capacity in [kg per cell] at best basal cover set
[ANNUAL].capacity 90
[P_PER].capacity 270
[U_PER].capacity 270
[Y_WOODY].capacity 270
[WOODY].capacity 600
****************************************************************

* Transition begin************************************************
temp_transition.soil_moist_min[BARE] 0.1 // soil moisture minimum for establishment
temp_transition.soil_moist_min[ANNUAL] 0.3
temp_transition.soil_moist_min[P_PER] 0.5
temp_transition.soil_moist_min[U_PER] 0.5
temp_transition.soil_moist_min[Y_WOODY] 0.5

temp_transition.on_switch[BARE] 30 //== off_switch for Annuals!
temp_transition.on_switch[ANNUAL] 10  // Number of days with sufficient soil moisture
(soil_moist_min) to switch vegetation type
temp_transition.on_switch[P_PER] 30
temp_transition.on_switch[U_PER] 30
temp_transition.on_switch[Y_WOODY] 30

// to switch from young woody to mature woody
temp_transition.mature_woody 269   // kg * cell^-1

// How many neighbours need to be of the same type for spatial transition? (Derived from
O'Conner et al.)
spat_transition.neigborhood 5

// capacity-dependent: percentage of max capacity.
// For veg. condition only perennials relevant, rest is hardcoded to zero
spat_transition.biomass[P_PER][HIGH] 0.435
spat_transition.biomass[P_PER][MEDIUM] 0.273
spat_transition.biomass[U_PER][HIGH] 0.435   // above this value = high
spat_transition.biomass[U_PER][MEDIUM] 0.273 // above this value = medium // below = poor
****************************************************************

* Initialization begin**********************************************
```

```
// intit values
init_values.soilmoisture 0.13
init_values.vigor[P_PER] 30.96
init_values.vigor[U_PER] 30.96
init_values.vigor[ANNUAL] 0.13
init_values.vigor[Y_WOODY] 2.77
init_values.vigor[WOODY] 2.77
init_values.vigor[BARE] 0.0

init_values.biomass[BARE] 0
init_values.biomass[ANNUAL] 120
init_values.biomass[P_PER] 120
init_values.biomass[U_PER] 120
init_values.biomass[Y_WOODY] 120
init_values.biomass[WOODY] 500

