Student thesis series INES nr 268

Refining fuel loads in LPJ-GUESS-SPITFIRE for wet-dry areas

-with an emphasis on Kruger National Park in South Africa

Ylva Persson

2013
Department of
Physical Geography and Ecosystem Science
Lund University
Sölvegatan 12
S-223 62 Lund
Sweden

Ylva Persson (2013). Refining fuel loads in LPJ-GUESS for wet-dry areas – with an emphasis on Kruger National Park in South Africa

Master degree thesis, 30 credits in *Physical Geography and Ecosystem Analysis*
Department of Physical Geography and Ecosystem Science, Lund University

Refining fuel loads in LPJ-GUESS-SPITFIRE for wet-dry areas

-with an emphasis on Kruger National Park in South Africa

Ylva Persson

Master degree in Physical Geography and Ecosystem Analysis, 30 credits

Supervisor
Veiko Lehsten
Department of Physical Geography and Ecosystem Analysis
Lund University

Department of Earth and Ecosystem Sciences,
Lund University, Sweden

Acknowledgement

First of all, I would like to thank researcher Veiko Lehsten at the department of Physical Geography and Ecosystem science, who invited me to join his world and his project almost two years ago. He has shown such incredible support and patience as I took my first cautious steps into the fairly unknown world of C++ programming, and shared much of the knowledge I've always admired. The encouragement and support which I have received during this process has been incredible and I will always feel truly grateful for the time we spent trying to work this thesis through.

I also am very grateful to Navashni Govender at Kruger National Park in South Africa who has provided some of their data and knowledge about the workings of the park, which has made my work much better and more precise than it otherwise would have been. Lastly, I send a special warm thank you to my family and friends who have supported me on my journey. Especially to my parents, who have given me encouragement at times when the whole process felt particularly difficult, and to Max who have patiently listened and discussed my endless ideas how to best solve encountered problems with my thesis and the incredible support he always gave me.

Abstract

Fire is one of the most important disturbance processes affecting the terrestrial biosphere, altering the vegetation composition and distribution, structure, plant diversity and biogeochemical cycles. Some of the most influenced ecosystems are wet-dry areas, here classified as savannah or Mediterranean regions. The influence can be studied in different ways, either by long-term experiments like the burn plot trial in Kruger National Park in South Africa, or by the use of models, for example LPJ-GUESS-SPITFIRE. SPITFIRE is a process-based fire model which have been coupled to a dynamic global vegetation model in order to predict fire spread, intensity and residence time of fires.

In LPJ-GUESS-SPITFIRE a variable called the turnover time, which is the logarithmic decomposition rate for litter at a defined temperature and moisture content is used to calculate how much available litter (or in other words fuel) is available in the modelled patch in order to determine the fire intensity. This constant is set to 2.85 and is used for all ecosystems around the world. In reality however, the turnover time varies depending on the existing circumstances, which makes it unrealistic to use the same constant. Data obtained from the burn plot trial in Kruger National Park was used for parameter refinements within the DGVM LPJ-GUESS-SPITFIRE in order to find more representative values. The litter pool was divided into two pools which are the main input for surface fires; leaf litter and wood litter and their turnover times were studied individually. A literature study showed that presently used values for the leaf turnover time are overestimated by the model and underestimated for wood. In order to find more suitable parameters, new values were tested, litter amounts for different fire return intervals were calculated and compared with measured litter amounts in the experiment in Kruger National Park. A turnover time of 0.6 years for leaf litter without trees was found to be the best representative for wet-dry areas. The turnover time for woody litter could not be adjusted, since there was no available data to compare them with. However, the effect of turnover times within the range found in the literature study was examined in order to better understand the effect wood litter had on these kinds of ecosystems. This thesis shows the importance to understand how different ecosystems work and that improvements still can be made in the used model.

Key words: Fire, wet-dry areas, fuel, turnover time, Kruger National Park, LPJ-GUESS-SPITFIRE

Sammanfattning

Eld är en av de viktigaste störningsprocesserna som påverkar den terrestra biosfären genom att forma vegetationens spridning, komposition, struktur, växtdiversitet och biokemiska cykler. Några av de mest påverkade ekosystemen är våt-torra områden, här klassificerade som savann eller Medelhavsområden. Denna påverkan kan studeras på olika sätt, antingen genom ett långvarigt och fortlöpande experiment, som i Kruger National Park i Sydafrika, eller genom att använda sig av modeller, som till exempel LPJ-GUESS-SPITFIRE. SPITFIRE är en processbaserad eldmodell som har kopplats samman med en dynamisk vegetationsmodell för att förutspå eldens spridning, intensitet och hur länge det kan brinna.

I LPJ-GUESS-SPITFIRE används en faktor som kallas omsättningshastigheten, vilket är ett halvtidsvärde för nedbrytning av biologiskt avfall vid en viss temperatur och fuktighet. Den används för att räkna ut hur mycket tillgängligt växtmaterial som finns i det modellerade området för att kunna bestämma eldintensiteten. Denna konstant är satt till 2.85 och är densamma i alla världens ekosystem. I verkligheten beror nedbrytningen på vilka de aktiva förhållandena är och det är därför orealistiskt att använda samma konstant. Data från experimentet i Kruger National Park användes för att förbättra parametrarna i DGVM LPJ_GUESS_SPITFIRE för att hitta mer representativa nedbrytningsvärden i våt-torra områden. Avfallet delades in i två pooler som är det huvudsakliga bränslet för markbränder; avfall i form av löv och trä och deras omsättningshastigheter studerades individuellt. En litteraturstudie visade att de nuvarande värdet för löv är för högt och för lågt satt för trä. Nya värden testades, avfallsmängder för olika eldintervall räknades ut och jämfördes med mätta mängder i Kruger National Park. En omsättningshastighet på 0.6 år visade sig vara bästa representanten för våt-torra områden för lövavfall utan träd. Ett värde för träavfall kunde inte hittas, då det inte fanns tillgång till data att jämföra värdena med. Däremot kunde effekten av omsättningshastigheten studeras för att få en bättre förståelse för vilken effekt det hade på dessa typer av ekosystem. Denna uppsats visar vikten av att förstå hur olika ekosystem fungerar och att det fortfarande kan göras förbättringar i den använda modellen.

Nyckelord: Eld, våt-torra områden, bränsle, omsättningshastighet, Kruger National Park, LPJ-GUESS-SPITFIRE

Table of contents

List of figures:

List of tables:

List of maps:

1 Introduction

There are many factors which play an important part in shaping and transforming the different ecosystems around the world. While climatic factors such as temperature and precipitation promote vegative growth, disturbances such as herbivory, drought and fire affect species adaptation and survival. Of all the disturbances, whether naturally or humanly caused, fire is one of the few that regularly kills mature plants which makes it an important agent structuring and providing for vegetation change (Bond & van Wilgen, 1996). About 40% of the world´s terrestrial area have a fireprone vegetation, which means the vegetative parts of the species are not only surviving but promoting fire outbreaks (Gill et al., 1981). In order to have a fire outbreak, some of the most important factors are fuel load, fuel moisture, fuel-bed continuity and sufficient wind speed. The only factor which humans can control in order to lower the risk of hazardous outbreaks in populated areas is the amount of fire fuel. According to Bradstock et al. (2012), fire fuel is a generic term describing combustible living and dead vegetation that may be consumed in the passage of fire. This in turn is dependent on the surrounding environmental conditions (Pyne et al., 1996). Together with ignition frequency, they are direct drivers of size and severity of annually burnt areas (Archibald et al., 2009).

Some of the most fire influenced ecosystems are wet-dry areas such, as the Mediterranean and savannah regions (Bond & van Wilgen, 1996). These areas are often highly influenced by human activities and fire occurrence, which often contradicts one another. Fire behaviour can however be a difficult task for managers to control. Since these areas often are highly populated, it is in their interest to keep the risk of destructive fires at a minimum level. But at the same time there must be a fire frequency and intensity high enough to sustain biodiversity as the ecosystem has adapted to fireprone conditions (Fujioka et al., 2009).

By modeling a fire regime, information about the underlying mechanisms of fire, its size, distribution and influence on the affected landscape can be attained without doing any harm to any existing communities. These results can then be used to determine the effect and impact on plant compositions and to predict what consequences different landscape management strategies might have on areas which have been burnt or what the distribution of larger and more hazardous fires might be (Loepfe et al., 2011). There have been several studies, either experimental or model-based, which have examined the effect of fire in different wet-dry areas. For an example, the experiments made by Govender et al. (2006) looked at the effect of fire season, frequency, rainfall and management on fire intensity and Lehsten et al. (2009) have with the help of LPJ-GUESS SPITFIRE and the global burned area database L3JRC simulated pyrogenic CO_2 emissions and investigated the relationships between seasonality and inter-annual variability in fire activity to climate and vegetation productivity. Most studies have focused on the effect of fires and its emissions and not particularly on the fuel distribution, which are one of the causes of emissions and different fire intensities. Ward et al. (1996) did a study on how different savanna ecosystems and fuel loads affected burning and trace emissions, but they only looked at fires which were burned after severe drought and not on the intensity of the fires during more regular conditions.

Three universities in Lund, Potsdam and Jena developed the modelling-framework LPJ, a dynamic vegetation model which also simulates the biogeochemical carbon and water exchange of terrestrial ecosystems. At Lund University, this framework has been extended to include age cohorts of vegetation in the version LPJ-GUESS. The vegetation is divided into Plant Functional Types (PFTs) which compete for resourses like light and water in the simulated patch (Smith et al., 2001). The effect of fire is also implemented into the framework, but is quite simple in its original form. Kirsten Thonicke and Allan Spessa subsequently developed the fire module SPITFIRE (SPread and InTensity of FIRE) to be integrated into LPJ. SPITFIRE is a process-based fire model based on Rothermels equations that explicitly considers the influence of fuel characteristics, calculates surface fire intensity and derivates the residence time of the flames. LPJ-SPITFIRE is used as a tool for predicting consequences of climate change for different fire regimes, vegetation and pyrogenic trace gas and particulate emissions (Thonicke et al., 2010). Since fuel characteristics is an important factor for the use of the model, the amount of available surface fuel will evidentely affect the simulated fire intensity. Meentemeyer (1978) published litter turnover times in years which are used in the calculation of the amount of litter present in the simulated patches. However, these are all set to the same value of 2.85 years despite type of fuel, ecosystem or climate and have not been evaluated before. For wet-dry areas which are highly influenced by fire, and evidently on the amount of available litter which fuels their outbreaks, it is therefore important to investigate if the chosen constants give a sufficiently good representation of available surface litter and if there are any possibilities for refinements.

1.1 Aim and objectives

Using the current version of LPJ-GUESS SPITFIRE, the aim of this thesis is to examine whether the currently simulated fuel loads are concordant with values found in both literature and observed data obtained from Kruger National Park in South Africa.

The hypothesis for this thesis is that the current decomposition rate which is used regardless of the litter type is not suitable to represent the litter decomposition in savannah ecosystems. It is also assumed that a refinement of the existing turnover times for surface fuel loads can be made in order to improve the model's performance.

The main questions for this project are:

* Is the existing LPJ-GUESS-SPITFIRE parameterization compatible with existing fuel load data for different wet-dry areas?

* Can an improvement be made which gives a more reasonable output compared to current model results?

-If not, what might be causing the difference?

In order to answer these questions, the thesis will be separated into two different parts:

- A literature study to find typical fuel loads for some selected Mediterranean and savanna ecosystems under different climatic conditions and fire return intervals. A special emphasis will lie on collecting articles and data related to the experiments in Kruger national park in South Africa, since observation data is already available for this site.

- Simulations in the existing LPJ-GUESS-SPITFIRE will be performed in order to evaluate model performance. The fuel load data found in the literature study will be incorporated in this step in order to find more suitable parameters for the model with the goal to enhance the agreement of the model with reality. This improvement will hopefully not only improve the model simulations for the observed area in Kruger National Park, but for other wet-dry areas as well.

1.2 Limitations

During the literature study, it has proven difficult to find any turnover times or build up rates of litter from wet-dry regions in different parts of the world. I have therefore decided to only look at Kruger National Park in South Africa as my representation of the savannah ecosystem, since this system covers a large range of the precipitation gradient and the most important climatic gradient for savannahs. Other savannah regions, such as the ones in North America, Australia and Brazil or the Mediterranean region in Chile will hence not be described, due to a lack of information from the areas or due to irrelevance to the completion of this thesis.

Furthermore, not all the processes and parameters which might have an effect on the fuel load build up or fire intensities have been taken into account due to a lack of data and possible risk of drift from the chosen subject. These activities are microbial activity, which is partly within the dependence of the decomposition rate and affected by the temperature and moisture content (Cornwell et al., 2009; Rock et al., 2008), herbivores which contribute to the vegetative pattern in an ecosystem (van Langevelde et al., 2003), nutrient composition (Rapp et al., 1999) or how much litter the vegetation generates per year (Cortez et al., 2007). So, even though all of these mentioned factors are highly influential on the build up and decomposition of litter as well as the fire regime, they will only be given a small presentation in the thesis.

2 Background

2.1 What is fire?

Fire is one of many types of disturbances which determines the major vegetation structures and compositions around the world (Gill et al., 1981). It is a chemical reaction not much different from our own cellular respiration. When the vegetation burns, which is called combustion, the chemical energy within the plant is transformed into thermal, radiant and kinetic energy (Pyne et al., 1996).

To describe the conditions involved in producing a fire, the fire triangle can be used (see figure 1). A fire has three requirements in order to burn: appropriate fuel, sufficiently dry conditions and a form of ignition. Fuel refers to a material that burns, its chemical composition, density and moisture content. Ignition refers to the temperature needed to reach an ignition point and a heat release sufficient enough to sustain combustion in the flammable fuel. Lastly, dryness refers to both fuel and past and present weather events. It affects the amount of burnable fuel which in turn might lead to more intense fires (Pyne et al., 1996).

Fig. 1: The fire triangle and its three fundamental requirements. Redrawn from Pyne et al., 1996.

There are four phases of combustion: 'pre-ignition', 'ignition', 'combustion' and 'extinction'. Pre-ignition is when the temperature of the fuel is raised to the point of free water evaporation and release of volatile compounds. Ignition is the transition zone between preheating and combustion, where the fuel ignition requires a minimum level of temperature increase to be reached. How fast this temperature is reached depends on the fuel composition. Ignition can be produced by lightning strikes, spontaneously as a result of internal pile heating, smouldering, microbial activity or induced by human activities. Combustion is the flaming, smouldering or glowing of fuel. Combustion doesn't necessary involve a flame and its efficiency varies with material and fuel dryness. A visible flame can be produced if the volatiles in the preheating phase ignite. But if the combustion is uncomplete, some of the volatile products remains suspended in the air as small droplets of liquid. Together with other residual carbonized particles, they float into the air and produce smoke. The last phase, extinction, is reached when there is no longer sufficient heat or a source of heat which will sustain combustion (Pyne et al., 1996).

2.2 The fire regime

A fire regime is a combination of three different elements: how often a fire occurs (frequency), when it occurs (season) and how fiercely it burns (intensity) (Gill et al., 1981). A change in the fire regime may lead to a change in vegetative composition, favouring one species or plant type at the expense of another (Bond & van Wilgen, 1996). Depending on the cause, frequency, season and intensity of fire as well as where it occurs, it can have direct effects on the vegetation dynamics since there might be some species who have a high tolerance against it, whilst others are very sensitive.

Fires can be classified according to where they burn, either as 'ground', 'surface' or 'crown' fires. A 'ground' fire burns the organic material below the surface litter or vegetation. A 'surface' fire is when the surface litter, other loose debris or low vegetation is burned and a 'crown' fire runs through the canopies of shrubs or trees. In comparison to the two first mentioned, crown fires can occur independently of surface fires either when the surface fuel is saturated by water or by a phenomenon called spotting. Spotting is when an ignition ahead of a flame front occurs by a transport of firebrands and is the dominant mechanism of spread in a high intensity forest fire.

Fires may be further categorised according to the wind direction, either as a 'head' (with), 'back' (against) or 'flank' (parallel) fire. All of these categories can occur at the same time on various parts of a fire outbreak (Gill et al., 1981).

2.2.1 Weather and climate

The weather and climate not only influences a fire's ignition, but also the type of fuels that burn (Benson et al., 2009). In order to have a fire occurrence, favourable environmental conditions have to be met not only within an annual or seasonal time frame (climate), but on a daily or even hourly basis (weather) as well. Fires can occur under most climate regimes, as long as there is a dry and sufficiently warm period at some point during the year. They rarely occur in deserts, where there is insufficient amounts of fuel, or in the rainforests, due to the high moisture content, and never occur in Antarctica which is both too dry, too cold and lack sufficient amount of fuel (Bond & van Wilgen, 1996).

When climate determines if it will burn, the weather determines how and when a fire will burn. It also affects the intensity and spread directly by different wind patterns and indirectly by the amount of moisture content in flammable vegetation and litter through the amount of rainfall, relative humidity and temperature (Bond & van Wilgen, 1996; Benson et al., 2009).

2.2.2 Source of ignition

Lightning is the main natural cause for fires in different vegetation structures, but they can also be lit by sparks from hardened quartzite rocks, eruptions from volcanoes or by humans (Bond & van Wilgen, 1996). Lightning is a worldwide contributor to wildfires, but only leads to an ignition when fuel type and moisture content are favourable.

In a study made by Latham and Williams (2001), it was found that some fuel types are more efficient in lightning-caused ignition than others. Trees for instance, both coniferous and deciduous, have a higher probability to ignite in comparison to grass, shrubs or croplands.

The importance of lightning-caused ignition compared to human-caused varies and depends amongst others on the density of the human population in different areas (Benson et al., 2009). Today, a majority of all fires are started by humans (Bond & van Wilgen, 1996). Humans affect the fire regime both directly and indirectly. With increasing human densities, the ignition regime is often altered leading to more ignition incidents, but at the same time it decreases the extent of fire by reducing fuel loads and by fragmenting the landscape due to different land use practices (Archibald et al., 2009). In African savannas, almost all fires are caused by humans. The main reasons are cultivation, herding and forestry. Pastoralists burn perennial grasses early in the season to stimulate regrowth of fodder for their cattle, farmers use it to release nutrients prior to the new farming season and natural parks, woodlands used for wood production and surrounding rural settlements burn the herbaceous layer in order to prevent destructive fires by the end of dry seasons (Saarnak, 2001).

2.2.3 Fuel load

According to Bradstock et al. (2012), fire fuel is a generic term describing combustible live and dead vegetation that may be consumed in the passage of fire. Fuel is dependent on the surrounding environmental conditions and can be described either by its type or its state. Fuel type is a description of the fuel itself and the physical properties which affect the way it burns. Such properties include size, shape, amount and arrangement. Fuel state on the other hand is often related to moisture and how much fuel there is available for combustion (Pyne et al., 1996). Fuel availability describes all available fuel which can potentially burn in a fire and the composition differs depending on the vegetation type generating the fuel. The yearly input of litter varies considerably between vegetation types. The amount produced in different communities will depend on the amount of foliage which is held and on the season (Gill et al., 1981). Depending on different climatic factors, such as for an example amount of available moisture, some species only shed their leaves during the dry periods in order to conserve their energy (Arianoutsou & Radea, 2000).

Fuels can be classified according to its size, where fine fuel is categorized as grass, needles, leaves and thin twigs and where coarse fuel is categorized as large branches, snags and logs. The fuel can also be defined in relation to their horizontal structure or its position in vertical layers (Krivtsov et al., 2009). Fine fuel has a diameter less than 0.63 cm and is often the primary carrier of wildland fires. Due to their small diameter size, they quickly respond to changes in relative humidity and temperature compared to coarser fuel types (Benson et al., 2009).

