The Phenology of the Enkangala Grasslands

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Declaration

I declare that this dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Signed: 27th day of July 2018 at The University of the Witwatersrand

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(Signature)

Abstract

Phenology is the study of the timing within the year of life history events in plants and animals. The phenology of plants is usually cued to climate; therefore climate change is likely to have an effect on the date of events such as greening and browning and thus the length of the growing season. Since the growth duration, the rainfall and the temperature all control primary productivity and transpiration, phenological change will lead to changes in the ecosystem services of forage provision and water yield. Remote sensing techniques are used to describe the grassland phenology at landscape scale in the high-altitude Enkangala grasslands of South Africa over a period of 18 years, using an ecologically-based phenological model, in which the parameters were related to climatic cues. A 100-year daily climate data record is then used to hindcast the grassland phenology over the 20th century and test for changes. Finally, possible future phenological trends are made based on climate change projections for the region. We found that the length of the growing season has not increased over the 18 year period but it has increased by 35 days over the past 100 years. This is due to the growing season starting at an earlier date than usual and ending at a later date.

Key Words: Phenology, Climate Change, Remote Sensing, MISR, Growing Season Length

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List of Acronyms

APAR – Available Photosynthetically-Active Radiation

ARC – Agricultural Research Council

AVHRR – Advanced Very High-Resolution Radiometer

EOS – End of the growing season

ERS – End of the Rainy Season

ESA – European Space Agency

ET - Evapotranspiration

EVI – Enhanced Vegetation Index

FAPAR - Fraction of Absorbed Photosynthetic Active Radiation

GPP – Gross Primary Production

GSD – Ground Sampling Distance

LAI – Leaf Area Index

MERIS – Medium Resolution Imaging Spectrometer

MISR – Multi-angle Image SpectroRadiometer

MISR-HR – Multi-angle Image SpectroRadiometer High Resolution

MODIS – Moderate-resolution Imaging Spectroradiometer

NASA – National Aeronautics and Space Administration

NDVI – Normalised Difference Vegetation Index

NPP – Net Primary Productivity

ORS – Onset of the Rainy Season

RDR – Relative Death Rate

RGR – Relative Greenup Rate

SAWS – South African Weather Service

SeaWiFS – Sea-Viewing Wide Field-of-View Sensor

SOS – Start of the growing season

WWF – World Wildlife Fund

1.Introduction

Introduction

Climate change is one of the key challenges of the 21st century. It is important to be able to predict the impact of climate change on ecosystem function, as this has an impact on human lives, via the delivery of ecosystem services such as grazing, water and food. Climate controls most ecosystem processes and the distribution of species (Grimm *et al.* 2013). Climate change has had an impact on terrestrial ecosystems such as grasslands. This impact is projected to be greater in the future (Walther *et al.* 2002; IPCC 2007; IPCC 2013). One of the first ecosystem attributes to respond to climate change is phenology. Phenology affects ecosystem services, including forage production, water yield and habitat suitability -- the key services delivered by the Afromontane Enkangala grasslands where this study is focussed (WWF-SA 2011; Carbutt *et al.* 2011; Carbutt and Martindale 2014).

Grasslands

Climate controls the distribution of ecosystems and biomes worldwide (Bond *et al.* 2005). The distribution vegetation can be predicted from temperature and precipitation. Fire also controls the distribution of biomes as much as climatic factors do (Whittaker *et al.* 1975; Woodward 1987; Bond *et al.* 2003; Bond *et al.* 2003). Fire determines the structure, function and composition of the grassland biome in South Africa (Bond 1997; O'Connor and Bredenkamp 1997; O'Connor *et al.* 2004).

According to Mucina and Rutherford (2006), the grassland biome in South Africa originally covered approximately 17% of the country (about 339 240 km^2). The biome is subdivided into 73 vegetation types. It covers several provinces and a wide range of rainfall (400mm to >1200mm per year), altitude (sea level to >3300 m above sea level) and soil types (O'Connor and Bredenkamp 1997). South African grasslands are high in biodiversity and contain many endemic plants and animals. Several conservation-worthy river ecosystems are embedded in the grasslands and dependent on them for sustained flow of clean water (Nel *et al.* 2007).