// note: seed can be set to ZERO (except for ANNUAL & BARE). Seeds were produced.
init_values.seed[BARE] 1
init_values.seed[ANNUAL] 1
init_values.seed[P_PER] 0
init_values.seed[U_PER] 0
init_values.seed[Y_WOODY] 0
init_animal_condition 80 // initial livestock condition between 0 to 100
**************************************************************
* Livestock begin ***********************************************
animal.water_dep -0.025 // Negative values. Smaller values, mean bigger water dependency
(exp. function, see Jeltsch1997b) zero means no water dependency; this is for cows
animal.exploitation 1   // the counterpart to palatability i.e. how much gets the LSU out of the
consumed fodder
animal.maxrange 267   // [cells = 30m] 267cells = 8.9 km
animal.fodder_per_lsu 300  // monthly fodder demand per LSU in kg (10kg per LSU/day (12kg
after Cotzee))
animal.browse 0    // Do animals browse? (0=grazer, 1=+browser/mixed feeder)
**************************************************************
* Management begin*******************************************
management.stocking_density 222 // cells per LSU -> 20 ha per LSU
management.resting_time 9         // number of months resting after grazing
management.grazing_time 3         // number of months grazing after resting
// When we e.g. have 4 camps there will be 1/4th (3months) grazed and 3/4th (9 months)
rested
management.woody_mort 0.1 // woody mortality (i.e. natural or wood removal) probability per
year / increase for manual wood removal by farmer
management.arboricideApplication 0 // 0= no application; 1= application of arboricide is turned
on
management.arboricideThreshold 0.4 // threshold that defines when application will be carried
out. Percentage of young AND old woody cells per camp
**************************************************************
###############################################################
# Parameter file end
###############################################################
```

C.2 Midessa - Rangeland Model Documentation - Screenshot

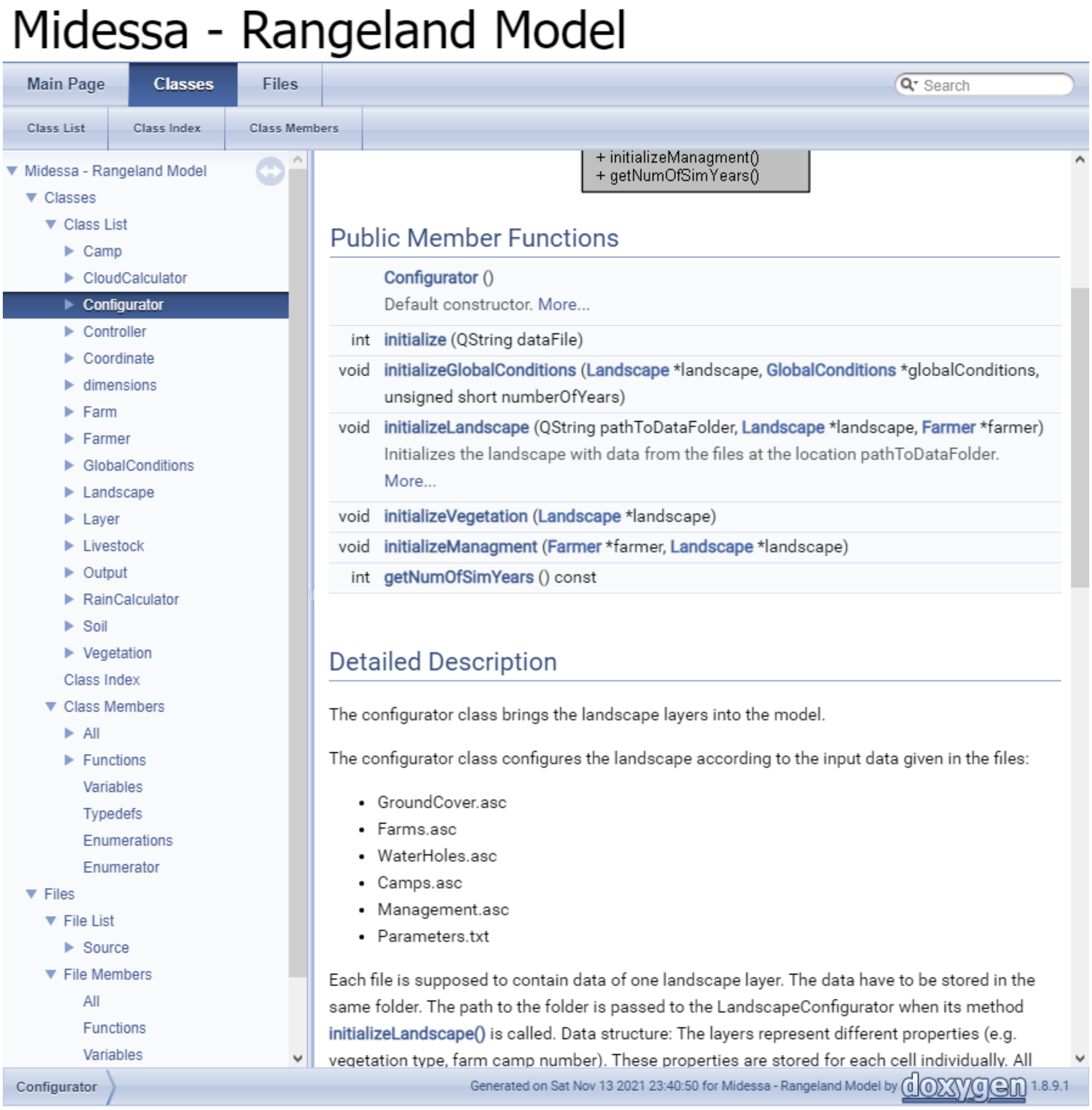


Fig. C. 1: Screenshot of the *Midessa - rangeland model documentation* which provides an overview and short explanations of the functions. The Midessa documentation is available on the digital appendix (DVD).

D Digital appendix

Additional information was stored digitally on a DVD that is attached to this thesis:

- Complete PioLaG model in NetLogo with input files and exemplary output
- Complete Midessa model code and executable with input files and exemplary output
- All parametrizations and output graphs used for the results in this thesis
- Midessa - Rangeland Model Documentation as html
- R-script for automated run of the Midessa model
- This document

Contents of DVD:

- /Midessa
  - Midessa-Model
    - Input with complete Zucchini database, example landscapes and parameter files
    - Source code of the model (I used the QT Creator IDE (Version 4.13.0) based on QT (Version 5.15.0, MSVC 2019) and compiled with MinGW 5.8.0 and 5.9.2 for C++)