Every plant possess traits which increase or decrease their susceptibility to fire. One of the most important traits is the production or retention of dead material. It is the dead fuel that initially carries fire and normally sustains it, as long as the dead material is not too moist (Bradstock et al., 2012). The live and dead fuel are often divided into four classes according to the time they need to acclimate to the ambient moisture level: 1hr (grasses, leaves and downed small twigs), 10 hr (downed large twigs), 100 hr (downed small branches) and 1000 hr fuels (logs, bole and large branches) (Thonicke et al., 2006). Apart from the individuals, the community as a whole may also influence the property of a started fire. In simple communities dominated by relatively few species, the property of the dominating species will determine the likelihood of a fire consuming the whole community. But in more species-rich communities, it is the combination of the traits of all species on site which determines the likelihood and how the vegetation will burn (Bond & van Wilgen, 1996).

2.2.4 Moisture

Atmospheric moisture, either in the form as water vapour or precipitation, limits fire occurrence and its behaviour by affecting the fuel moisture in both dead and living material. When fuel moisture increases, it retards the rate of combustion, preheating of fuel and ease of ignition. Since water is a heat sink, it has to be boiled away before ignition temperatures can be reached (Pyne et al., 1996).

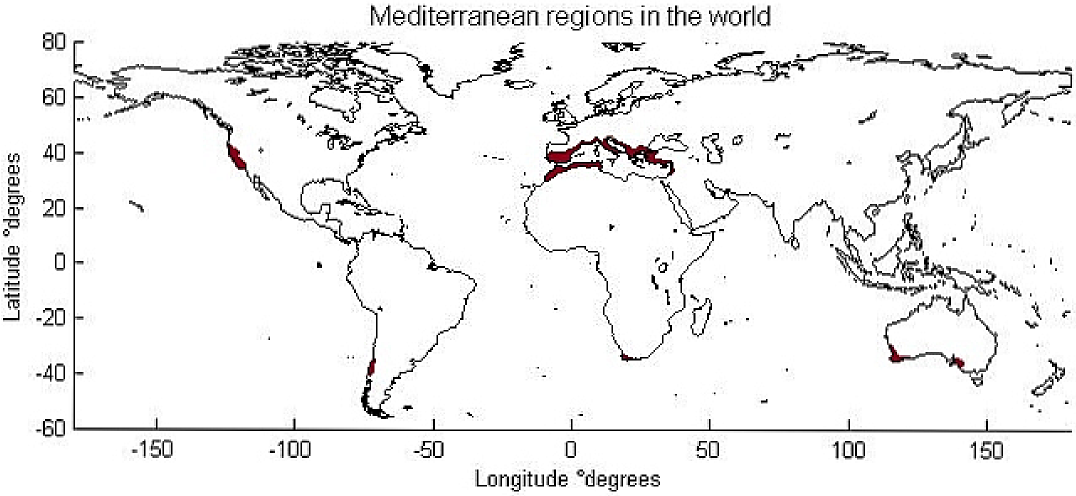
According to Fujioka et al. (2009), fuel moisture content is expressed as 'the mass of water present in a fuel' and is typically expressed as the fraction of the weight excluding the oven-dry fuel mass. Fuel is often categorized into dead and living fuels depending on its moisture content. When it is less than 30% the fuel is categorised as dead, but is living when it ranges between 30% to around 300% (Sun et al., 2006). In living plants, water plays an important part in photosynthesis, cellular metabolism and structural support. In dead material, water maintains the cellular structure until it has decomposed (Benson et al., 2009). When the dead material is lit, the heat from the combustion does not only drive moisture out of the dead fuel, but out of the present living fuels as well. If the leaves have a low moisture content, such as leaves with high fibre content and leaf specific weights, less water needs to be driven out prior to ignition and the material will therefore burn more easily (Bond &

van Wilgen, 1996). Apart from ignition, fuel moisture also affect other aspects of fire behaviour, such as spread rate, intensity, smoke production, fuel consumption and plant mortality. The plant mortality depends on how much moisture there is in the live vegetation. If the vegetation is dry, it leads to more intensive fires and a higher plant mortality and if the vegetation is moist the fuel may act as a heat sink and retard fire propagation (Pyne et al., 1996).

2.3 Wet-dry areas

The global distribution of different biomes are determined mainly by different climatic factors, such as temperature and precipitation. Some of the biomes which can be classified into a wet-dry area are savannah and the Mediterranean. They both have a more pronounced wet and dry season compared to other terrestrial biomes and high biodiversities due to different adaptations to seasonal and disturbance effects. The difference between them is that the savannah usually occurs in the interior of continents (Chapin et al., 2002), with heavy zenithal rains during the summer period and arid conditions during the cooler season, whilst the Mediterranean is found by the coast of continents, milder winters and where most of the rain falls during winter (Breckle, 2002).

A more thorough description of the savannah biome in South Africa and the Mediterranean regions can be found in appendix A. Other savannah regions, such as the ones in North America, Australia and Brazil or the Mediterranean region in Chile will however not be described, due the focus on savannahs in Africa.



Map 1: The location of Mediterranean regions in the world. (Redrawn after Dallman, 1998)

2.4 Fire models

The occurrence of fire and its behaviour can be complex for those who have to manage it and managers all over the world use different systems to track its influence (Fujioka et al., 2009). For more than 40 years, mathematical models have been developed in order to predict how a fire will spread in different environments and what intensities it will have under certain climatic conditions and fuel availability (Rothermel, 1972).

Most of the models used today are based on the work of Rothermel, who produced a National Fire Danger Index Rating System (NFDIRS). He was the first to develop a mathematical model for predicting rate of spread and intensity in a continuous stratum of fuel. It is developed around the statement that the most essential process of the flame propagation mechanism is the heating of fuel ahead of the flame. When the surface is dehydrated and surface temperatures are raised, the fuel begins to pyrolyze and release combustible gases which can be ignited (Rothermel, 1972).

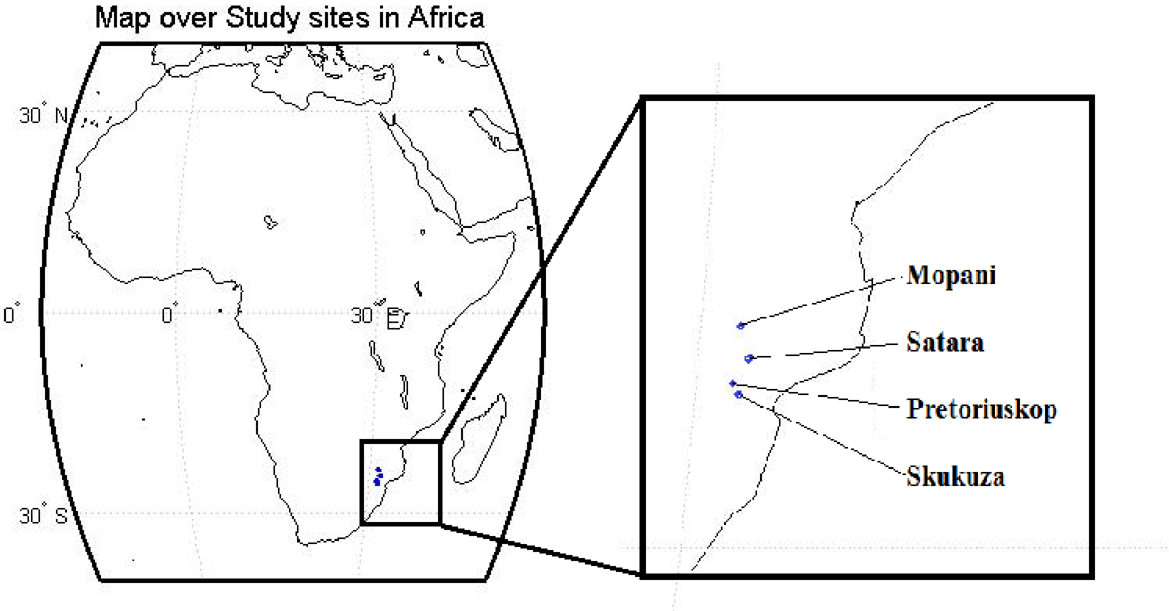
A fuel model in this context is a mathematical description of the structure and texture of a particular fuel type (Bachmann & Allgöwer, 2002). In order to achieve this model, a few assumptions had to be made about the fuel load. One assumption concerns the heterogeneity of fuel size and its distribution. Fine fuels, such as needle litter, grass, brush, and logging slash are easy to model, whilst accumulation of broken branches, treetops, snags and other lesser vegetation are harder due to a more discontinuous pattern in which they are found. It is also assumed that fuel with similar properties can be grouped into different categories, for example depending on if it is living or dead fuel or by its size (Rothermel, 1972). The model which Rothermel produced is the basis for many other models, for example the fire module SPITFIRE. SPITFIRE use the same equations as have been developed by Rothermel in order to determine the fire rate of spread and was chosen since it can be applied to many different biomes (Thonicke et al., 2010).

3 Method

3.1 Study area

The Kruger National park was established in 1926 and is located in the north-eastern part of South Africa. It has an area of 1.95 *10^6 ha (Van Wilgen et al., 2004) where approximately 1983 plant species can be found, including more than 400 tree and shrub species and over 220 different grasses. The climate is characterized by extended wet and dry periods over the year, with a mean annual rainfall amount from around 750 mm in the south to 350 mm in the north.

In 1954, an experimental burn plot (EBP) trial was initiated by the newly formed Biological Section of Kruger National Park, with the intention to study the effect of fire during different seasons and how fire frequencies affected their local biotic populations. At present, it is one of few ongoing long-term projects in Africa focusing on research in fire ecology. The trial consists of 16 strings of plots made up of four replicates in four different landscapes called Mopani, Pretoriuskop, Satara and Skukuza (see map 2). Each of these replicates consists of 12 full plots, which all receives different fire treatments. The plots are approximately 7 ha in size and the total sum of plots at each site is divided into two randomised sections. Of all the scheduled burns, more than 80% have been applied since the beginning of the experiment. The reason for deviation is either too sparse vegetation cover due to drought and/or herbivory impact or too high moisture content for successful ignition and burning. Other complicating factors affecting the results of the experiment is the lack of duff randomisation and soil variability. One suggestion made in order to improve the experiment even further is to time the burning of plots to specific conditions (e.g. spring rains) instead of specific calendar months used today (Biggs et al., 2003).



Map 2: Map over the four study sites in South Africa.

The vegetation and average annual rainfall at each site can be seen in table 1. Mopani is classified as a *Colophospermum mopane* shrubveld, which hardly consist of any larger trees or shrubs, but the field layer is however rich in herbaceous species. Pretoriuskop is classified as Lowveld Sour Bushveld, which is an open tree savannah with relatively few low shrubs and a sparse grass cover. Satara is an Acacia savannah with Knobthorn as the dominant plant. It has a moderate to sparse shrub layer and sparse forb layer. Lastly, Skukuza is classified as *Combretum* woodland, which is a dense bush savannah with sparsely dispersed larger trees and a dense grass layer (Gertenbach, 1983). The FTC (Fractional Tree Cover) was only available for the Skukuza site and ranged between 0-60%, Whilst LAI (Leaf Area Index) estimates ranged between 0.22-0.44 (Kirton et al., 2009). LAI data was also achieved from Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) via remote sensing. They indicate that the average yearly LAI of all the sites between 2000-2006 varies between 0.54-1.59, with a variance between a maximum of 6.8 in Pretoriuskop down to bare ground (a LAI of 0) in all sites (daac.ornl.gov). Despite some higher LAI values under favourable conditions, the overall value is fairly low As with most African savannahs, the grass fuel loads are dominant and contribute around 70-98% of the total fuel (Shea et al., 1996). The soil consists of mainly sand and sandy loam at site Pretoriuskop and Satara and a higher clay content (between 20-50%) at site Mopani and Skukuza (Gertenbach, 1983).

The fire intensity in the park is not only influenced by the amount and type of fuel load, but is also dependent on the season at which the fire is lit. This is mainly a result of changes in fuel moisture. The mean fire intensities were lowest in summer fires (1225 kW/m), followed by autumn fires (1724 kW/m) and highest in winter fires (2314 kW/m). However, the spring fires showed more variability and a higher frequency of high intensity fires. It has also been shown that the season has a higher effect on the intensity compared to post-fire age (Govender et al., 2006).

Table 1: The coordinates for the four different sites together with the average amount of rainfall.

Site	Latitude	Longitude	Average annual rainfall (mm)	Type of vegetation
Mopani	-23.31	31.23	496,3	shrubveld
Pretoriuskop	-25.10	31.16	737,2	bushveld
Satara	-24.23	31.46	543,7	Acacia savanna
Skukuza	24.59	31.35	550,4	woodland

3.2 LPJ-GUESS-SPITFIRE

In order to understand and predict the complex dynamics of different ecosystems around the world, a series of models have been constructed with various approaches depending on what the main goal of the model is. A Dynamic Global Vegetation Model (DGVM) combines representations of biogeochemical and vegetation dynamic processes and vegetation composition, which ultimately changes ecosystem properties. The LPJ (Lund-Potsdam-Jena) model has been developed as a DGVM which is process-based but still computationally efficient, including the major processes of vegetation dynamics and a limited fire module with an emphasis on comprehensive evaluation.

The vegetation within each site is classified into PFTs (Plant Functional Types). Every higher plant species belongs to a PFT, whose dynamics and physiology all have similar key attributes. The phenology can be evergreen, summergreen or raingreen. Herbaceous PFTs are treated as evergreens, except under water- or temperature-limited conditions where they adopt a raingreen or summergreen phenology instead (Sitch et al., 2003). It is also assumed that all the plants within each PFT react in a similar way to a fire disturbance (Krivtsov et al., 2009). Usually 10 PFTs, eight woody and two herbaceous, are defined and each PFT has bioclimatic limits which determines whether it can survive and/or regenerate at current climatic conditions in different locations. Furthermore, LPJ includes vegetation structure, dynamics, competition between other PFTs and soil biogeochemistry.

Opposite to LPJ-DGVM, the model framework LPJ-GUESS contains a cohort-mode, using a number of simulated patches replicates. GUESS stands for General Ecosystem Simulator and is based on the same formulations as LPJ-DGVM (described in further detail in Smith et al., 2001) and models the structure and dynamics of terrestrial ecosystems from a landscape to global scale. It also represent the vegetation with different age classes, growth characteristics and stages of recovery or succession following a disturbance. The coverage of a site is simulated as the average among the replicate patches (Smith et al., 2001).

Fire is the only natural disturbance represented in LPJ explicitly (Sitch et al., 2003), but the original fire model is very limited and an implementation of the combined effect of fire occurrence and its effect on the ecosystem was required. The result was the development of a process-based module called Spread and InTensity of FIRE (SPITFIRE). It uses a simplification of Rothermels equation in order to predict the rate of fire spread, intensity and residence time of the flames (Thonicke et al., 2010). To start a fire in the model, a minimum temperature at which the current fuel ignites must be reached. Another requirement is an sufficient amount of fuel. A fuel load less than 0.2 kg/m² is insufficient and little or no area will be burned despite favourable conditions. The third threshold is fuel moisture. If the fuel moisture is high, most of the available energy is consumed by vaporization of water. This threshold is called 'moisture of extinction'. Only if all favourable conditions are met, a fire is promoted. The effect of fire is assumed to be determined by the length of the fire residence time and fire resistance. Fire resistance is the fraction of individuals killed in a fire. Grasses and leaves which are classified as leaf litter, are fully consumed, whilst woody litter is only partly consumed depending on their composition (Thonicke et al., 2001). Living trees are seldom fully consumed (Pyne et al., 1996). Instead, parts of the simulated vegetation dies and is transferred into the dead litter pool. When the next fire event takes place, then it can be partly consumed (Thonicke et al., 2001).

The model experiment setup was applied on a 1*1 degree longitude/latitude grid cell over the different study sites in South Africa where all sites are included within this box. The simulations started with a spin up period of 1000 years without fires in order to reach a stable vegetation structure. The number of patches simulated in the model was set to 50, in order to eliminate sudden stochastic processes, for an example caused by tree mortalities.

3.3 Turnover times and build-up rates

Table 2-5 show the different turnover times, decomposition rates in ratio litter decomposed each year and lastly the build up rates for leaves and wood, which have been found in the literature study for previously mentioned sites. The defined temperature for turnover times in LPJ is 10 degrees, whilst the temperatures for the different sites found in the literature study varied between 10 in Europe to 25 in Australia. Since the values found in the literature has not had the same defined temperature, they cannot be compared directly to the values in LPJ. In table 2, the total range of all the turnover times is between 0.28-7.14 years, but most of them range between 0.8-2.5. This shows that for almost all of the sites, the turnover time of 2.85 years used in the model might be too high to give a proper representation of the wet-dry areas.

A higher turnover time might be caused by many different reasons. For Mediterranean ecosystems, the decomposition of litter is a slow process due to its physical structure and chemical composition, but also because of a water deficit during summer. It has been found where water availability is limited in dry Mediterranean areas, the rate of litter loss is positively correlated with the water content within the litter (Arianoutsou & Radea, 2000). Another reason is given by Bengtsson et al. (2011), where the leaf litter decomposition in the Mediterranean fynbos climate range between 0.28-5.56. The reason presented for the variance was both due to the nutrient status in the soil and different fire frequencies, where some species decayed faster than others. They also showed that plant litters with a higher nutrient content composed faster compared to nutrient poor litter.

Table 2: turnover times for leaf litter in years at a defined temperature and moisture content and the decomposition rate in amount decomposed per year for different wet-dry areas.

Turnover times and decomposition rate for leaf litter (years)

Site	Turnover time	Decomposition rate	Source
Africa savanna	0.3—1.5	0.67—3.33	Attignon et al., 2004
Africa fynbos	0.28—5.56	0.18—3.57	Bengtsson et al., 2011
Australia	0.89—2.33	0.43—1.12	Aerts, 1998
Australia	1.5—3.5	0.29—0.67	O'Connell, 1988
Europe	0.93—7.14	0.14—1.08	Aerts, 1998
Europe	0.37—2.85	0.35—2.7	Cortez, 1998
Europe	0.79—2.36	0.42—1.27	Escudero et al., 1992
California	2.5—4.76	0.21—0.4	Aerts, 1998
California	4.35—4.88	0.2—0.23	Schlesinger & Hasey, 1981

Table 3 presents the annual build-up rates for leaf litter, which ranges between 0.09 in Australia to 2.91 kg/m² in Europe. The amount of litter produced depends mainly on the age of the stand, the morphology of the plants, temperature and precipitation. For the Mediterranean ecosystem, the annual input of litter consists mainly of leaves, where it usually varies between 60-80% of the total litter input. For ecosystems which have nutrient-poor soils, the input and decomposition of leaves are important processes which in turn affect the stand productivity. Another important factor is water availability, where some species shed their leaves during dry periods in order to conserve energy and moisture (Arianoutsou & Radea, 2000).

Table 3: The yearly build up rates for leaves in kg/m² for different wet-dry areas.