Natural grasslands are found in areas which have a long dry season (Watkinson and Omerod 2001). This is because grasslands have a high recovery potential for plant growth (grasslands are resilient). This enables them to persist in dry climates (Reichstein *et al.* 2013). The distribution and extent of grasslands are determined by several factors such as fire, grazing and climatic conditions such as temperature and precipitation (O'Connor and Bredenkamp 1997; Watkinson and Omerod 2001). The productivity of grasslands is also influenced by climatic factors which include temperature, water availability and atmospheric CO_2 concentration (Hall and Scurlock 1991). Fire is a tool that is widely used to manage grasslands, for instance, to control bush encroachment and removes old, dead, unpalatable grass. Fire in grasslands is an important factor in the global carbon cycle (Hall and Scurlock 1991).

The grassland biome is one of the most transformed biomes in the world because grasslands are so suitable for crop agriculture. South African grasslands are not an exception. Habitat transformation, habitat loss and fragmentation are major threats to the grassland biome in South Africa (O'Connor and Bredenkamp 1997). The biodiversity in grasslands is partially controlled by grazing. Understanding plant responses to grazing gives us an idea of the impact grazing has on a community structure (Watkinson and Omerod 2001). Biodiversity loss comes as a result of habitat transformation (Neke and du Plessis 2004). Southern African grasslands are highly transformed. This biome supports a large human population and there is a demand for resources. Some of the causes of transformation in this biome include cultivation, mining (particularly coal mining in the eastern Highveld region of South Africa), power generation, human settlement and grazing for livestock (Fairbanks *et al.* 2000; Reyers and Tosh 2003; Reyers *et al.* 2005; O'Connor and Kuyler 2009).

Africa has a grassland biome. Grasslands in Africa are usually associated with temperate areas but there are tropical grasslands in Africa (White 1981). The grassland patches are not extensive because most of Africa has savanna vegetation. There are two conditions which control the occurrence of grasslands in Africa. Grasslands can either be hydromorphic, where they occur in swampy, marshy areas where trees cannot grow (flood plain type). The other type of grassland, are the high altitude (montane) grasslands that are being examined in this study. Montane grasslands in South Africa used to be extensive but have been reduced to small patches and one of them is the Enkangala Grasslands. This term is used by the WWF to distinguish it from the other types of grasslands such as the Drakensberg grassland and the Highveld grasslands. The Enkangala grasslands are low latitude, high altitude grasslands and this what makes them unusual and interesting.

Climatic Conditions

It is important to understand climate variability at different spatial and temporal scales to anticipate the impact of climate change on ecosystem services and human well-being (Nash *et al.* 2016).The rainy season in the Enkangala Grasslands is usually between September and March (Figure 1.1), with the maximum amount of rainfall coming in January (Nicholson 2000). The seasonal cycle tends to have a single rainfall and temperature peak during the summer (unimodal). Plant growth is vigorous during this time period. The rainfall mostly takes the form of thunderstorms and growth is vigorous during this time period (Cook *et al.* 2004; Thomas *et al.* 2007; Palmer *et al.* 2010; Nash *et al.* 2016). Rainfall in grasslands is always variable and the variation is predicted to increase regardless of whether rainfall or decreases. Part of this fluctuation may be associated with postulated 20-year cyclicity (Tyson *et al.* 1975; Dyer and Tyson 1977). Variation can be cyclic or aperiodical. Cyclicity has been detected by many people particularly Dyer and Tyson (1977) and it is incredibly weak and only accounts for a small percentage of the variation. It has been shown that it is possible that this cyclicity does not exist anymore. (Mason and Jury 1997; Meadows and Hoffman 2002; Moyo 2015).