    - Executables with necessary libraries (might need to be adapted to system)
    - R-Script to run simulations automatically
  - Output for all simulations in this thesis
  - Midessa - Rangeland Model Documentation
- /PioLaG
  - NetLogo model used for the results ins this thesis
    - all necessary input files to run the model
    - Output files for all PioLaG landscapes in this thesis
  - Latest version of NetLogo model
  - Publication: Hess B, Dreber N, Liu Y, et al. (2020) PioLaG: a piosphere landscape generator for savanna rangeland modelling
  - NetLogo code of PioLaG as pdf
- This dissertation

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Eigenständigkeitserklärung

Doktoranden-Erklärung der Georg-August-Universität Göttingen

Name: Bastian Heß

Anschrift: Büsgenweg 4, 37077 Göttingen

Ich habe eine Dissertation zum Thema: *Modelling, management and restoration of savannas in southern Africa* an der Georg-August-Universität Göttingen angefertigt. Dabei wurde ich von Frau Prof. Dr. Kerstin Wiegand betreut.

Ich gebe folgende Erklärung ab:

1. Die Gelegenheit zum vorliegenden Promotionsvorhaben ist mir nicht kommerziell vermittelt worden. Insbesondere habe ich keine Organisation eingeschaltet, die gegen Entgelt Betreuerinnen und Betreuer für die Anfertigung von Dissertationen sucht oder die mir obliegenden Pflichten hinsichtlich der Prüfungsleistungen für mich ganz oder teilweise erledigt.

2. Hilfe Dritter wurde bis jetzt und wird auch künftig nur in wissenschaftlich vertretbarem und prüfungsrechtlich zulässigem Ausmaß in Anspruch genommen. Insbesondere sind alle Teile der Dissertation selbst angefertigt; fremde Hilfe habe ich dazu weder unentgeltlich noch entgeltlich entgegengenommen und werde dies auch zukünftig so halten. Das 3. Kapitel dieser Dissertation basiert auf einem Manuskript, das in einer wissenschaftlichen Zeitschrift publiziert wurde. Die Schaffung dieses Kapitel wurde im typischen wissenschaftlichen Rahmen durch die angegebenen Mitautoren, gerade mit Blick auf Aufbau und Sprache, unterstützt. BH und YL entwickelten den Landschaftsgenerator mit Unterstützung von KW, KMM und ND; ML und HM klassifizierten die Luftbilder; BH analysierte die Vegetationsmuster um die Wasserpunkte auf den Luftbildern; BH schrieb das Manuskript mit Input von ND und KW; alle Autoren unterstützten bei der Ergänzung des Textes. Für die Autorenreihenfolge wurde der "Sequence-Determines-Credit"-Ansatz genutzt. Das Midessa Weidesimulationsmodell im 4. Kapitel basiert auf dem Molopo Modell von Sebastian Hanß (Hanß 2013). Weitere Details über die Unterstützung beim Entstehen dieser Arbeit sind den *Acknowledgements* zu entnehmen.

3. Die Ordnung zur Sicherung der guten wissenschaftlichen Praxis an der Universität Göttingen wurde und wird von mir beachtet.

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Göttingen, 20.12.2021

____

Bastian Heß