Build-up rate for leaf litter (kg/m²)		
Site	**Range**	**Source**
Africa savanna	0.3—0.4	Govender et al., 2006
Africa savanna	0.19—0.5	Tiessen et al., 1998
Africa fynbos	0.35	Bond & van Wilgen, 1996
Australia	0.09—0.6	Gill et al., 1981
Australia	0.2—0.25	Gould et al., 2011
Europe	0.25—0.29	Almagro & Martínez-Mena, 2012
Europe	0.33—1.31	Baeza et al., 2006
Europe	0.26—0.5	Fioretto et al., 2003
California	0.36	Bond & van Wilgen, 1996

In table 4 the turnover time for wood varies between 2.94-32 and most values range between 6-20, which is considerably higher than the 2.85 years originally set by the model. However, they cannot be compared directly since they have not had the same temperature conditions. Woody materials are high in cellulose and ligning content, which makes it more difficult to decompose compared to leaves (Pyne et al., 1996). One of the highest variations found in the study was for Europe by Paul & Polgase (2004), where the turnover time varied between 2.94-25 years. However, according to the authors, one of the reasons for the longer decomposition rates were due to a possible overestimation of litterfall and littermass since the accumulation of litter had not yet reached equilibrium in many of the study sites. Bark and wood material are more rarely replaced or dropped and the decomposition time is longer due to their molecular structure and resistance to different decomposition activities. The values presented by Harmon et al. (1986) representing turnover times for wood from species found in the Chaparral also shows high variance, ranging between 6-32 years. Here it is said that the turnover times are influenced by species, size, micro-climate and the type of mortality. A tree killed by a fire appears to decay slower compared to trees killed by insect herbivory, since the insects reduce the particle size, modifies the wood during their digestion and introduces microbes.

Table 4: turnover times in years at a defined temperature and moisture content and the decomposition rate in amount decomposed per year for different wet-dry areas.

Turnover times for wood litter (years)			
Site	**Turnover time**	**Decomposition rate**	**Source**
Africa savanna	6—24	0.042—0.17	Harmon et al., 1986
Africa fynbos	7.14—25	0.04—0.14	Paul & Polgase, 2004
Australia	5.75—14.93	0.067—0.17	Brown et al., 1996
Australia	5—7.14	0.14—0.2	Paul & Polgase, 2004
Europe	2.94—25	0.04—0.34	Paul & Polgase, 2004
Europe	4.26—20	0.05—0.23	Rock et al., 2008
California	6—32	0.031—0.17	Harmon et al., 1986

The yearly accumulation of wood ranges between 0.01 kg/m² in Europe and 3 kg/m² in California. According to Harmon et al. (1986), the build up rate in California is primarily influenced by the massiveness and productivity of the present trees. However, the values can increase markedly if there is some kind of disturbance present during the observation period, like a fire or insect outbreak.

Table 5: Yearly build up rates for wood in kg/m² and for different wet-dry areas.

Build-up rate for wood litter (kg/m²)		
Site	**Range**	**Source**
Africa savanna	0.19	Tiessen et al., 1998
Africa fynbos	0.35	Bond & van Wilgen, 1996
Africa fynbos	0.07—0.08	Arianoutsou & Radea, 2000
Australia	0.174	O'Connel, 1987
Europe	0.01—0.12	Arianoutsou & Radea, 2000
Europe	0.28—0.65	Rapp et al., 1999
California	0.05—3	Harmon et al., 1986

The result of the literature study shows that within LPJ-GUESS, there is an overestimation of the turnover time for leaves and an underestimation for wood. According to these results, new parameter values will be tested in order to get a better representative. For turnover times for leaves ($\tau_{LITTER\,leaf}$) new values between 0.3-2.4 with an interval of 0.3 will be tested and for turnover times for wood ($\tau_{LITTER\,wood}$) it will be values between 4-12 with an interval of 0.5.

3.4 Comparison of simulated and observed fuel loads

The data used to analyse the accuracy and to improve the LPJ-GUESS-SPITFIRE framework are based on four study sites in Kruger National Park. These study sites are divided into plots with different fire intervals and are burned at specific months of the year. The sampled intervals are:

- annual burning in August (all four sites)
- biennial burning in February, April, August, October and December (all four sites)
- triennial burning in February, April, August, October and December (all four sites)
- quadrennial burning in October (Mopani and Satara)
- sextennial burning in October (Mopani and Satara)

Observed data from these sites were obtained between 1982 to 2003 and used for comparison of simulated values. Due to some complication with commencing fires, as mentioned in section 2.1, there were sometimes delays for several months in burning before the litter loads were measured and then set aflame. If the delays were more than two months prior or after the prescribed month of fire ignition, the data was excluded from the analysis. If there were multiple burns at the same time but at different patches, the average value of these sites was extracted.

Since the focus in LPJ-GUESS-SPITFIRE lies on litter used in surface fires, the two constants which will be examined further are the turnover times of leaf ($\tau_{LITTER\,leaf}$) and wood ($\tau_{LITTER\,wood}$). The τ values used in LPJ-GUESS-SPITFIRE are presented by Meentemeyer (1978), representing the logarithmic litter decomposition in years at a temperature of 10°C and ample soil moisture. In the original setup of the model, all of the decayrates are set to 2.85 years. From these parameters in connection with the litter production of the vegetation, the decayrate, amount of litter presently on the ground and the amount of carbon going through different soil layers are calculated. The model does not differ between leaf litter input from grasses or trees.

The litter decomposition is dependent on soil temperature and moisture. For above-ground litter decomposition, it is also dependent on air temperature calculated by using the modified Arrhenius equation (Lloyd & Taylor, 1994):

$$g(T) = \exp[308.56 \times (\frac{1}{56.02} - \frac{1}{(T+46.02)})] \qquad (1)$$

where T is temperature (°C). The modification is represented as a decline in activation energy as temperature increase. For soil moisture, the following empirical relationship from Foley (1995) is used:

$$f(W_1)=0.25+0.75\times W_1 \tag{2}$$

where W_1 is the monthly average soil moisture content in the upper soil layer. The monthly decomposition rate with respect to temperature and soil moisture is calculated by the following formula:

$$k=\frac{(\frac{1}{\tau 10})\times g(T)\times f(W_1)}{12} \tag{3}$$

where τ10 is turnover times in years at different soil depths. It is said in the model that decomposition follows the first-order of kinetics (Olson, 1963):

$$\frac{dC}{dt}=-kC \tag{4}$$

where C is the pool size, *t* is time and *k* the monthly decomposition rate. When the formula is integrated with respect to time, the pool size at any time can be given:

$$C=C_0\cdot e^{-kt} \tag{5}$$

where C_0 is the initial size of the pool.

The decayrates are calculated on a daily basis and all the different litter pools are summed up into one. Since leaf litter and woody litter are used in surface fires, a new output file was programmed which writes out the daily litter amount of leaves and wood individually. The output is written in a standard unit of kg Carbon/m^2, but in order to get plant dry mass (kg/m^2), a factor of 2.2 was multiplied with the output (Tang et al., 2010).

In order to evaluate how well the existing model parametrisation simulates fuel load over the precipitation gradient covered by Govender et al. (2006), Mathworks MATLAB® R2011a was used to generate instruction files, start up LPJ-GUESS with similar settings as have been observed in Kruger National Park and to make meshplots. In the paper by Govender et al. (2006), the relationship between mean annual rainfall, fire interval and grass fuel loads where calculated and plotted. They fitted the following formula to the measured data:

$$z=\frac{382.9}{3.3x}+979.4y-0.001x^2+0.37xy-161.8y^2 \tag{6}$$

where z = fuel load (kg/ha), y = time since last fire (year) and x = mean annual rainfall over the previous two years (mm). To be able to make a model comparison with what the current LPJ-GUESS-

SPITFIRE model simulates, the output was compared by making a similar graph. When the model was used to simulate the fuel load at the different sites, the fuel load were taken at the same date and year and then compared to the observed fuel loads, month and year.

3.5 Simulation set up

Temperature and amount of precipitation are two important variables which affect what types of PFTs that can be present in an area, its growth and evidently the amount of litter it produces. The simulated climate affecting these PFTs is usually driven by monthly climate data as is described in Smith et al. (2001) and linearly interpolated to pseudo-daily values. The PFTs present at the simulated area are Tropical broadleaved raingreen tree (TrBR) and C4 grasses according to Govender et al. (2006). The trees are part of a group called tropical trees, where the parameters for the minimum daily temperature requirement in order to survive and the minimum daily temperature in order to establish has been set to 15,5°C. This minimum value is meant to reflect the coldest month rather than the coldest day. Since the standard LPJ-GUESS uses monthly climate with one value per month the value is linearly interpolated and hence a whole month as cold as this minimum value (on average) can lead to an exclusion of the trees. In order to get an establishment of tropical trees which were excluded due to present single cold days in the data, the parameters of minimum temperature for establishment and survival were lowered from 15.5°C to 10°C. This was also done in order to get an establishment of C4 grasses.

The other important variable affecting litter production from the different PFTs is precipitation. A higher water input leads to increased growth and evidently increased litter production. Hence the precipitation had to be adapted to the values measured at the site, since the available climate has a very coarse resolution of 1*1 degree longitude/latitude. The precipitation values were read in for each site either artificially varied over a gradient or according to the data measured at the site provided by Navashni Govender. This made it possible to choose a specific rainfall amount which is to be met every year, without disrupting the rainfall pattern existing for the specific site. For the studied sites, monthly precipitation values were obtained but daily values would have been preferable. Actual monthly precipitation were provided for the different sites and for a time period between either 1980-2006 or 1974-2006. The monthly or annual values were read in and superimposed on the daily rainfall data by Weber et al. (2009) to maintain the intra-annual and intra-monthly variability.

A problem which often occurs when certain aspects of simulated ecosystems are of interest is that if both grasses and trees are present, they may not be present at the same proportion as has been measured under the experiment for which the aspect (in this case fuel load) has been measured. In

LPJ-GUESS-SPITFIRE, trees dominated over grasses for the simulated sites, which lead to an over-representation of this category. Since grasses have been found to be more dominant for savannah ecosystems, the decision was made to make them more competitive. It is known that all trees except Tropical Broadleaved Raingreen tree (TrBR) are absent in Kruger National Park and hence all others were excluded from the simulation. Additionally, the model was changed from the standard settings of Sitch et al. (2003) to include a species specific water uptake and a drought tolerance of 0.45 was given to TrBR. A drought tolerance of 0 was given to C4 grasses. A low value indicates a drought tolerance in the PFT, whereas a higher value leads to drought susceptibility. Since C4 grasses got a value of 0, it will therefore be less sensitive to drought and be able to grow at lower water inputs compared to TrBR. Few studies were available to give a proper range of drought tolerances in savannah ecosystems. Gaff (1977) looked at different plant species in South Africa and their drought tolerance, where it was specified as the survival rate of 50% or more of the tissue after severe drought. None of the species tested had a drought tolerance over 0.3, but is not quite the same as the definition used in the model. It was therefore decided to compare simulated LAI values with observed values from ORNL (daac.ornl.gov) until similar LAI values were produced by the model. Lastly r_ck, which is the proportion of individuals killed if the tree is covered in fire were increased from 0.87 to 0.99, in order to have a smaller proportion of trees surviving a fire outbreak in favour of the grasses.

3.6 Statistics for quantifying the agreement between observed and modelled data sets

To quantify the agreement between actual and simulated fuel loads, RMSE (root mean square error) was used for both leaf and wood. RMSE is an accuracy measure used when comparing different methods applied to the same data set. The RMSE is defined as:

$$\text{RMSE} = \sqrt{\frac{\Sigma_{i=1}^{n}(x_{1,}i - x_{2,}i)^2}{n}} \qquad (7)$$

where x1 are the observed values and x2 are the simulated values. A value of 0 means the two different data sets are exactly the same and with increasing RMSE the difference increase as well. It is a good estimator when testing the effect of a particular constant, but not for testing more than one restriction (Toro-Vizcarrondo & Wallace, 1968). The RMSE was calculated by comparing the simulated data with fitted relationship between fire-return interval, precipitation and fuel load of Govender et al. (2006). Furthermore, RMSE will be calculated for different annual rainfall amounts as well in order to evaluate what influence the amount of rainfall has on the simulated data.

After the first simulations have been made, a series of boxplots were produced; one for the effect of fire interval on leaf fuel load (figure 7), two over the seasonal variation of observed and modelled outputs for site Mopani and Pretoriuskop (figure 8 and 9) and two for the same sites but only with fuel loads measured in October. Figures for Satara and Skukuza can bee seen in appendix B. The simulated data is extracted from the model for the date prior to a fire being lit and at different fire return intervals, where the same fire times in the sites have been replicated into the simulation set up of the model. This data is then compared to the observed data at each site. In order to compare the model's concordance with observed fuel loads and how the amount of rainfall influences the amount, combined scatter and line plots where produced for each site and with or without refinements. A burn interval of two years was chosen, since it had most available data.

4 Results

4.1 Decomposition rates with and without parameter refinements

Table 6 shows the results of the simulation runs for different τ_{LITTER} values for leaves, their corresponding averages, medians, standard deviations, and RMSE values within the combined sites precipitation range of 100 to 700 mm. The best RMSE values were for a turnover time of 0.9 years. This value was chosen as the optimal one since it falls well into the range of observed fuel loads varying between 0.06-0.4 kg/m^2. It has an average build up rate of 0.18 kg/m^2, which is slightly lower than the lower limit of 0.19 kg/m^2 found in the literature study, but fits in well overall. The worst RMSE overall without the inclusion of the presently used value of 2.85 is for a turnover time of 2.4 years.

Table 6: The average, median, standard deviation and RMSE values (modelled versus observed data from Govender et al. (2006)) for different turnover times of leaves. Average, median and RMSE is given in plant dry mass (kg/m^2) and has been generated by simulating the fuel load at an average annual rainfall between 100-700 mm and a fire interval between 1-6 years.

Turnover times and fuel loads for leaf litter				
τ_leaf (years)	**Mean (kg/m²)**	**Median (kg/m²)**	**St. dev (kg/m²)**	**RMSE (kg/m²)**
0,3	0.15	0.13	0,11	0.14
0,6	0.21	0.21	0.13	0,12
0,9	0.25	0.24	0.15	0,11
1,2	0.28	0.27	0.16	0,12
1,5	0.31	0.30	0.17	0.13
1,8	0.33	0.31	0.18	0.15
2,1	0.34	0.33	0.19	0.16
2,4	0.37	0.38	0.20	0.17
Original (2,85)	0.38	0.38	0.21	0.18

Table 7 shows the turnover times if only grass litter is simulated, with the average, median, standard deviation and RMSE values. Since there are no trees within the simulated area competing for resources, all the values are slightly higher compared to table 6. If only grasses were considered and modelled, a turnover time of 0.6 years would be more preferable than 0.9 years. Furthermore, the RMSE value increases more sharply in comparison to table 6.

Table 7: The average, median, standard deviation and RMSE values for different turnover times of grass. Average, median and RMSE is given in plant dry mass (kg/m²) and has been generated by simulating the fuel load at an average annual rainfall between 100-700 mm and a fire interval between 1-6 years.

Turnover times and fuel loads for grass litter				
τ_grass (years)	Mean (kg/m²)	Median (kg/m²)	St. dev (kg/m²)	RMSE (kg/m²)
0,3	0.24	0.26	0.13	0.073
0,6	0.31	0.35	0.15	0.072
0,9	0.39	0.44	0.17	0,11
1,2	0.43	0.43	0.19	0.14
1,5	0.46	0.46	0.21	0.17
1,8	0.49	0.49	0.23	0.20
2,1	0.52	0.52	0.25	0.23
2,4	0.54	0.54	0.26	0.24
Original (2.85)	0.56	0.56	0.28	0.27

Table 8 gives the RMSE values for different annual rainfall amounts for the present and refined set up with and without an inclusion of trees. The best RMSE values are obtained at low rainfall values and the error increases if the precipitation increases. One of the best RMSE values within a higher precipitation range is found for a turnover time of 0.9 years and an annual rainfall amount of 600, which is within range for most of the studied sites. The table also shows that if trees are excluded the RMSE is better for a rainfall amount of 700 mm , but does not differ much for the others. But if the original turnover times were used, τ_{grass} would have been much worse compared with an inclusion of trees.

Table 8: RMSE values with or without trees in relation to amount of annual rainfall. τ_{leaf} list simulated values including TrBR and grasses and τ_{grass} lists simulations with only grasses. The original turnover time of 2.85 years is compared with the preferred turnover time of 0.9 years for τ_{leaf} and 0.6 years for τ_{grass} .

RMSE values of τ rates with/without trees and at different annual rainfall amounts				
Annual rainfall (mm)	τ_leaf (0.9 years)	τ_grass (0.6 years)	τ_leaf (2.85 years)	τ_grass (2.85 years)
100	0.092	0.110	0.073	0.073
200	0.057	0.075	0.081	0.083
300	0.039	0.045	0.17	0.17
400	0.088	0.039	0.27	0.28
500	0.110	0.078	0.32	0.36
600	0.075	0.088	0.13	0.39
700	0.30	0.072	0.19	0.39

Table 9 shows the turnover times for wood litter, with the range from minimum to maximum level, average, median and standard deviation. It should be noted that the table only considers annual precipitation between 100-400. Any higher values lead to unreasonable results, since some conditions promoted a higher increase in wood litter compared to others. This changes the mean values considerably, but not the median values. The highest average of wood litter load of 0.003 kg/m^2 was found at a $\tau_{LITTER\,wood}$ value of 11 and 12. The highest median of 0.0029 kg/m^2 was at $\tau_{LITTER\,wood}$ values of 5 and 6. This means more simulated fuel loads at different scenarios of fire interval and yearly average rainfall were higher compared to results from other turnover times. Since no observation data was available for wood litter, a further refinement of the data could not be done. Furthermore, due to the fact that the standard deviation is almost as high as the average in all the simulated turnover times, it is very hard to draw any conclusions and the result becomes questionable. What can be stated is that the production of wood litter is general fairly low, which the model was meant to do. But together with the standard deviation the table also show that once trees are able to establish, the amount of wood litter quickly increases.

Table 9: The average, median and standard deviation for different turnover times of wood. Average and median values is given in plant dry mass (kg/m^2) and has been generated by simulating the fuel load at an average annual rainfall between 100-400 mm and a fire interval between 1-6 years.

Turnover times and fuel loads for wood litter

τ_wood (years)	Mean (kg/m^2)	Median (kg/m^2)	St. dev
4	0.0024	0.0024	0.0015
4,5	0.0027	0.0027	0.0015
5	0.0028	0.0029	0.0016
5,5	0.0027	0.0026	0.0017
6	0.0029	0.0029	0.0018
6,5	0.0029	0.0028	0.0019
7	0.0028	0.0023	0.0019
7,5	0.0029	0.0027	0.0019
8	0.0029	0.0028	0.0019
8,5	0.0029	0.0028	0.0020
9	0.0029	0.0024	0.0020
9,5	0.0029	0.0027	0.0020
10	0.0028	0.0024	0.0020
10,5	0.0029	0.0027	0.0020
11	0.0030	0.0028	0.0020
11,5	0.0029	0.0026	0.0020
12	0.0030	0.0025	0.0021
(Original) 2.85	0.0022	0.0021	0.0013

4.2 Fuel loads

Figure 2, 3 and 5 shows the leaf litter load at different fire intervals and annual rainfall amounts, figure 4 shows values for simulations with trees and figure 6 without trees. It should be noted that figure 3 and 5 are shown in a different angle in order to see the change in litter at different simulated annual rainfall amounts. As can be seen in figure 2, the grass fuel load in Kruger National Park increases with increased rainfall and fire interval until it reaches a fire interval of 4 years, where the fuel load starts to decrease with increasing fire interval instead. According to Govender et al. (2006), the mean grass fuel load in the annually and in the sextennially burnt plots were 0.29 kg/m² over the years of the ongoing fire experiment and in the bi-, tri- and quadrennial burnt plots average fuel load was 0.4 kg/m².