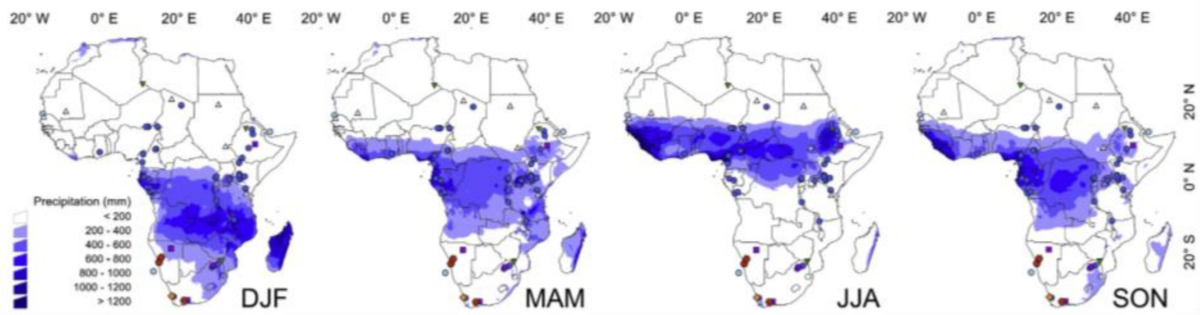


Figure 1.1: Map of the seasonal distribution of precipitation in Africa (data from Hijmans *et al.* 2005). The Enkangala grasslands are in the South East of Africa, with rainfall predominantly between September and February.

Ecosystem Services

Grasslands, apart from frequently having a high biodiversity, also provide a variety of ecosystem services that support humans. This is why it is important that we conserve grasslands (Reyers *et al.* 2005; Egoh *et al.* 2011). Habitat transformation leads to a decrease in the biodiversity and primary production and regulated water yield of grasslands. This threatens the delivery of ecosystem services (Egoh *et al.* 2011; O'Mara 2012; Parr *et al.* 2014; Everson and Everson 2016).

Ecosystem services are "the benefits humans derive from ecosystems which ultimately underpin human well-being". These ecosystem services can be direct (food provision, medicinal plants) or indirect (climate regulation) (Millennium Ecosystem Assessment 2003; Egoh *et al.* 2007; Egoh *et al.* 2011). Some of the ecosystem services that are provided by grasslands include carbon sequestration where carbon is stored below the ground as soil organic matter (Burke *et al.* 1989; Sala and Paruelo 1997). This reduces the amount of carbon in the atmosphere. Grasslands play a crucial role in the hydrological cycle and are important for water supply. They reduce the runoff and erosion and store water as groundwater (Egoh *et al.* 2011). Changes in the phenology with respect to climate change have an implication for ecosystem services (Schroter *et al.* 2005). These changes will be discussed below.

Carbon Cycle

It is important to study grasslands and the impacts of climate change on grasslands because they play an important role in the global carbon cycle. The role of grasslands in the global carbon cycle is poorly understood (Chen *et al.* 2014). Understanding the grassland ecosystem carbon cycle will help us to how to use grassland resources sustainably (Piao *et al.* 2006). Grasslands do not have high biomass but they have characteristically large soil carbon stores. The turnover time of C in soil is relatively long (Ni 2002). These carbon stores have been underestimated (Scurlock and Hall 1998). Changes in the amount of carbon stored in grasslands have an implication on global carbon cycles (Parton *et al.* 1995). Most studies on the carbon cycle focus on forests as trees store more above ground compared to grasses which store their carbon in the soil as soil organic carbon (Belsky *et al.* 1993; Hibbard *et al.* 2001). It has been suggested that natural grassland ecosystems are a carbon sink that stores about 20% of the total carbon produced in the world (Scurlock and Hall 1998). Understanding the responses of vegetation growth and the carbon cycle to environmental changes is important. The interaction between terrestrial ecosystems and the climate system has to be understood (Ni 2002; Zhang *et al.* 2013). The timing and duration of vegetation activity help us to understand how variable the terrestrial carbon sink is. The amount of carbon that is taken up by the landscape is linked with the changes in the phenology of vegetation (Garonna *et al.* 2016).