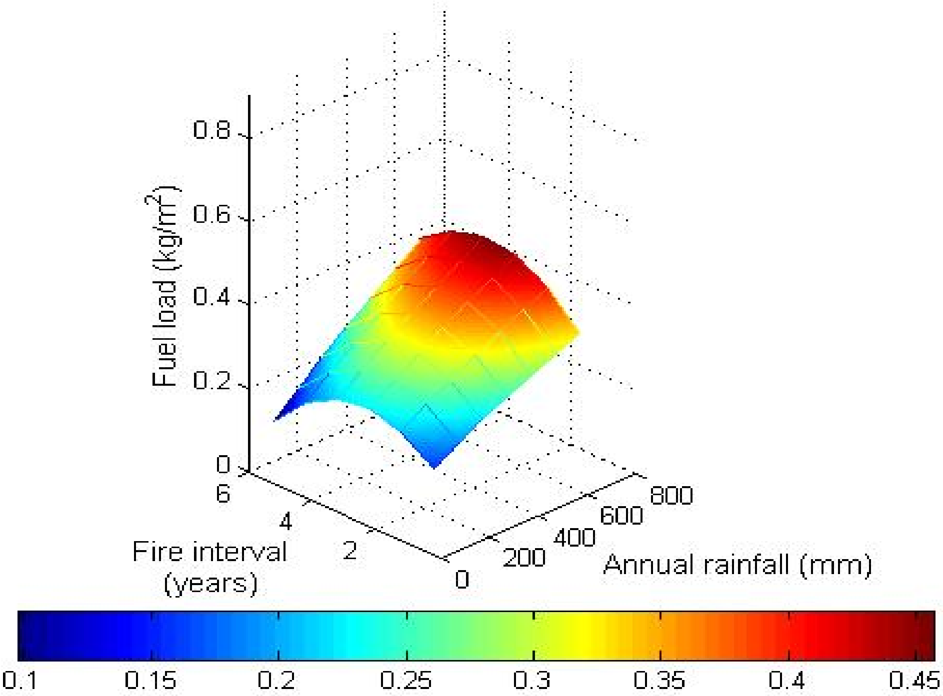


Fig. 2: The average leaf fuel load for all of the experimental burning plots in Kruger National Park, depending on fire interval and average yearly rainfall. The fire interval is between 1-6 years and amount of annual rainfall is between 100-700 mm. The figure has been drawn from Govender et al., (2006).

Figure 3 shows the simulation for leaf litter loads done for the same location in LPJ-GUESS with its original turnover time of 2.85 years. In this simulation, the fuel load increase with increasing amount of rainfall and fire intervals up to an annual rainfall of 500 mm. At sites with higher precipitation, TrBR starts dominating the patches and less leaf grass litter is produced. Only if the fire interval is short enough can grasses maintain their dominant position, which is more related to reality. The model does not have the same decrease in fuel load after the fire interval exceeds 4 years. The fuel load seems to increase with improving growth conditions up to a certain point and is afterwards decreased by tree establishment. Figure 3 also has a slightly higher maximum leaf litter load and is almost twice as high at an annual rainfall amount of 500 mm compared to figure 2.

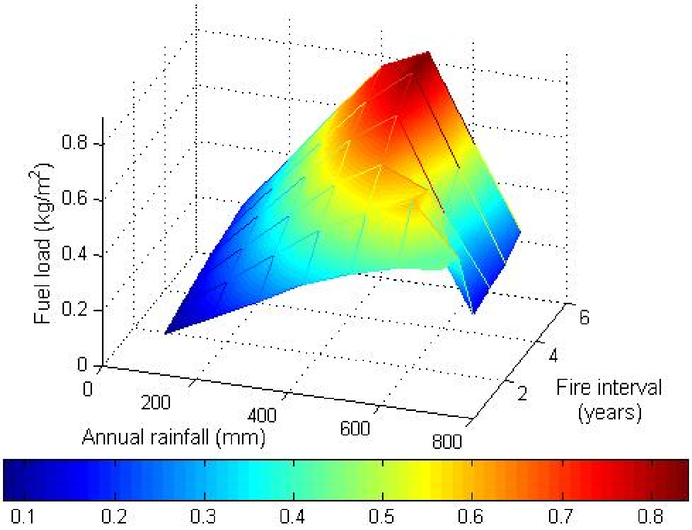


Fig. 3: The average leaf fuel load simulated by LPJ-GUESS depending on fire interval and average yearly rainfall, with no parameter optimisation. The fire interval is between 1-6 years and amount of annual rainfall is between 100-700 mm. $T_{LITTER\,leaf}$ is set to 2.85.

Figure 4 shows the average fuel load for wood litter with similar settings as figure 3 at a litter turnover time of 2.85 years. Together with figure 3, it shows the transition from a more dense grass vegetation within the patches to a tree dominated simulation as the amount of rainfall and fire interval increase. The increase in wood litter becomes clear at an yearly rainfall amount of 500 mm, which is the same value as for figure 3 where leaf litter start to decrease. It should be noted however that this figure cannot be compared with figure 2, since it only encompasses grass litter.

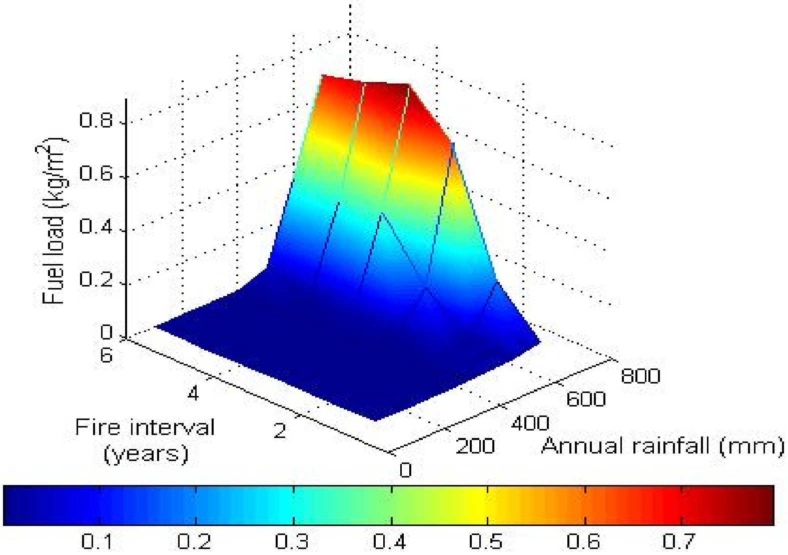


Fig. 4: The average wood fuel load simulated by LPJ-GUESS depending on fire interval and average yearly rainfall, with no parameter optimisation. The fire interval is between 1-6 years and amount of annual rainfall is between 100-700 mm. $T_{LITTER\,wood}$ is set to 2.85.

Figure 5 is a meshplot of the leaf litter simulation using the optimized $\tau_{LITTER\,leaf}$ of 0.9 years. The shape of the curve is very similar to figure 3 with no parameter optimisations, with the difference of a lower upper limit of fuel load, which gives a better agreement with the plot made by Govender et al., (2006) (see figure 2).

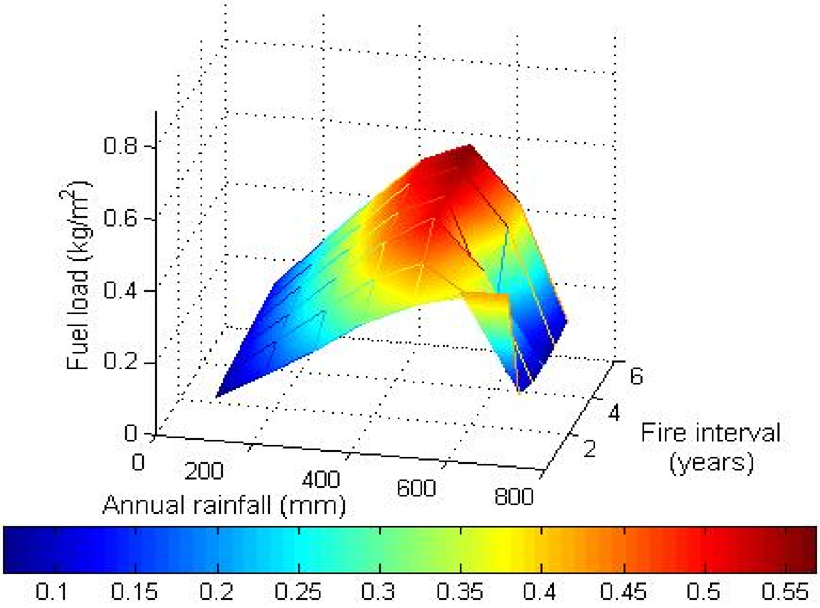


Fig. 5: The average leaf fuel load simulated by LPJ-GUESS depending on fire interval, average yearly rainfall and with parameter optimisation. The fire interval is between 1-6 years and amount of annual rainfall is between 100-700 mm. $T_{LITTER\,leaf}$ is set to 0.9.

Figure 6 shows the grass fuel load if all the trees were excluded from the simulated site, with a turnover time of 0.6 years together with the experimental values by Govender et al. (2006) (see equation 6). Even though the simulated fuel load increases faster compared to Govender's data, it still shows the best similarity compared to the previously shown figures. However, the model does not have the same decrease in litter with increasing fire interval, but nevertheless follows a similar pattern to what has been found on site. Compared with tree inclusion, the model further simulates a small source release in NEE (Net Ecosystem Exchange) of carbon for these sites (with an average of 0.0064 ±0.0084 kg/m² over a period of 20 years) and an increase in heterotrophic respiration (0.12 ±0.0082 kg/m² averaged over the same time period). Without current parameterisation, NEE was on average 0.056 ±0.023 kg/m² and heterotrophic respiration was 0.08 ±0.013 kg/m².

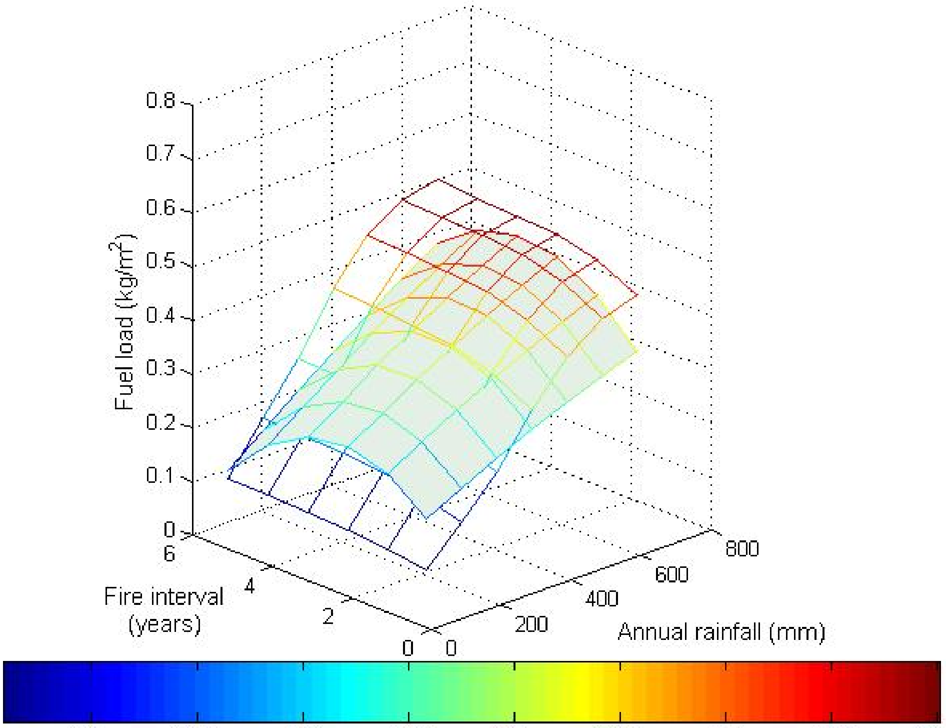


Fig. 6: The average grass fuel load variation simulated by LPJ-GUESS with tree exclusion depending on fire interval, average yearly rainfall and with parameter optimisation. The fire interval is between 1-6 years and amount of annual rainfall is between 100-700 mm. The slightly coloured meshplot is the figure made by Govender et al. (2006) and $T_{LITTER grass}$ for the uncoloured plot is set to 0.6 years.

4.3 Statistics result

In comparison to figure 2, figure 7 shows not only the increase in accumulating fuel loads followed by a decrease when the fire interval exceeds four years, but also shows the variation within the park itself. The highest variation in fuel load with the highest amount of outlying values can be found with an fire interval of two and three years and the lowest is found at four years. However, this is partly influenced by the fact that more data were available for fire intervals below four years since these were executed in a higher number of plots at each site compared to the fire intervals of four and six years.

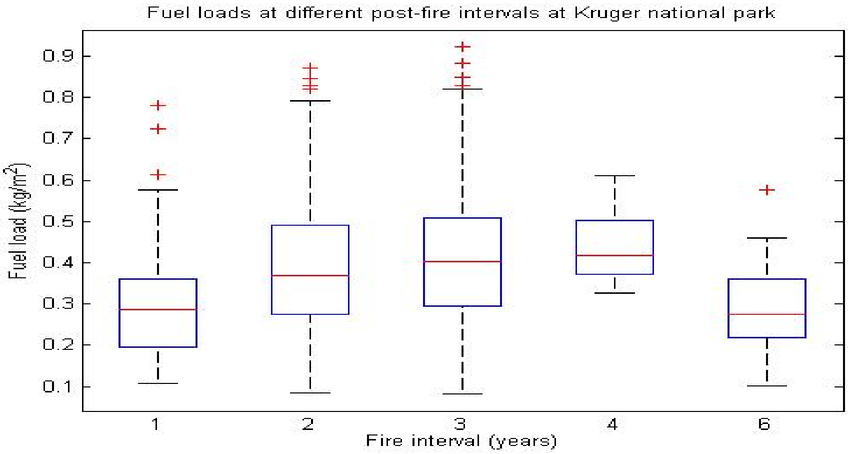


Fig. 7: Boxplot of the fuel load variation in Kruger National Park in relation to burning intervals. The top and the bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data. The red crosses represent extreme values.

Figure 8 and 9 shows the site specific variation of leaf fuel loads for site Mopani and Pretoriuskop together with the modelled values for the same rainfall amount and fire interval. The turnover time for all simulated sites are set to 0.6 years without trees and figures for the sites Satara and Skukuza can be found in appendix B. For the observed data, the highest simulated median of 0.44 kg/m² can be found in Pretoriuskop with a fire interval of 2 years and the lowest median of 0.2 kg/m² is in Skukuza with an annual fire interval. Pretoriuskop is classified as a bushveld, a densely grassed vegetation type, whilst Skukuza is classified as a woodland, which is more of a low density forest and with less available grass in between. This could explain the difference in grass litter fuel loads at the different sites. Among the modelled values, the highest median of 0.45 kg/m² was found in Pretoriuskop with an annual fire interval and the lowest median of 0.18 kg/m² was found in Mopani with a fire interval of 3 years.

The boxplots show that the agreement between model and observed data is higher at shorter fire interval and an increased overestimation of litter as the interval increases in the simulations. The boxplots also show in general a higher variation of fuel loads in the observed values in comparison to the modelled boxes. Furthermore, shorter fire intervals tend to vary more compared to the longer ones, which is also due to data availability. A fire interval of two or three years contain data from all of the five months when measurements are taken in Kruger National Park, whilst annual fire intervals only have data in August and a fire interval of four and six years only have data measured in October (as mentioned in section 3.4).

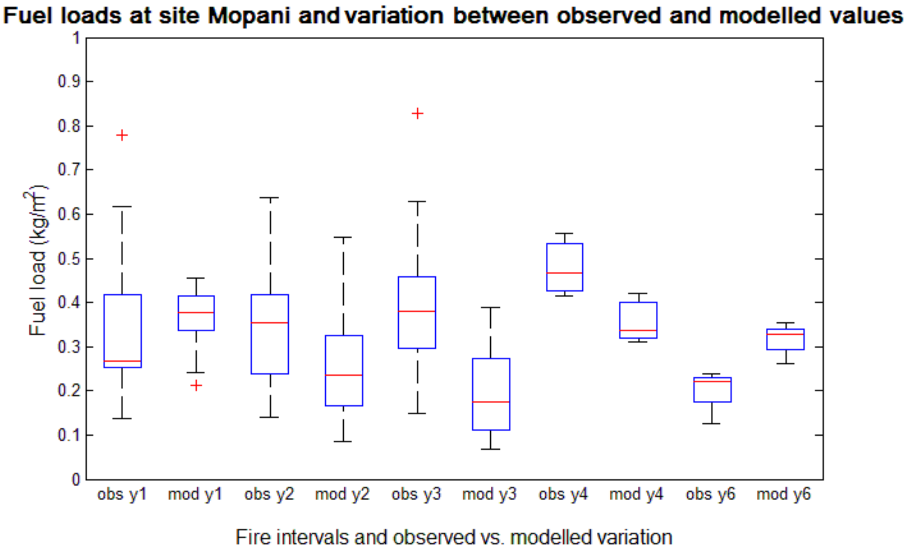


Fig. 8: Observed/measured fuel load at a modelled turnover time with tree exclusion of 0.6 prior to different burning intervals in Mopani. The top and the bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data. The red crosses represent extreme values.

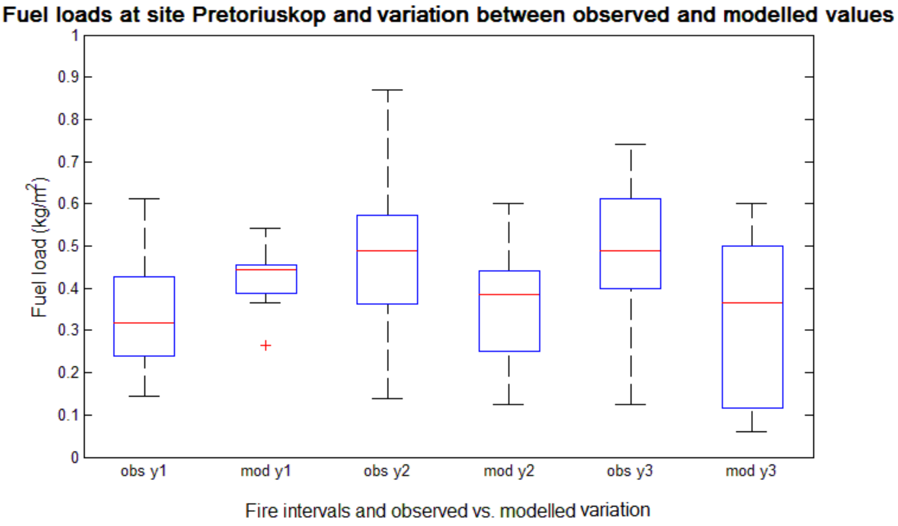


Fig. 9: Observed/measured fuel loads prior to different burning intervals at site Pretoriuskop. The top and the bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data. The red crosses represent extreme values.

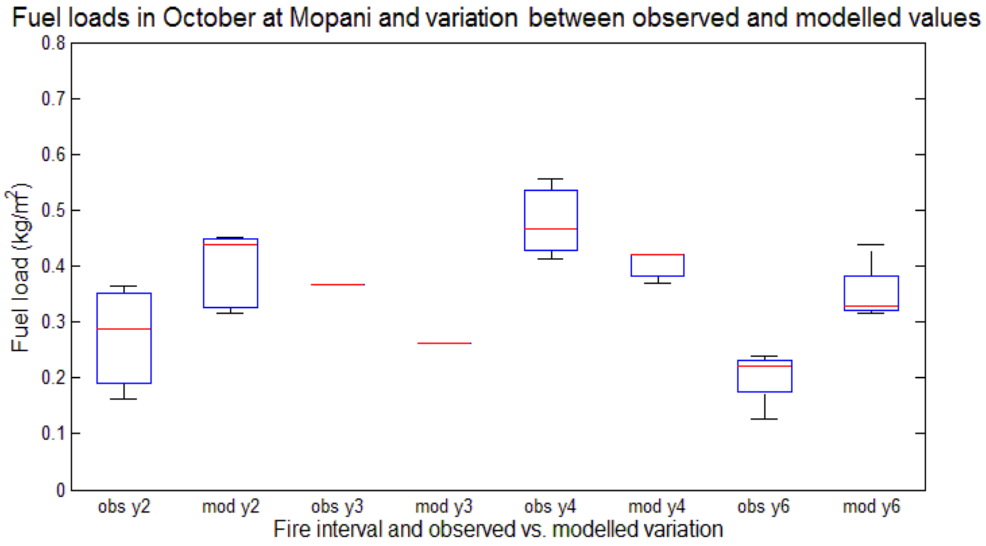


Fig. 10: Observed/measured fuel load prior to different burning intervals in Mopani. The leaf litter loads are all measured in October. The top and bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data.

Figure 10 and 11 show the difference in observed and measured fuel loads at site Mopani and Pretoriuskop with the same set turnover time of 0.6 years, but only for measurements taken in October (site Satara and Skukuza is found in appendix B). Site Satara and Skukuza is in good agreement at almost all of the measured fire intervals, but for site Mopani and Pretoriuskop there is a higher variation. Mopani, which have an average yearly rainfall amount of 496 mm, tend to have a high median litter load for most of the simulated fire intervals. The decrease in year three might be due to a lack of available data. Pretoriuskop on the other hand, with an average yearly rainfall amount of 737 mm, produces more leaf litter due to a higher water availability.

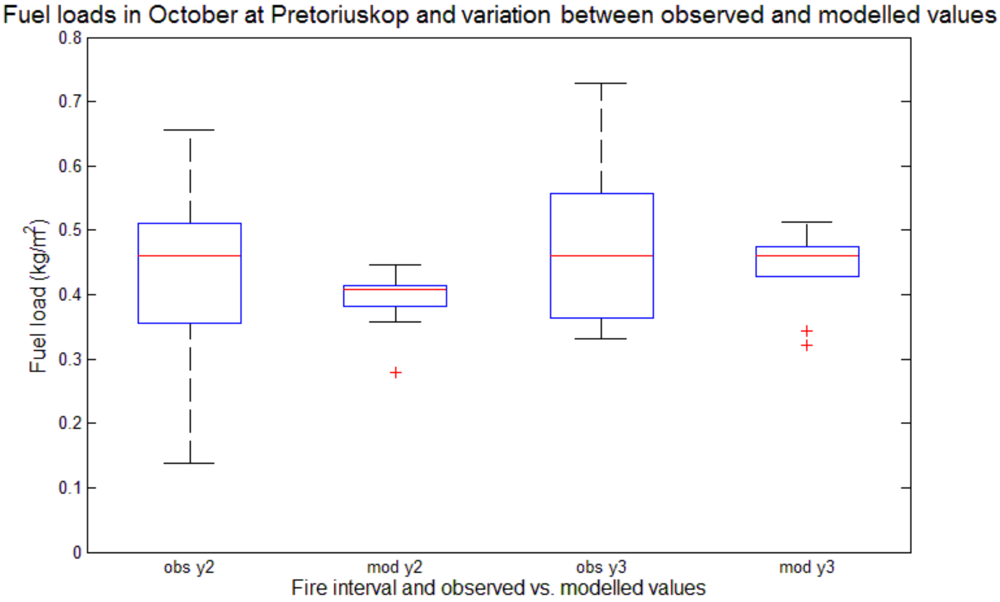


Fig. 11: Observed/measured fuel load prior to different burning intervals in Pretoriuskop. The leaf litter loads are all measured in October. The top and bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data.

Figure 12 and 13 shows the observed and simulated fuel loads together with smoothed rainfall data at site Mopani and Pretoriuskop (see appendix C for sites Satara and Skukuza). The blue bars represents the rainfall data, black dots are observed fuel loads, green stars are modelled fuel loads with a turnover time of 2.85 years and purple crosses are modelled fuel loads with a turnover time of 0.6 years. With a turnover time of 2.85, the model is in general overestimating the amount of leaf litter available in comparison to actual litter data. On the other hand, a turnover time of 0.6 has a tendency to underestimate fuel loads, but is overall more accurate compared to a turnover time of 2.85. This is true for all available sites.

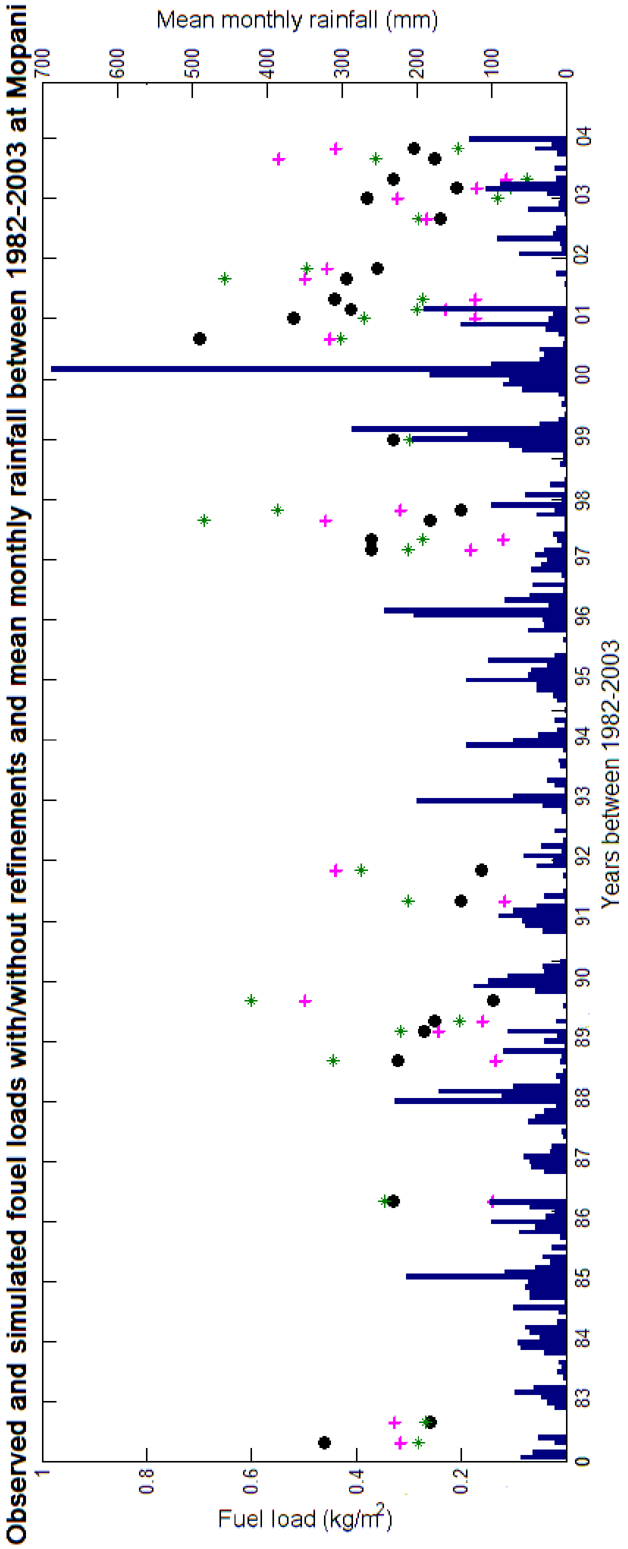


Fig. 12: Observed/measured fuel loads at Mopani between years 1982-2003, together with monthly rainfall data. The fire interval is every second year. The blue bars represents monthly amount of rainfall, black dots represent actual fuel loads, green stars are simulated litter loads with the model's original turnover time of 2.85 and purple crosses are simulated litter loads with a turnover time of 0.6.

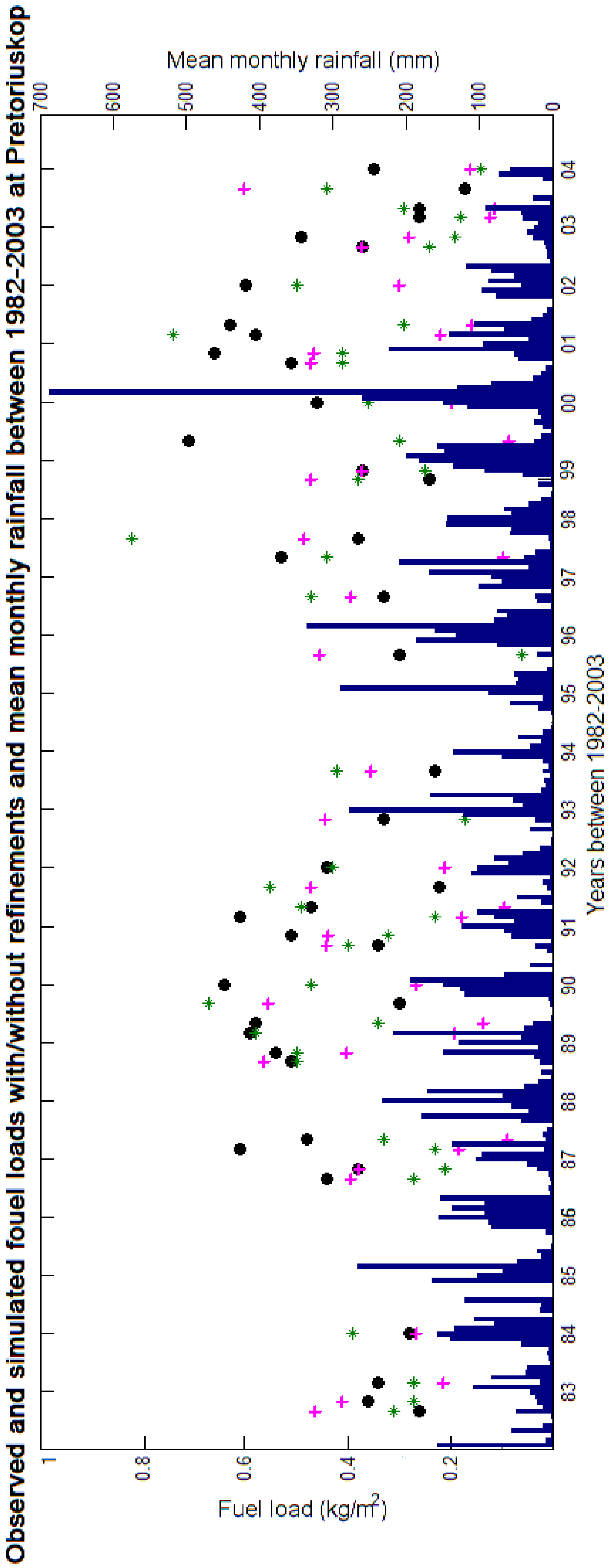


Fig. 13: Observed/measured fuel loads at Pretoriuskop between years 1982-2003, together with monthly rainfall data. The fire interval is every second year. The blue bars represents monthly amount of rainfall, black dots represent actual fuel loads, green stars are simulated litter loads with the model's original turnover time of 2.85 and purple crosses are simulated litter loads with a turnover time of 0.6.

5 Discussion

The main questions for this thesis was if the fuel load simulated by the existing LPJ-GUESS-SPITFIRE was in agreement with existing fuel load data for different wet-dry areas and if an improvement could be made. The following sections will go into further detail of how the refinements have affected the litter output and some suggestions on how the model can be developed further.

5.1 Observed and simulated fuel loads

As the model is parametrised presently, it does not capture the general increase of litter production in comparison to the observed data. At an average annual rainfall amount of 500 mm, the available leaf litter simulated by the model without refinements is almost twice as high compared to what has been observed. When the turnover time was changed to 0.6 and all the trees where excluded, leaf litter load was still high for the same rain amount, but not unreasonable. If the constant was set lower, the overall result with tree inclusion showed worse agreement since sites with higher rainfall amounts produced less leaf litter compared to if a higher constant was chosen.

A comparison between observed and measured fuel loads was made in figure 12, 13 and figures in appendix C which emphasize the importance of the choice of turnover times. When the model was parametrised with a value of 2.85, there was a higher rate of overestimation of leaf litter since it takes more time for the litter to decompose. It however gave a better correlation to higher observed litter rates compared to a turnover of 0.6. On the other hand, a turnover time of 0.6 had a higher rate of underestimation of leaf litter compared to 2.85, but was overall better correlated to observed litter loads. How well the model was able to simulate actual leaf litter loads depended highly on the amount of rainfall present on the site. With higher precipitation, the model simulates more trees and less grasses. Since grasses are an important contributor to leaf litter, it therefore gives a higher underestimation of leaf litter compared to plots with a lower annual rainfall amount. But at the same time, the sites with high precipitation also has the highest simulated litter values since growth in general is increased. So at sites where mostly leaf litter is simulated, the model has a higher tendency to overestimate the total litter production.

This result shows the importance in choosing suitable parameters. If the used parametrisation is not properly tested for accuracy against observed values, it could lead to high errors and uncertainties in the final output. It can also be said that the simulation of TrBR trees have been of high influence on the overall results. Since it has been stated by Shea et al. (1996) that grasses is an important contributor to fire fuel, a new simulation was made with only C4 grasses being present. This relationship showed a better agreement to observed changes and increased in a similar way as the relationship shown by Govender et al. (2006), but the model still had difficulties in accurately simulating the fuel load decrease with a fire interval over four years. The fuel load is also much higher compared with the figures where TrBR is included, since there is not any competition which keeps the growth of grasses down. An exclusion of TrBR is therefore not relevant.

5.2 The effect of ecosystem processes on observed and simulated fuel loads

There are many factors which might explain the discrepancies between observed and simulated fuel loads, two being precipitation and fire interval. An increase in annual amount of rainfall leads to a higher primary production and subsequently to an increased input in litter since the overall biomass increases, whilst an increase in fire return rate arguably leads to more litter on the ground due to a lower removal of litter. What the model does not capture is the decrease in grass litter as the fire interval exceeds four years. This response have always been a problem to capture when attempting to model these kinds of ecosystems. According to Govender et al., (2006), the reason for the decline in fuel loads as the fire interval increases is believed to be a combination of grazing, decomposition and loss of grass vigour. Gill et al. (1981), is in favour of this statement and presented a similar graph but for tropical grasslands in Australia. In another study by Ward et al. (1996), they measured both grass and other types of litter at Pretoriuskop for the biannually burnt plots. The average litter fuel load varied between 0.05-0.19 kg/m² whilst grass fuel load varied between 0.06-0.25 kg/m². The measurements were taken in August and October, which is classified as winter and spring periods and the fuel load will therefore be quite low in comparison to other months. But the decrease might also be the result of succession from a cover primarily consisting of grasses to a higher content of bushes and trees. As trees and bushes take up more space, it in turn shades of some of the grasses. Archibald et al. (2009) states that if the tree cover exceeds 40%, the maximum percent of burnt area declines since the succession of trees reduces the amount grass fuels which are the prior fire fuel. Archibald et al. (2009) further showed that tree cover can only exceed 40% if there is an annual rainfall over 800 mm. On the other hand, it has also been argued by van Langevelde et al. (2003) that trees are highly affected by herbivores which either kills trees or reduces them in size. This is not incorporated in the model currently.

Another important variable which might have an influence on the vegetation is what type of soil the different sites have. Pretoriuskop has been classified to have a sandy soil, which leads to more water reaching lower soil layers and where trees have more roots. This would give the trees an advantage and ability to grow more numerous at the expense of the grasses. Mopani on the other hand, has a higher clay content, which lead to less permeability and a higher degree of water content in upper layers. Since grasses have the majority of their roots in the upper soil, they have better rates of survival in comparison to a more sandy soil. This relationship is however not captured by the model, where the vegetation instead increase with increasing precipitation.

5.3 Simulation set up

As LPJ-GUESS often overestimates woody vegetation in comparison to grasses in areas with a highly specified rainfall seasonality. Trees almost always out-compete grasses unless there is a high level of drought or short fire return intervals leading to a higher mortality rate. It therefore took a lot of effort in order to have both TrBR trees and C4 grasses present and at the same time not letting one of the PFTs have too high dominance over the other. Another important issue was that since the actual simulations were quite time consuming, it was difficult to find enough time to try other parameters which might have influenced the litter production, like different soils or fire intensities.

As mentioned in section 3.5, the model had to be altered in order to get an establishment of the trees and C4 grasses that has been observed in the study area. In the instruction file, where the parameters for different groups and PFTs are read in, the minimum temperature set in order to get establishment and survival for tropical trees and C4 grasses were too high in order to get any establishment of this observed vegetation. If only one day had a lower mean daily temperature than 15.5°C, the trees which should have been present were not able to establish or survive. In order to get a wood accumulation and tree establishment, the minimum temperature had to be lowered from 15.5°C to 10°C. In reality the vegetation is not harmed by a few of these temperature drops, but in the model it has a huge effect on what PFTs that are present at different locations.

Once an establishment was made, the next problem was to make the PFT TrBR less dominant. According to Shea et al. (1996), leaf litter often contributes approximately 70-98% of the total fuel load in savannah ecosystems. This is presently underestimated by the model and the patches quickly gets overgrown by the more dominant PFT TrBR, leaving hardly any space left for the grasses especially at relatively high precipitation rates.

In order to lower the competition from trees and to get a higher establishment of C4 grasses, TrBRs competitiveness was altered. Instead of having a general water uptake, LPJ-GUESS-SPITFIRE was changed to be species specific in order to make TrBR more sensitive to drought. The drought tolerance was set to 0.45 in order to suppress the growth of trees. However, this value only suppressed the trees as long as the annual amount of rainfall were below 500 mm. After that, the amount of water was sufficient enough to percolate to lower soil layers to the advantage of trees. This can be seen in particular when site Mopani and Pretoriuskop are compared to each other (see figure 8 and 9). Mopani has an average annual rainfall of 496 mm, which is the lowest rainfall amount of the sites, and the simulated values were quite similar to observational data until it reached a fire interval of four years. At a fire interval of six years, a decrease in observed fuel loads becomes prominent, but is not captured by the model (see section 5.4). Figure 9 shows simulated and observed fuel loads for site Pretoriuskop, where an underestimation of simulated fuel loads can already be seen when the fire interval exceeds two years. The reason for this underestimation is probably that the simulated trees establish faster at Pretoriuskop compared to Mopani mainly due to a higher amount of rainfall. Since more trees are simulated suppressing C4 grasses, less leaf litter is available at Pretoriuskop compared to Mopani.

The final change was to increase r_ck, which is the proportion of individual trees killed if completely covered by fire from 0.87 to 0.99. Since more trees die there will be a higher input of wood into the litter pool at first and eventually evens out as the litter decays and fewer trees are available for further input. But the biggest advantage is that the fire opens up more patches for grasses to take over in comparison if the r_ck was set to 0.87.

All changes conducted to the standard settings of LPJ-GUESS-SPITFIRE were made in order to simulate site conditions as similar to the observed conditions as possible in order to assess the effect of the parameters of interest. While the performed changes of the standard parameters have lead to a better representation at the simulated sites, they might not lead to an improvement at another site or at a larger scale.

5.4 turnover times with and without parameter refinements

The turnover times of 2.85 for $\tau_{LITTER\,leaf}$ and $\tau_{LITTER\,wood}$ presently used in the model have been over- respectively underestimated for most of the wet-dry areas. The best RMSE value of 0.11 kg/m² for $\tau_{LITTER\,leaf}$ were found for a turnover time of 0.9 years. But in combination of other variables such as build up and range of available leaf litter at different fire intervals, a constant of 0.6 was chosen which is in range for most of the published turnover times except for Australia and California (see table 2).