Phenology

Phenology is the study of the timing of biological events in plants and animals. The timing of these events is influenced by the environment (Cleland *et al.* 2007). Phenology, as defined by the International Biological Program (IBP) is "the study of the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species" (Lieth, 1974). Phenology focuses on the link between biological cycles and climate and provides a measure of how ecosystems respond to climate change (White *et al.* 2009). Vegetation phenology is highly sensitive to climate change and it influences many feedbacks of vegetation to the climate system as shown in Figure 1.2 (Cleland *et al.* 2007; Morisette *et al.* 2009; Penuelas *et al.* 2009; Richardson *et al.* 2013). It is among the simplest ways to study the response of species to climate change as it is an easily observable and sensitive indicator compared to other natural indicators (Walther *et al.*. 2002; Badeck *et al.* 2004; Rosenzweig *et al.* 2007; Stocker and Dahe 2013): for instance, by detecting changes to the growing season. Phenology is studied at different scales from the level of the individual plant to the landscape level (Gonsamo *et al.* 2012). Phenology changes depending on the vegetation type and the climate of a particular area and the phenology of individual species can determine the structure of an ecosystem and how an ecosystem functions (Cleland *et al.* 2007; Richardson *et al.* 2013). Changes in the environment can have an effect on vegetation phenology. Changes in leaf phenology affect the amount of time that green leaves are actively photosynthesising and taking up carbon and transpiring water. Therefore phenological changes affect the water and carbon cycles, as well as nutrient cycling, exchange of energy between the atmosphere and the surface, species distribution and trophic dynamics (Myneni *et al.* 1997; Gu *et al.* 2003; Chen *et al.* 2005; Piao *et al.* 2007; Noormets *et al.* 2009; Penuelas *et al.* 2009; White *et al.* 2009; Keenan and Richardson 2015). These changes vary geographically and local conditions play a part in the phenology of vegetation in a particular area (Linderholm 2006). Changes in the phenology show how plants and animals have been responding to changes in the climate (Parmesan and Yohe

2003; Gordo and Sanz 2006). These changes could lead to earlier onset of spring (Myneni *et al.* 1997; Zhou *et al.* 2001) or earlier senescence (De Beurs and Henebry 2004).

The phenology of individual species in a community determines the structure of that particular ecosystem and also how that ecosystem functions (Cleland *et al.* 2007). Ecosystem functions respond to the changes in the timing of phenological events. These changes cause the ecosystem to have feedbacks to the climate system (Richardson *et al.* 2013). Phenology is one of the primary indicators of climate change as it is sensitive to changes in climate (Stocker and Dahe 2013). This has many implications on ecosystems and the services provided by them (Schroter *et al.* 2005).

Understanding phenology is important so that we are able to identify changes in the phenology in response to a change in the climate (Menzel 2002; Cleland *et al.* 2007; Chambers *et al.* 2013; Fitchett *et al.* 2015). The drivers that control phenology should be better understood. Phenology models based on climate data can be used to predict the seasonal pattern of greenness because climate is the biggest primary driver of plant phenology at larger scales. A lot of attention has been given to the spring phenology (events at the start of the growing season) while autumn phenology (events at the end of the growing season) is not well understood (Richardson *et al.* 2013). Autumn phenology is neglected because the drivers of autumn phenology are very complex. Autumn events also happen over a longer period of time (gradually) compared to spring events that happen suddenly (Gallinat *et al.* 2015).