To evaluate the turnover time was also examined if there would be a difference in RMSE if the trees were excluded, since many authors (in particular Shea et al., 1996) have stressed the importance of grass litter in the Savannah ecosystem. In table 5 the values for grass litter was represented and it seems that the turnover time was of more importance and had a bigger effect on the fuel loads in comparison with table 4. Since no trees were present to compete with the grasses, more litter could be produced by the grasses and therefore become less similar to what has been measured at Kruger National Park. It can therefore be concluded that an exclusion of trees all together would not be advisable. As for the effect of annual rainfall and the similarity between observed and measured data, the RMSE value in general increased with an increase in annual rainfall (see table 6). Low precipitation gave a good comparison, since both the model and observed fuel loads were low. One of the best RMSE values was found with tree inclusion, a turnover time of 0.9 and a annual precipitation of 600 mm. This is in close range of most of the observed sites.

The turnover time for wood was more difficult to evaluate, since no observational data were available for this study. But even if it would have been available, the output from the model would probably not give any reasonable results. Since minimum temperature for establishment and survival had to be lowered in order to get any PFTs in the area, it has also led to a dominance and too high representation of TrBR in the patches. The model is constructed in such a way that trees outcompete grass when the conditions are favourable and the grass establish and grows in areas not occupied by any woody PFTs. This can be seen in the average values of NEE. Without parameterisation the NEE was higher compared with NEE for grasses, understating that the model is simulating too many trees. In order to lower this dominance, LAI data was used. According to Kirton et al. (2009), measured LAI values ranged between 0.22-0.44 and for data measured by ORNL DAAC (daac.ornl.gov), the average of all the sites varied between 0.54-1.59. The highest value obtained was at Pretoriuskop where it reached 6.8. In LPJ-GUESS-SPITFIRE LAI ranged between 1-5, which lies within the upper range of the measured LAI values.

Since no data was available for wood litter, $\tau_{LITTER\,wood}$ was examined in the effect different turnover times had on the size of the available wood litter pool. It is quite clear that if $\tau_{LITTER\,wood}$ increased, more litter was available on the ground. By looking at what turnover times other experiments have found, it will be easier to find the proper range once wood data is available. The turnover time found varies for most areas between 6-32, which is considerably higher compared to the constant presently used. But the higher turnover times for wood should be looked at with care, since many of the authors (like Paul & Polgase, 2004 and Harmon et al., 1986) pointed out that they are probably overestimated. Since it takes time for wood to not only reach an equilibrium in its accumulation but also where the decay might take several years, it restricts the number of experiments which have been able to examine the process to the fullest (Harmon et al., 1986; Paul & Polgase, 2004). But even though this is of high relevance in re-estimating $\tau_{LITTER\,wood}$, the current value is very likely to be a too low estimate.

It has also been shown by Harmon et al. (1986) that areas which have been burned have longer decayrates compared to other disturbances, such as insect herbivory. For areas such as savannah and Mediterranean regions where fire outbreaks are an important and regular disturbance, it could only be argued it would have an impact on the wood decay as well.

Some suggestions for further development of the model is to have a better implementation of different seasons. However as the model is programmed presently, the seasonal variation is not as represented as would have been preferred. Most of the litter inputs are either calculated at the end of the year or gradually increasing as the amount of available water decreases, but does not capture the importance and effect that different seasons have (Archibald et al., 2010; Arianoutsou & Radea, 2000; Gill et al., 1981). In order to have an even better correlation to reality, the model should be constructed in such a way that it includes more of these variations. It would also be interesting to look at the actual litter production for wood so that it does not outcompete grass litter when the precipitation reaches certain thresholds.

Another development of LPJ-GUESS involves the inclusion of different soils as have been mentioned in section 5.2. The effect of soil is presently not considered in the LPJ-GUESS-SPITFIRE model to the extent which would be desirable. The soil differ between the different sites and with it its water holding capacity. What should also be noted and taken into consideration is the effect of nutrient status and species chemical composition on decomposition. According to Arianoutsou & Radea (2000) and Harmon et al. (1986), the nutrient status in the soil influences the turnover time of litter since it might be the most important nutrient input in that area. This in turn is affected by the species present in the plot, where some decay faster after a fire event compared to others. Depending on the species present in the plot it would therefore also effect the decomposition in different regions and would be an interesting feature to study even further.

6 Conclusion

The aim of this thesis was to examine whether currently simulated fuel loads are concordant with measurements for wet-dry areas with special emphasis on observed data from Kruger National Park. The work was divided into a literature study to examine current knowledge on turnover time and build up rates for different wet-dry ecosystems and a simulation part where an optimisation of decomposition rates in the biogeochemical model LPJ-GUESS-SPITFIRE was performed.

The first question asked in this thesis was if the existing turnover times in LPJ-GUESS-SPITFIRE was compatible with existing fuel load data for different wet-dry areas. From the literature study, it has been shown that the current turnover times are not well representable and that it is set too high for leaves and too low for wood.

The second question was if an improvement could be made which gives more reasonable results compared to present model settings. The model had to be altered before the run of the simulations in order to have an establishment of trees which could coexist with grasses. These alterations gave a better representation of the ecosystem compared to the model without any refinements.

The work that has been done shows that an improvement can be made in the model which gives better and more realistic values. The best value for $\tau_{LITTER\,leaf}$ is a turnover time of 0.6 years with tree exclusion, which means present model settings need to be lowered. For $\tau_{LITTER\,wood}$ no value could be chosen due to a lack of observational data, but the effect on available surface litter was studied instead. The work might be of importance for example in development of different fire models or for calculating carbon stocks on a regional level. For a further development of LPJ-GUESS_SPITFIRE, the new $\tau_{LITTER\,leaf}$ value of 0.6 should be tested for more sites and more observational data for both $\tau_{LITTER\,leaf}$ and $\tau_{LITTER\,wood}$ is needed in order to choose a more realistic parametrisation for the decomposition in wet-dry ecosystems.

This work shows that the hypothesis that the current decomposition rate is not suitable to represent the litter decomposition in savannah ecosystems have been confirmed and new values have been presented. It further shows the difficulty in modelling such ecosystems and the importance of further study and development in order to accomplish more representable simulations.

7 References

Aerts, R. (1997), Climate, leaf litter chemistry and leaf litter decomposition in terrestrial ecosystems: a triangular relationship. *OIKOS, 79*, 439-449.

Almagro, M., Martínez-Mena, M. (2012), Exploring short-term leaf-litter decomposition dynamics in a Mediterranean ecosystem: dependence on litter type and site conditions. *Plant and Soil*, *358*, 323–335. doi:10.1007/s11104-012-1187-6

Archibald, S., Nickless, A., Govender, N., Scholes, R.J., Lehsten, V. (2010). Climate and the inter-annual variability of fire in southern Africa: a meta-analysis using long-term field data and satellite-derived burnt area data. *Global Ecology and Biogeography*, *19*(6), 794–809. doi:10.1111/j.1466-8238.2010.00568.x

Archibald, S., Roy, D.P., van Wilgen, B.W., Scholes, R.J. (2009). What limits fire? An examination of drivers of burnt area in Southern Africa. *Global Change Biology*, *15*(3), 613–630. doi:10.1111/j.1365-2486.2008.01754.x

Arianoutsou, M., Radea, C. (2000), Litter production and decomposition in pinus halepensis forests. *Ecology, Biogeography and Management of Pinus halepensis and P. brutia Forest Ecosystem in the Mediterranean Basin*, 183–190.

Attignon, S.E., Weibel, D., Lachat, T., Sinsin, B., Nagel, P., Peveling, R. (2004), Leaf litter breakdown in natural and plantation forests of the Lama forest reserve in Benin, *Applied Soil Ecology, 27*, 109–124. doi:10.1016/j.apsoil.2004.05.003

Bachmann, A., & Allgöwer, B. (2002), Uncertainty propagation in wildland fire behaviour modelling. *International Journal of Geographical Information Science*, *16*(2), 115–127. doi:10.1080/13658810110099080

Baeza, M.J., Raventós, J., Escarré, A., Vallejo, V.R. (2006), Fire Risk and Vegetation Structural Dynamics in Mediterranean Shrubland. *Plant Ecology*, *187(2)*, 189–201. doi:10.1007/s11258-005-3448-4

Bengtsson, J., Janion, C., Chown, S.L., Leinaas, H.P. (2011), Variation in decomposition rates in the fynbos biome, South Africa: the role of plant species and plant stoichiometry. *Oecologia*, 165(1), 225–235. doi:10.1007/s00442-010-1753-7

Benson, R.P., Roads, J.O., Weise, D.R. (2009), Climatic and Weather Factors Affecting Fire Occurrence and Behavior. *Developments in Environmental Science*, *8*, 37-59. doi:10.1016/S1474-8177(08)00002-8

Biggs, H.C., Dunne, T.T., Govender, N. (2003), Experimental burn plot trial in the Kruger National Park : history , experimental design and suggestions for data analysis. *Koede,* 46(1), 1-15.

Bond, W.J., van Wilgen, B.W. (1996), Fire and plants, Chapman & Hall, London, ISBN 0 412 47540 5.

Bradstock, R.A., Gill, A.M., Williams, R.J. (2012), Flammable Australia: Fire regimes, Biodiversity and Ecosystems in a Changing World. CSIRO Publishing, Collingwood, Australia, ISBN 9780643104822.

Breckle, S-W. (2002), Walter's Vegetation of the Earth: the Ecological Systems of the Geo-Biosphere. 4th ed, Springer, Berlin, ISBN 978-3-540-43315-6.

Brown, S., Mo, J., McPherson, J.K., Bell, D. T. (1996). Decomposition of woody debris in Western Australian forests. *Canadian Journal of Forest Research*, *26*, 954–966.

Chapin, F.s., Matson, P.A., Mooney, H.A. (2002), Principles of Terrestrial Ecosystem Ecology. Springer Verlag, New York, ISBN 0-378-95443-0.

Cornwell, W.K., Cornelissen, J.H.C., Allison, S.D., Bauhus, J., Eggleton, P., Preston, C.M., Scarff, F., Weedon, J.T., Wirth, C., Zanne, A.E. (2009), Plant traits and wood fates across the globe : rotted, burned, or consumed ?. *Global Change Biology, 15,* 2431–2449. doi:10.1111/j.1365-2486.2009.01916.x

Cortez, J. (1998), Field decomposition of leaf litters: relationships between decomposition rates and soil moisture, soil temperature and earthworm activity. *Soil Biology and Biochemistry*, *30*(6), 783–793. doi:10.1016/S0038-0717(97)00163-6

Cortez, J., Garnier, E., Pérez-Harguindeguy, N., Debussche, M., Gillon, D. (2007), Plant traits, litter quality and decomposition in a Mediterranean old-field succession. *Plant and Soil*, *296*, 19–34. doi:10.1007/s11104-007-9285-6

Dallman, P.R. (1998), Plant life in the world's Mediterranean climates. Oxford University Press, Oxford, ISBN 019 850464 0.

Escudero, A., Arco, J.M., Sanz, I.C., Ayala, J. (1992), Effects of leaf longevity and retranslocation efficiency on the retention time of nutrients in the leaf biomass of different woody species. *Oecologia*, *90*(1), 80–87. doi:10.1007/BF00317812

Fioretto, A., Papa, S., Fuggi, A. (2003), Litter-fall and litter decomposition in a low Mediterranean shrubland. *Biology and Fertility of Soils*, *39(1)*, 37–44. doi:10.1007/s00374-003-0675-5

Foley, J.A. (1995), An equilibrium model of the terrestrial carbon budget. *Tellus, 47B*, 310-319.

Fujioka, F.M., Gill, A.M., Viegas, D.X., Wotton, B.M. (2009), Fire Danger and Fire Behavior Modeling Systems in Australia, Europe, and North America. *Developments in Environmental Science*, *8*, 471-497. doi:10.1016/S1474-8177(08)00021-1

Gaff, D. F. (1977), Desiccation Tolerant Vascular Plants of Southern Africa. *Oecologia*, *31*, 95–109.

Gertenbach, W. P. D. (1983), Landscapes of the Kruger National Park. *Koede*, *26*, 9-121.

Gill, A.M., Groves, R.H., Noble, I.R. (1981), Fire and the Australian Biota, Australian Academy of Science, Canberra, ISBN 0 85847 057 8.

Gould, J.S., McCaw, W.L., Cheney, N.P. (2011), Quantifying fine fuel dynamics and structure in dry eucalypt forest (*Eucalyptus marginata)* in Western Australia for fire management. *Forest Ecology and Management*, 262(3), 531–546. doi:10.1016/j.foreco.2011.04.022

Govender, N., Trollope, W.S.W., Van Wilgen, B.W. (2006), The effect of fire season, fire frequency, rainfall and management on fire intensity in savanna vegetation in South Africa. *Journal of Applied Ecology*, *43*(4), 748–758. doi:10.1111/j.1365-2664.2006.01184.x

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V, Lattin, J.D., Anderson, N.H., Cline, S.P., Aumem, J.R., Sedell, J.R., Lienkaemper, G.W., Cromack, K.JR., Cummins, K.W. (1986), Ecology of Coarse Woody Debris in Temperate Ecosystems. *Advances in Ecological research*, *15*, 133–302. doi:10.1016/S0065-2504(08)60121-X

Higgins, S.I., Bond, W.J., Trollope, W.S.W. (2000), Fire, resprouting and variability: a recipe for grass-tree in savanna coexistence, *Journal of Ecology, 88*(2), 213–229.

Higgins, S.I., Bond, W.J., February, E.C., Bronn, A., Euston-Brown, D.I.W., Enslin, B., Govender, N., Rademan, L., O'Reagan, S., Potgieter, A.L.F., Scheiter, S., Sowry, R., Trollope, L., Trollope, W.S.W. (2007), Effects of four decades of fire manipulation on woody vegetation structure in Savanna. *Ecology*, 88(5), 1119–1125.

Kirton, A., Scholes, B., Verstraete, M., Archibald, S., Mennell, K., Asner, G. (2009), Detailed structural characterisation of the savanna flux site at Skukuza, South Africa. *Geoscience and Remote Sensing Symposium, 2009 IEEE International, IGARSS 2009*, *2,* II-186-II-189. doi: 10.1109/IGARSS.2009.5418037

Krivtsov, V., Vigy, O., Legg, C., Curt, T., Rigolot, E., Lecomte, I., Jappiot, M., et al. (2009). Fuel modelling in terrestrial ecosystems: An overview in the context of the development of an object-orientated database for wild fire analysis. *Ecological Modelling*, *220*(21), 2915–2926. doi:10.1016/j.ecolmodel.2009.08.019

Latham, D., Williams, E. (2001). Lightning and forest fires. Forest fires: Behavior and ecological effects. Academic Press, San Diego, CA, 375–418.

Lehsten, V., Tansey, K., Balzter, H., Thonicke, K., Spessa, A., Weber, U., Smith, B., Arneth, A. (2009). Estimating carbon emissions from African wildfires. *Biogeosciences, 6,* 349–360.

Lloyd j., Taylor, J.A. (1994), On the temperature dependence of soil respiration. *Functional Ecology, 8*, 315-323.

Loepfe, L., Martinez-vilalta, J., & Piñol, J. (2011). Environmental Modelling & Software An integrative model of human-influenced fire regimes and landscape dynamics. *Environmental Modelling and Software*, 26(8), 1028–1040. doi:10.1016/j.envsoft.2011.02.015

Médail, F. (2008), Mediterranean, Ecosystems, p. 2296-2308.

Meentemeyer, V. (1978), Macroclimate and ligning control of litter decomposition rates. *Ecology, 59(3)*, 465–472.

O'Connel, A. (1988). Decomposition of Leaf Litter in Karri (*Eucalyptus diversicolor*) Forest of Varying Age, *Forest Ecology and Management, 24*, 113–125.

O'Connell, A. (1987) Litter Dynamics in Karri (*Eucalyptus Diversicolor*) Forests of South-Western Australia. *Journal of Ecology*, *75*(3), 781–796.

Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC). 2011. MODIS subsetted land products, Collection 5. Available on-line [http://daac.ornl.gov/MODIS/modis.html] from ORNL DAAC, Oak Ridge, Tennessee, U.S.A. Accessed: December 13, 2012.

Olson, J.S. (1963), Energy storage and the balance of producers and decomposers in ecological systems. *Ecology, 44*(2), 322-331.

Paul, K.I., Polglase, P.J. (2004). Prediction of decomposition of litter under eucalypts and pines using the FullCAM model, *Forest Ecology and Management, 191*, 73–92. doi:10.1016/j.foreco.2003.11.007

Pausas, J.G., Vallejo, V.R. (1999). The role of fire in European Mediterranean Ecosystems. In:Chuvieco, E. (ed.) *Remote sensing of large wildfires in the Mediterranean basin,* Springer-Verlag, Berlin, 3-16.

Pyne, S.J., Andrews, P.L., Laven, R.D. (1996), Introduction to Wildland Fire. second edition, John Wiley & Sons. Inc, Canada, ISBN 0-471-54913-4.

Rapp, M., Santa, I., Rico, M., Gallego, H.A. (1999), Biomass, nutrient content, litterfall and nutrient return to the soil in Mediterranean oak forests, *Forest Ecology and Management, 119*, 39-49.

Rock, J., Badeck, F.-W., Harmon, M.E. (2008). Estimating decomposition rate constants for European tree species from literature sources. *European Journal of Forest Research*, *127*(4), 301–313. doi:10.1007/s10342-008-0206-x

Rothermel, R. (1972), A mathematical model for predicting fire sprad and wildland fuels.

Rundel, P.W., Montenegro, G., Jaksic, F.M. (1998), Landscape Disturbance and Biodiversity in Mediterranean-Type Ecosystems. Ecological Studies vol. 136, Springer-Verlag Berlin Heidelberg, Germany, ISBN 3-540-64475-X.

Saarnak, C.F. (2001), A shift from natural to human-driven fire regime: implications for trace-gas emissions. *The Holocene*, *11*(3), 373–375. doi:10.1191/095968301669139230

Schlesinger, W.H., Hasey, M.H. (1981), Decomposition of Chaparral Shrub Foliage: Losses of Organic and Inorganic Constituents from Deciduous and Evergreen Leaves. *Ecology*, 62(3), 762–774.

Shea, R.W., Shea, B.W., Kauffman, J.B., Haskins, C.I., Scholes, M. C. (1996), Fuel biomass and combustion factors associated with fires in savanna ecosystems of South Africa and Zambia. *Journal of Geophysical Research*, *101*(D19), 23551–23568.

Sitch, S., Smith, B., Prentice, I. C., Arneth, a., Bondeau, a., Cramer, W., Kaplan, J. O., et al. (2003), Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biology*, *9*(2), 161–185. doi:10.1046/j.1365-2486.2003.00569.x

Smith, B., Prentice, I.C., Sykes, M.T. (2001), Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography*, *10*(6), 621–637. doi:10.1046/j.1466-822X.2001.t01-1-00256.x

Solbrig, O.T., Medina, E., Silva, J. F. (1996). Biodiversity and tropical savanna properties: A global view. *Functional Roles of Biodiversity,* Mooney, H.A. Et al., Eds., Springer, 185-211.

Specht, R.L. (1969), A comparison of the sclerophyllous vegetation characteristic of Mediterranean type climates in France, California, and southern Australia. *Australian Journal of Botany, 17*, 277-292.

Stocks, B.J., Van Wilgen, B.W., Trollope, W.S.W., Mcrae, D.J., Mason, J.A., Weirich, F., Potgieter, A.L.F. (1996). Fuels and fire behavior dynamics on large-scale savanna fires in Kruger National Park, South Africa. *Journal of Geophysical Research, 101*(D19), 23541-23550.

Sun, L., Zhou, X., Mahalingam, S., & Weise, D.R. (2006). Comparison of burning characteristics of live and dead chaparral fuels. *Combustion and Flame*, *144*(1-2), 349–359. doi:10.1016/j.combustflame.2005.08.008

Tang, G., Beckage, B., Smith, B., Miller, P.A. (2010), Estimating potential forest NPP, biomass and their climatic sensitivity in New England using a dynamic ecosystem model. *Ecosphere*, *1*(6), art18, 1-20. doi:10.1890/ES10-00087.1

Thonicke, K., Venevsky, S., Sitch, S. (2001). The role of fire disturbance for global vegetation dynamics : coupling fire into a Dynamic Global Vegetation Model, 661–677.

Thonicke, K., Spessa, A., Prentice, I.C. (2006). Model description of SPread and InTensity of FIRE (SPITFIRE), (March), 1–28.

Thonicke, K., Spessa, a., Prentice, I.C., Harrison, S.P., Dong, L., & Carmona-Moreno, C. (2010), The influence of vegetation, fire spread and fire behaviour on biomass burning and trace gas emissions: results from a process-based model. *Biogeosciences*, *7*(6), 1991–2011. doi:10.5194/bg-7-1991-2010

Tiessen, H., Feller, C., Sampaio, E.V.S.B., Garin, P. (1998), Carbon sequestration and turnover in semiarid savannas and dry forest. *Climatic Change, 40*, 105-117.

Toro-Vizcarrondo, C., Wallace, T.D. (1968), A Test of the Mean Square Error Criterion for Restrictions in Linear Regression. *Journal of the American Statistical Association*, *63*(322), 558–572.

Van Langevelde, F., van de Vijver, C.A.D.M., Kumar, L., Van de Koppel, J., De Ridder, N., Van Andel, J., Skidmore, A.K., Hearne, J.W., Stroosnijder, L., Bond, W.J., Prins, H.H.T., Rietkerk, M. (2003), Effects of fire and herbivory on the stability of Savanna ecosystems. *Ecology, 84*(2), 337–350.

Van Wilgen, B.W., Govender, N., Biggs, H.C., Ntsala, D., Funda, X.N. (2004), Response of Savanna Fire Regimes to Changing Fire-Management Policies in a Large African National Park. *Conservation Biology*, *18*(6), 1533–1540. doi:10.1111/j.1523-1739.2004.00362.x

Ward, D.E., Hao, W.M., Susott, R.A., Babbitt, R.E., Shea, R.W., Kauffman, J.B., Justice, C.O. (1996), Effect of fuel composition on combustion efficiency and emission factors for African savanna ecosystems. *Journal of Geophysical Research*, *101*(D19), 23569-23576. doi:10.1029/95JD02595

Weber, U., Jung, M., Reichstein, M., Beer, C., Braakhekke, M.C., Lehsten, V., Ghent, D., Kaduk, J., Viovy, N., Ciais, P., Gobron, N., Rödenbeck, C. (2009), The interannual variability of Africa's ecosystem productivity: a multi-model analysis. *Biogeosciences*, *6*(2), 285–295. doi:10.5194/bg-6-285-2009

Appendices

Appendix A: The different wet-dry areas mentioned in section 2.3 in further detail

A1. Savannah in South Africa

According to Solbrig et al., (1996), the savannah biome is the most common vegetation structure in the tropics and subtropics. Globally it occupies 11% of the earth's land-surface (Higgins et al., 2007) and in Africa approximately 5.91 * 10^8 ha of their terrestrial landscape, with the majority of their tropical savannah occurring in the south (Shea et al., 1996). The term savannah describes a vegetation which has a herbaceous lower layer and an upper layer of woody plants, with up to 75% canopy cover (Stocks et al., 1996; Solbrig et al., 1996; Higgins et al., 2000). The climatic characteristic which affect the savannah ecosystems the most is rainfall seasonality. The dry season is not specified to a certain point of the year for the whole biome, but it has a duration which usually varies between three to nine months.

Depending on the seasonality of rainfall and the density of woody vegetation, the structure of the savannah can be subdivided into different categories. A dry savannah gets roughly less than 700 mm of annual precipitation whilst a moist can get up to 1500 mm. The amount of woody species in an area determines if the savannah will be classified as grassland, bush savannah or woodland. It is classified as a grassland if there is no woody species at all or if the herbaceous stratum is taller than the occurring trees/shrubs, a bushland if the total tree/shrub cover is between 2-15% and a woodland if the tree cover is greater than 15% (Solbrig et al., 1996). When an ecosystem's composition and structure is determined by fire and where some of the species promote a fire outbreak, it is classified as a fire-prone ecosystem. African savannah are an example of a fire-prone ecosystem, where the evolution has promoted a fire-tolerant and fire-dependent flora and where an exclusion of the mentioned disturbance would lead to a change in ecosystem structure from an open savannah to a closed woodland (Govender et al., 2006).

A semiarid savannah is characterized by having a continuous grass layer intermixed with a discontinuous amount of trees and shrubs. The composition is determined by the amount of available soil moisture and disturbances such as grazing and fires. If the grass biomass would increase, more intense fires and more damage to trees would occur and in turn favour a further increase in grass biomass. However, if there is a decrease in grass biomass, for an example by grazing, less intense fires would develop and may lead to bush encroachment (Van Langevelde et al., 2003). In order for the savannah trees to survive and grow into an adult population, it has to escape the zone of influence from grass fires, either by prolonged fire intervals or by a variance fire intensity (Higgins et al., 2000).

A2. Mediterranean

The Mediterranean ecoregions are defined by their particular climates, with a dry and hot summer period of variable length followed by mild and wet winters (Médail, 2008). In order to sustain this ecoregion, the amount of rain during winter must be adequate to produce new fuel and the summer drought must be sufficiently prolonged to extend the fire season over the rest of the year (Pyne et al., 1996). The Mediterranean regions are all centred between 30° and 40° north or south of the equator, exposed to similar atmospheric and oceanic circulation patterns and occur only along the western sides of continents.

There are five ecoregions in the world which form the Mediterranean biome: the Mediterranean Basin in Europe, California, central Chile, the southern and southwestern Cape Province of South Africa and the southwestern and parts of Australia (see map 1) (Médail, 2008). These ecoregions contain among the highest regional biodiversities in the world, with nearly 20% of the Earth's total plant diversity. The reason for such a high biodiversity are natural disturbances and the severe and contrasted stresses to habitats and species which are induced by the Mediterranean climates (Benson et al., 2009). Typical vegetation types for Mediterranean areas are the evergreen and sclerophyllous shrublands or heathlands. These areas are called macquis and gerrigue in the Mediterranean Basin, chaparral in California, matoral in Chile, fynbos in SW Africa and kwongan and mallee in SW Australia. All of these biomes are heavily influenced and fashioned by anthropogenic activities, where grazing of domesticated livestock and fires have become intimately associated with each other (Pyne et al., 1996).

Aridity together with temperature are the biggest influences on the Mediterranean ecosystem's structure and composition. Rainfall is extremely variable and mean annual precipitation usually range between 100 to 2000 mm. To survive, the plants have developed different water conservation features, such as sunken stomata and low cuticular conductance, complex root systems, cellular tolerance to low water potentials or high secondary compound production. In severely dry areas, some plants have evolved into annual plants known as ephemerophytes, which can complete their whole lifecycle within a few weeks when there a sufficient water supply is available. These climatic factors further impacts the soils and plant available nutrients by water-driven erosion and leaching. Even though there are large differences between ecoregions and their soil composition the seasonal droughts and moderately to strongly leached soils characterizes these regions by a low availability in nutrients, especially in phosphorous and nitrogen (Benson et al., 2009).

Another important disturbance to the Mediterranean regions are fire, where the fire-prone vegetation cover constitutes about 40% of the world's land surface. For the Mediterranean environments, fire is one of the major selective forces shaping the evolution of plant reproductive traits. How different plant species respond to fires depend on their life cycles, subjected fire regimes and the local postfire environment. In order to survive, vascular plants in highly fire disturbed ecosystems had to adapt traits which would enhance their survival and reproduction. One of these traits is to protect their buds in the soil. Due to a combination of heat rising from the ground and the effective insulation of the soil, only a small portion of the heat penetrates the ground. It is therefore a valuable refuge, not only for plants, but for all other living matter as well.

There are a number of mechanisms for placing buds into the ground. Some species have contractible roots which can draw their apices far into the ground. Others use lignotubers, a basal woody swelling associated with proliferating buds. Lignotubers are especially common in Australia. Species who lack lignotubers, usually depend on bark protection of stem buds in order to survive. The bark has to be able to diffuse heat, be sufficiently thick and be less flammable than the rest of the plant in order to successfully protect its buds.

There are three reproduction traits which are enhanced through fire; flowering response, release of seeds or fire-stimulated germination. An increased flowering response and seed production could lead to a higher exploitation of newly open and nutritionally enriched seed beds and ultimately increased species regeneration. However, some species produce seeds beforehand by flowering at a low level in the interfire period, but retain their seeds until a release is triggered by the heat of a fire. This strategy increase the probability of finding new niches since the seeds are already produced and can germinate quicker compared to species which is flowering at the time, but at the expense of a higher risk of the seeds being destroyed instead. Some seeds are therefore stored in the soil in order to lower the heat exposure.

All mentioned traits of plants in the local community effect the ecological succession of their environment. Following a disturbance such as fire, species compete and progressively occupy the affected site, each giving way to its successor until a stable state occurs where the current community can reproduce itself indefinitely (Gill et al., 1981). Apart from direct influences on the environment, such as driving landscape diversity, ecosystem heterogeneity, vegetation dynamics and species differentiation, fire indirectly determines environmental changes with greater fluctuations in temperature, increases oxygen concentration in soils, increases light and water availability, reduces aboveground competition and determines a proper regeneration niche for plants which are fire-adapted (Médail, 2008).

Apart from the natural variation and role for vegetation succession, fire has also been exploited quite extensively for agricultural purposes or by aboriginal people. But over the past decades, the use of Mediterranean regions has shifted from an agricultural approach and the locals do not actively try to reshape the landscape for their needs. Abandoned lands have encouraged wildfires as more available fuel accumulates and as fire management becomes more effective, the Mediterranean regions suffer from deteriorating biodiversity and with larger and more vicious fires (Pyne et al., 1996).

A2.1. Australia

There has been a long history of fire exposure in the Australian region (Gill et al., 1981) and the word kwongan is an aboriginal word referring to open, scrubby vegetation on sandy soil. It is most similar to the fynbos of South Africa with its open spacing of shrubs and abundance of understory plants. Mallee refers to the growth of *Eucalyptus* and is found in the transition zone towards woodlands and forests (Dallman, 1998). Its forests are classified as patchy and open woodlands dominated by *Eucalyptus (E. diversicolor, E. marginata)*, *Banksia*, *Acacia*, *Melaleuca* and *Allocasarina*. The shrublands are either kwongan and scrub-heaths with Proteaceae (*Banksia*, *Grevillea* and *Hakea*) or mallee dominated by different species of *Eucalyptus* (*E. incrassata*, *E. oleosa*, *E. socialis*) and the grasslands are usually very scarce and patchy with annual everlasting (*Helichrysum*; *Helipterum*) or perennial plants (*Lechenaultia*) (Médail, 2008).

In Australia, 'bushfire' is a common term for any fire that is out of control and burning in the rural landscape. The flammability of the vegetation is largely due to a high volatile oil content in the sclerophyll species, low inorganic matter in their leaves and a rapid fuel accumulation due to low decomposition rates. Their most common survival mechanism is vegetative regeneration, which typically consists of thick protective bark, lignotubers and dormant buds instead of a large production and highly protected quantities of seeds.

In dry sclerophyll forests, there is a natural maximum fire frequency of 3-4 years and is highly determined by litter accumulation and species composition. All species require a fire-free period in order to germinate and establish. But at the same time, a lack of fires usually degenerates the vegetation due to a lack of nutrients and an increase competition, herbivoral attacks and diseases. In heathlands, seedling regeneration becomes more important as the foliage protective cover decreases. Their seedling regeneration is limited to the period immediately after a bushfire event, when the plants can spread their seeds and germinate. Seedling survival after germination is then closely related to the following wet season. If there isn't sufficient water during the end of the season, the amount of surviving individuals will reduce (Gill et al., 1981).

A2.2. California

The vegetation of the Mediterranean region in southern California is called Chaparral, which comes from the spanish term *chaparro* and translates to scrub oak. It is used as a general term for a group of sclerophyllous shrub species (Pyne et al., 1996). It lies west of the Sierra Nevada mountain range and includes a part of coastal Baja California to the south (Dallman, 1998). There are three distinct shrublands: those with coextinction with coniferous forests, those with woodland-grassland ecotones and those that support periodic conflagrations. The three types respond differently to fire or a lack of fire, with a decrease in forests in the first two types with increased fire frequency and reforestation when fire is excluded. The third type remains as Chaparral with or without fire. It produces seeds early in the season and accumulate large seedbanks which lay dormant in the soil. This dormancy can be broken by a fire, which results in germination of the seeds. Within a year after a fire, endemic forbs and annual grasses have emerged. These decline within five years due to a gain in chaparral shrub species. During the shrubs mature phase, between the ages 6 and 20, fires are uncommon due to insufficient fuel loads. But as time progresses and the structure of the shrubs changes, the flammability increases and the old shrublands are replaced by new and young shrublands with the next fire (Pyne et al., 1996).

A2.3. Europe

The Mediterranean basin extends from Portugal and Spain around the coast of southern France, Italy, the coastal Balkans and towards Greece, Syria and Israel (Specht, 1969). It is a strongly human-influenced landscape with a long history of pressures, e.g. burning, cutting, grazing on non-arable lands, clearing, cutting and the use of different agricultural practices (Pausas & Vallejo, 1999). The high biodiversity in the region and its stability over the centuries of anthropogenic exploitation is connected to both grazing and fire regimes. Grazing maintains open habitats through regular disturbance which promotes a continuous rejuvenation of the landscape. A continuous disturbance also led to less frequent and intense fires, but they occurred often enough to maintain the fire-dependent species and give them a chance to reproduce (Rundel et al., 1998). But with the industrial revolution, the Mediterranean countries shifted from a traditional land-use, to an abandonment of large areas of farm-land and increased vegetation recovery.

Compared to other Mediterranean areas, the pattern and seasonal timing of rainfall in the Mediterranean Basin is extremely varied, due to the large area of where the ecosystem can be found. However, even though it has a high internal variance, summer is always the driest season (Dallman, 1998). The dominant specie in the basin is *Quercus coccifera*, which is a shrub with rhizomes that quickly recovers after fire (Pausas & Vallejo, 1999). Most of the plants are resprouters with only a few exceptions which are seed dispersers (Rundel et al., 1998).

A2.4. South Africa

Africa on the southern side of the equator has a small Mediterranean region close to the southern coast (Archibald et al., 2010). Their Mediterranean area is called fynbos which means 'small bush' and consists of small-leaved plants in the families of *Ericaceae, Proteaceae* and *Restionaceae* (Rundel et al., 1998). It is the most extensive and varied form of vegetation in this area and includes 80% of the plant species in the Mediterranean region (Dallman, 1998). A large part of the region experience fire relatively often (about 34% has burned at least once over a period of 8 years), but the extent and frequency depends on available tree cover, rainfall and human land-use activities. Its fire regime is affected by a range of human, environmental and climatic factors, but it is only the climatic factors that vary from year to year. The factors affecting the extent of fire the most are amount of rainfall, which in turn affect fuel loads, availability of dry fuels and the occurrence of high fire danger conditions (Archibald et al., 2010).

A high population density has also shown to affect the fire regime with an increase in number of fires with increasing population, but a decrease in spread as the landscapes becomes more fragmented and more intensely used (Archibald et al., 2009). Most of the land where there is soil nutritious enough for cultivation has already been transformed and it is mainly in the mountain regions where the Mediterranean ecosystems are preserved (Rundel et al., 1998).

Appendix B: Boxplots of observed and measured fuel loads with and without seasonal variation for site Satara and Skukuza

Figure B1 and B2 show the variation of the litter load at different fire intervals. For the simulated litter loads, the turnover time was set to 0.6 years. The figures show a relatively good agreement between actual and simulated litter loads for most of the different fire intervals. Please note that a comparison with different fire intervals cannot be done, since the months when measurements were taken varies between the different intervals.

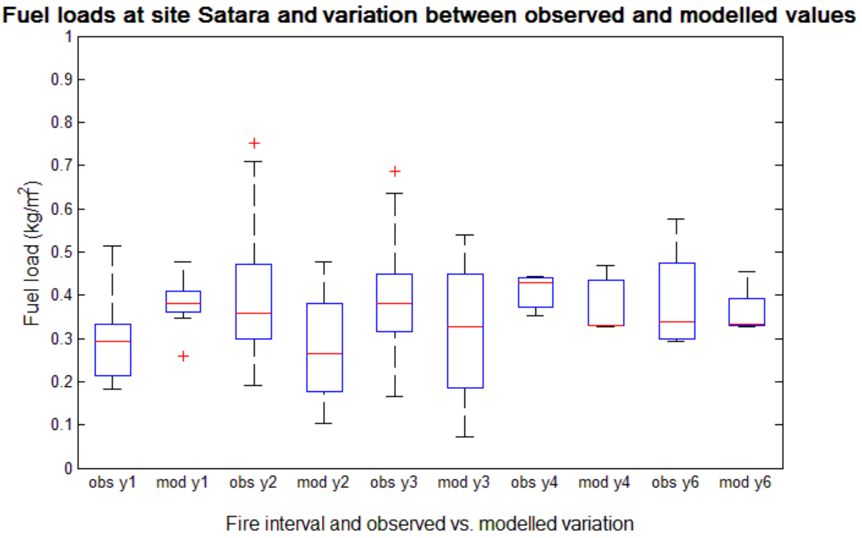


Fig B1: Observed/measured fuel load variation at a modelled turnover time of 0.6 prior to different burning intervals in Satara. The top and bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data. Red crosses are extreme values.

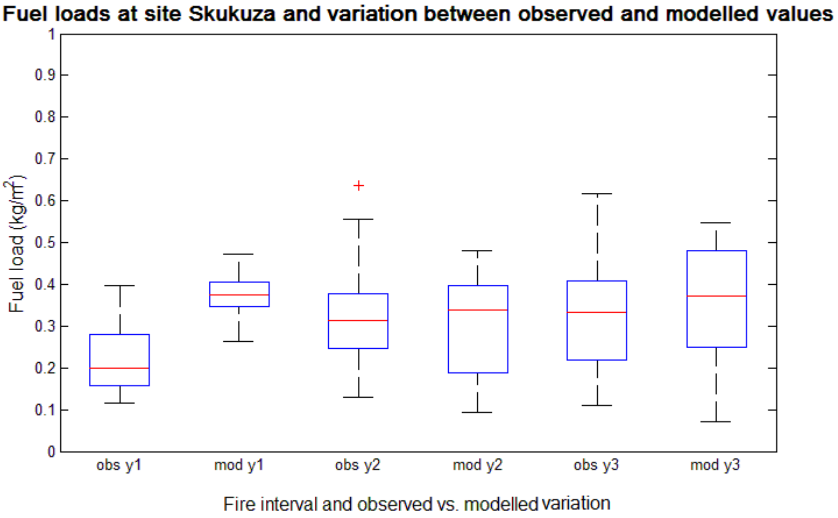


Fig. B2: Observed/measured fuel load variation at a modelled turnover time of 0.6 prior to different burning intervals in Skukuza. The top and bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data. Red crosses are extreme values.

Figure B3 and B4 shows the actual and modelled litter loads at site Satara and Skukuza in October at the fire intervals where data was available. Except for a fire interval of 2 years in Satara and a median decrease in observed litter load which is not seen in the simulated values, the model is in good agreement with observed litter data.

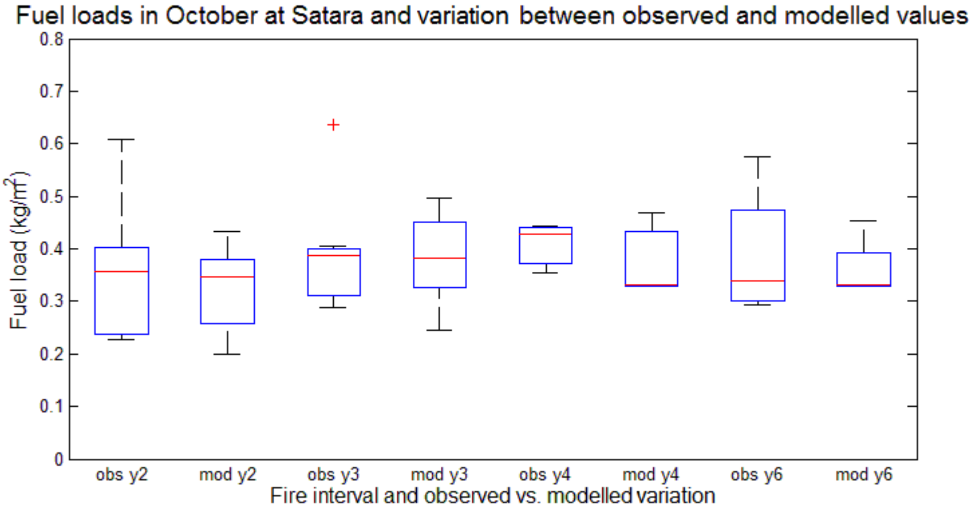


Fig B3: Observed/measured fuel load variation prior to different burning intervals in Satara. The leaf litter loads are all measured in October. The top and bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data. Red crosses are extreme values.

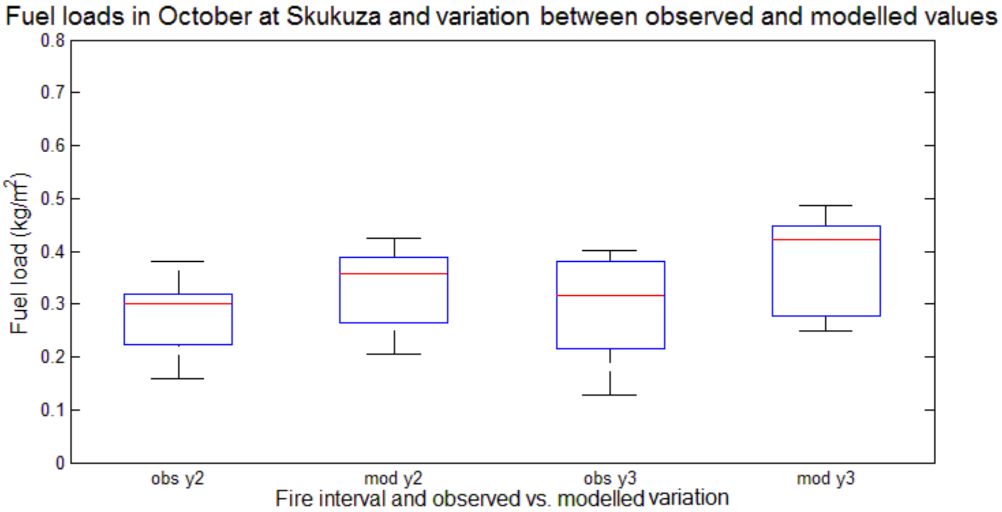


Fig B4: Observed/measured fuel load variation prior to different burning intervals in Skukuza. The leaf litter loads are all measured in October. The top and bottom of the box represent the 25th and 75th percentile, the red band within the box is the median and the upper and lower whiskers represent the 10th and 90th percentiles of the data. Red crosses are extreme values.

Appendix C: Observed and measured fuel loads together with mean monthly rainfall at site Pretoriuskop, Satara and Skukuza

Figure C1 shows the measured and observed data at site Satara, where the blue bars represents monthly rainfall, the green stars are the current fuel loads produced by the model, the purple crosses are the new fuel loads and the black dots are actual fuel load data collected at site. It is better correlated compared to Pretoriuskop, with a slight overestimation of the litter load with a turnover time of 2.85 and a slight underestimation with a turnover time of 0.6 with trees excluded. But overall, a turnover of 0.6 years gives a better correlation to reality compared to the one presently used. Figure C2 is plots for site Skukuza and shows a similar pattern as for Satara.

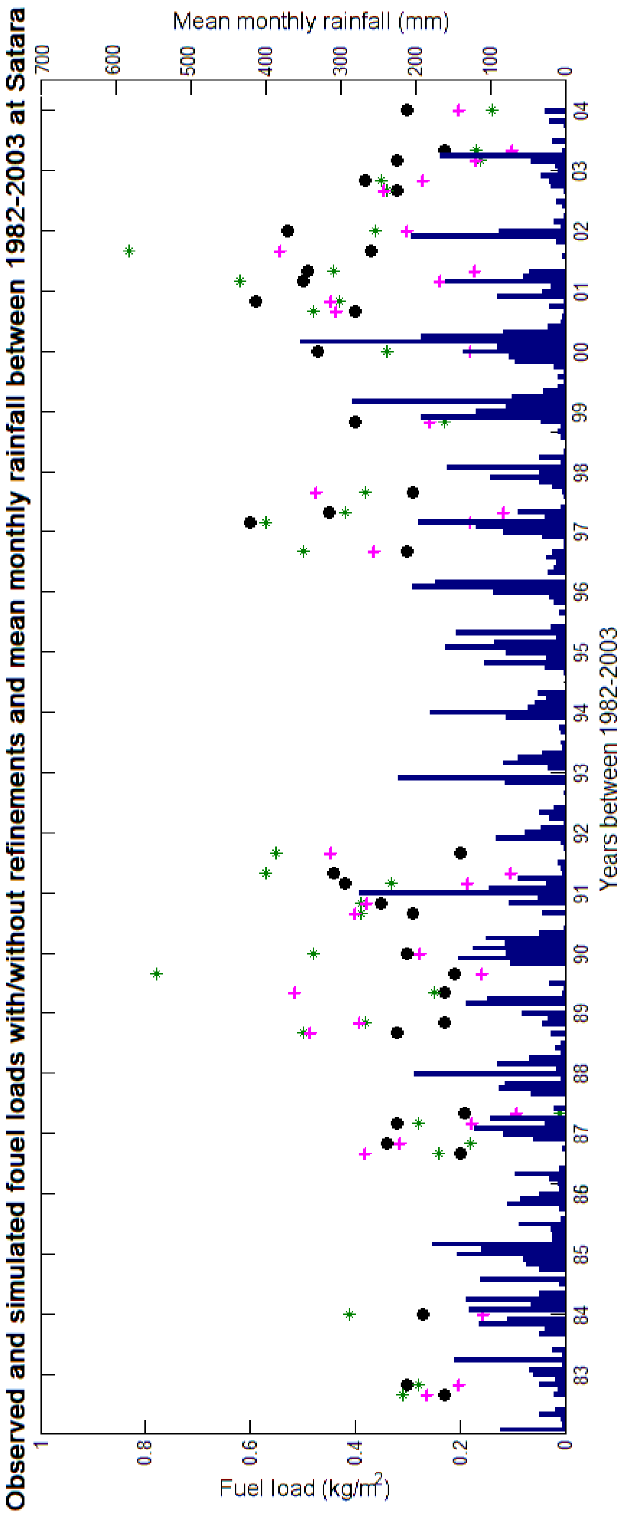


Fig. C1: Observed/measured fuel loads at Satara between years 1982-2003, together with monthly rainfall data. The fire interval is every second year. The blue bars represents monthly amount of rainfall, black dots represent actual fuel loads, green stars are simulated litter loads with the model's original turnover time of 2.85 and purple crosses are simulated litter loads with a turnover time of 0.6.

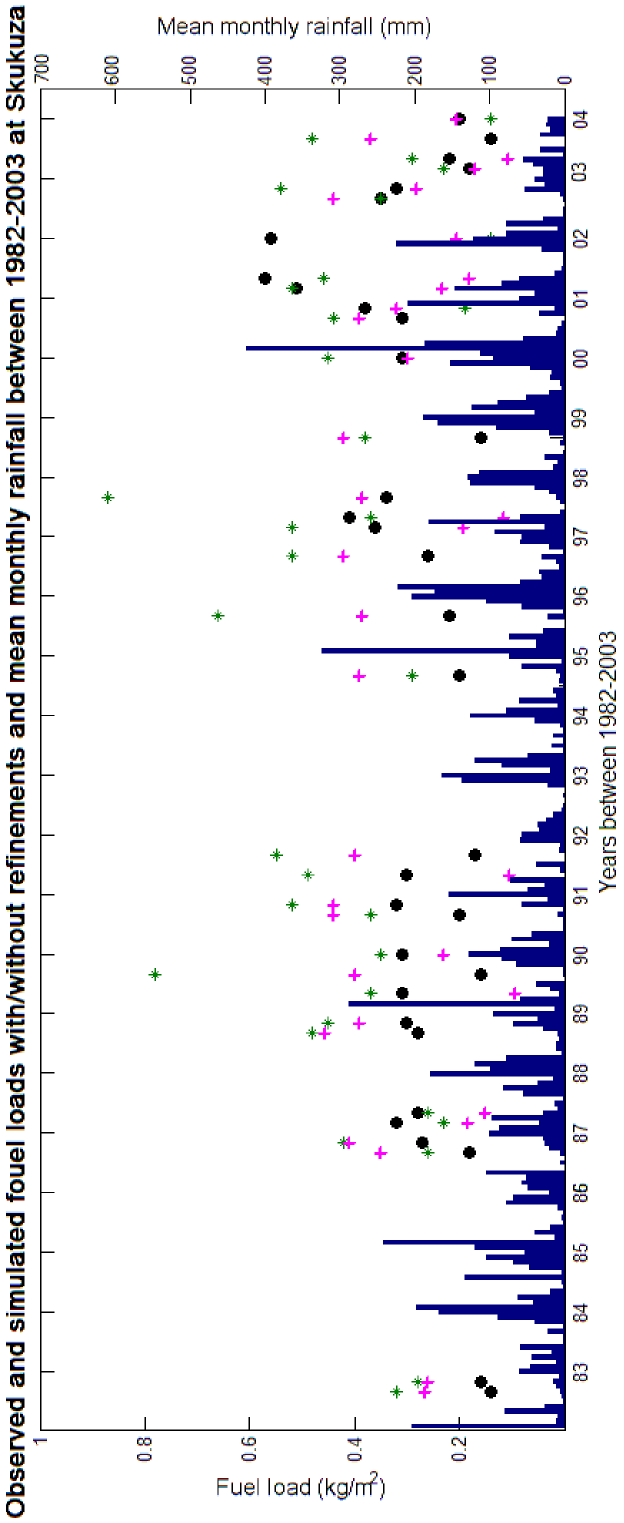


Fig. C2: Observed/measured fuel loads at Skukuza between years 1982-2003, together with rainfall data. The fire interval is every second year. The blue bars represents monthly amount of rainfall, black dots represent actual fuel loads, green stars are simulated litter loads with the model's original turnover time of 2.85 and purple crosses are simulated litter loads with a turnover time of 0.6.

Appendix D: CD with folder explanation

Included with this thesis is a CD containing three folders: an altered version of LPJ-GUESS-SPITFIRE, MATLAB-scripts and Raw data used in the thesis. The following section gives a small description on what the folders contain, what different codes do and what their respective output is. Further description of the folders is available on the CD.

D1. Altered version of LPJ-GUESS-SPITFIRE

For the completion of this thesis, the presently used LPJ-GUESS-SPITFIRE model had to go through some alterations. In this folder there are two additional folders; eclipse_fire and fire_mit_pheno. The folder with eclipse_fire holds the altered instruction file whilst fire_mit_pheno contains all the different modules.

D2. MATLAB-scripts

The folder contains three MATLAB scripts of which have been used to produce most of the figures. Any other data produced, for an example values for mean, median and standard deviations, where done in excel.

The Boxplot script simulates the leaf litter load at different times of the year which is later used for making boxplots for different sites. Each site, year and month were simulated independently, where the output was saved and compared with the observed data at the same conditions. In the first section, $\tau_{LITTER\,leaf}$, amount of annual precipitation, fire interval and when the plots are burn are decided and written in. The numbers next to prec_take_over_all is the annual precipitation for Mopani, Pretoriuskop, Satara and Skukuza. Fixfirereturninterval_take_over_all determines the fire interval and the last fixburnday decides when the site is burned. The new values is then read in to make a new instruction file of which LPJ-GUESS-SPITFIRE reads in and writes out the desired output. Both fixburnday and desired output values are found in the correlationscript. The script is first divided into month and year and later followed by site division. The values are multiplied with 2.22 in order to change the output from carbon weight to dry weight. The script ends with making a grouping in order to make the boxplot. Depending on how many boxes the figure will hold, its ranges have to first be determined by the grouping.

The Govender script is based on the same equation and produces the same figure as presented by Govender et al. (2006). y is the fire interval, x stands for amount of annual rainfall and z produces the fuel loads at given values. Since the output was in kg/ha, the litter loads had to be converted to kg/m².

The newfile_inread script reads in and calculates the different τ_{LITTER} values produced by the model. New parameters are specified, number of runs are decided, produces a new instruction file to be read by the model, the model is started and finally the specified output is written. When this is done, the loop returns to the beginning and reads in the next values. When all the loops have been running, the final output is written out, multiplied with the standard unit and plots a graph of the final result.

The twoplot script produces the line and scatterplots (figure 12, 13 and appendix C), but in order to generate it, precipitation data is needed of which was not allowed to be distributed.

D3. Raw data

The Raw data folder contains the data needed in order to make simulations. African sites is a sheet where the four different sites have been divided into specific tables and an additional table with their coordinates. Due to data publication, it was not allowed to list the precipitation data. However it can be obtained by contacting Navashni Govender at navashni.govender@sanparks.org.

Institutionen för naturgeografi och ekosystemvetenskap, Lunds Universitet.

Student examensarbete (Seminarieuppsatser). Uppsatserna finns tillgängliga på institutionens geobibliotek, Sölvegatan 12, 223 62 LUND. Serien startade 1985. Hela listan och själva uppsatserna är även tillgängliga på LUP student papers (www.nateko.lu.se/masterthesis) och via Geobiblioteket (www.geobib.lu.se)

The student thesis reports are available at the Geo-Library, Department of Physical Geography and Ecosystem Science, University of Lund, Sölvegatan 12, S-223 62 Lund, Sweden. Report series started 1985. The complete list and electronic versions are also electronic available at the LUP student papers (www.nateko.lu.se/masterthesis) and through the Geo-library (www.geobib.lu.se)

225 Johanna Engström (2011) The effect of Northern Hemisphere teleconnections on the hydropower production in southern Sweden
226 Kosemani Bosede Adenike (2011) Deforestation and carbon stocks in Africa
227 Ouattara Adama (2011) Mauritania and Senegal coastal area urbanization, ground water flood risk in Nouakchott and land use/land cover change in Mbour area
228 Andrea Johansson (2011) Fire in Boreal forests
229 Arna Björk Þorsteinsdóttir (2011) Mapping *Lupinus nootkatensis* in Iceland using SPOT 5 images
230 Cléber Domingos Arruda (2011) Developing a Pedestrian Route Network Service (PRNS)
231 Nitin Chaudhary (2011) Evaluation of RCA & RCA GUESS and estimation of vegetation-climate feedbacks over India for present climate
232 Bjarne Munk Lyshede (2012) Diurnal variations in methane flux in a low-arctic fen in Southwest Greenland
233 Zhendong Wu (2012) Dissolved methane dynamics in a subarctic peatland
234 Lars Johansson (2012) Modelling near ground wind speed in urban environments using high-resolution digital surface models and statistical methods
235 Sanna Dufbäck (2012) Lokal dagvattenhantering med grönytefaktorn
236 Arash Amiri (2012)Automatic Geospatial Web Service Composition for Developing a Routing System
237 Emma Li Johansson (2012) The Melting Himalayas: Examples of Water Harvesting Techniques
238 Adelina Osmani (2012) Forests as carbon sinks - A comparison between the boreal forest and the tropical forest
239 Uta Klönne (2012) Drought in the Sahel – global and local driving forces and their impact on vegetation in the 20th and 21st century
240 Max van Meeningen (2012) Metanutsläpp från det smältande Arktis
241 Joakim Lindberg (2012) Analys av tillväxt för enskilda träd efter gallring i ett blandbestånd av gran och tall, Sverige
242 Caroline Jonsson (2012) The relationship between climate change and grazing by herbivores; their impact on the carbon cycle in Arctic environments
243 Carolina Emanuelsson and Elna Rasmusson (2012) The effects of soil erosion on nutrient content in smallholding tea lands in Matara district, Sri Lanka
244 John Bengtsson and Eric Torkelsson (2012) The Potential Impact of Changing

Vegetation on Thawing Permafrost: Effects of manipulated vegetation on summer ground temperatures and soil moisture in Abisko, Sweden
245 Linnea Jonsson (2012). Impacts of climate change on Pedunculate oak and Phytophthora activity in north and central Europe
246 Ulrika Belsing (2012) Arktis och Antarktis föränderliga havsistäcken
247 Anna Lindstein (2012) Riskområden för erosion och näringsläckage i Segeåns avrinningsområde
248 Bodil Englund (2012) Klimatanpassningsarbete kring stigande havsnivåer i Kalmar läns kustkommuner
249 Alexandra Dicander (2012) GIS-baserad översvämningskartering i Segeåns avrinningsområde
250 Johannes Jonsson (2012) Defining phenology events with digital repeat photography
251 Joel Lilljebjörn (2012) Flygbildsbaserad skyddszonsinventering vid Segeå
252 Camilla Persson (2012) Beräkning av glaciärers massbalans – En metodanalys med fjärranalys och jämviktslinjehöjd över Storglaciären
253 Rebecka Nilsson (2012) Torkan i Australien 2002-2010 Analys av möjliga orsaker och effekter
254 Ning Zhang (2012) Automated plane detection and extraction from airborne laser scanning data of dense urban areas
255 Bawar Tahir (2012) Comparison of the water balance of two forest stands using the BROOK90 model
256 Shubhangi Lamba (2012) Estimating contemporary methane emissions from tropical wetlands using multiple modelling approaches
257 Mohammed S. Alwesabi (2012) MODIS NDVI satellite data for assessing drought in Somalia during the period 2000-2011
258 Christine Walsh (2012) Aerosol light absorption measurement techniques: A comparison of methods from field data and laboratory experimentation
259 Jole Forsmoo (2012) Desertification in China, causes and preventive actions in modern time
260 Min Wang (2012) Seasonal and inter-annual variability of soil respiration at Skyttorp, a Swedish boreal forest
261 Erica Perming (2012) Nitrogen Footprint vs. Life Cycle Impact Assessment methods – A comparison of the methods in a case study.
262 Sarah Loudin (2012) The response of European forests to the change in summer temperatures: a comparison between normal and warm years, from 1996 to 2006
263 Peng Wang (2012) Web-based public participation GIS application – a case study on flood emergency management
264 Minyi Pan (2012) Uncertainty and Sensitivity Analysis in Soil Strata Model Generation for Ground Settlement Risk Evaluation
265 Mohamed Ahmed (2012) Significance of soil moisture on vegetation greenness in the African Sahel from 1982 to 2008
266 Iurii Shendryk (2013) Integration of LiDAR data and satellite imagery for biomass estimation in conifer-dominated forest
267 Kristian Morin (2013) Mapping moth induced birch forest damage in northern Sweden, with MODIS satellite data