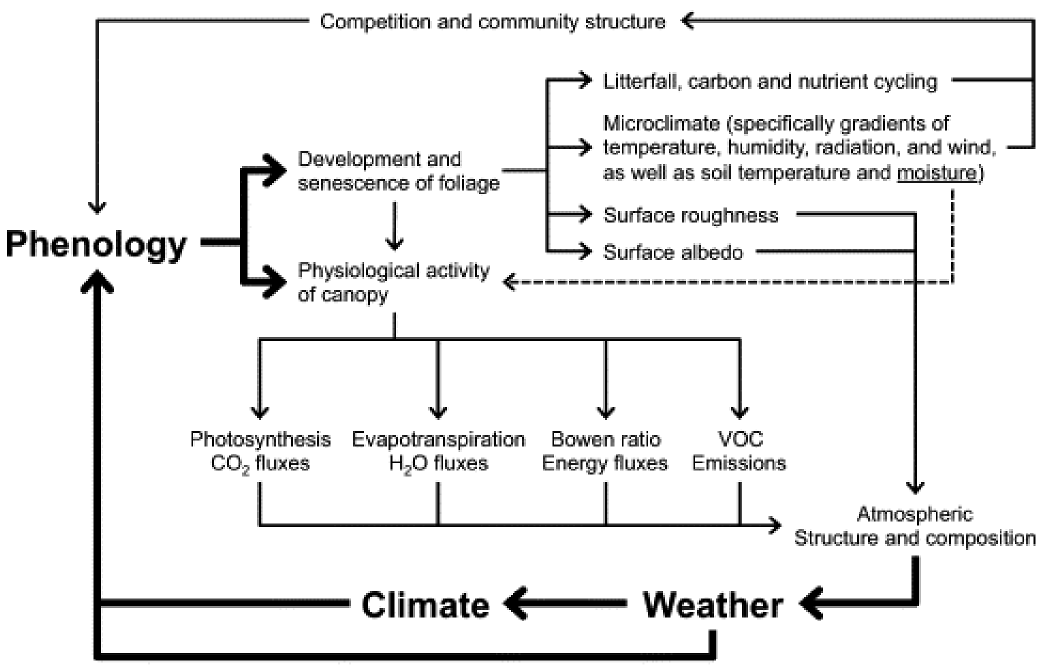


Figure 1.2: Feedbacks between vegetation and the climate system that are influenced by vegetation phenology (Richardson *et al.* 2013)

Most phenological studies were carried out in the northern hemisphere and on temperate or boreal ecosystems, such as forests (Menzel *et al.* 2006; Cleland *et al.* 2007; Parmesan 2007). Of the studies done in the southern hemisphere, most were focused on forests, dominated by trees, or savannas which contain both grass and trees (Archibald and Scholes 2007; Chidumayo 2001; Jin *et al.* 2013; Higgins *et al.* 2011; Whitecross *et al.* 2016). Tree phenology uses different cues and has different attributes to that of grasses (Whitecross *et al.* 2016). Not many phenological studies have been carried out on African grasslands. More have been carried out in savannas. The phenology of savannas has been shown to be variable between years due to the variability in the seasonal rainfall which is a major contributor to green-up (Whitecross *et al.* 2016). The grass responds to different cues from the trees (Whitecross *et al.* 2017). Most grassland phenology studies have been conducted in the extra-tropical, temperate grasslands of the Northern Hemisphere, especially in China, Mongolia and Tibet (Xiao *et al.* 1995, Yu *et al.* 2003, Zhou *et al.* 2001, Zhang *et al.* 2004, Chen *et al.* 2014) and in the United States of America (White *et al.* 2009). Models developed for high latitude grasslands do not necessarily apply at low latitudes; for instance, at low latitudes day length variation is much less prominent, and the winter cold period is much less pronounced. Northern Hemisphere seasonality is out of phase with Southern Hemisphere seasonality

Water availability controls the phenology of semi-arid savannas. Leaves start growing after the first big rainfall event (about 15mm) (Scholes and Archer 1997; Chidumayo 2001; Archibald and Scholes 2007, Hachigonta *et al.* 2008). In temperate ecosystems, cold temperatures control the phenology in those regions. Photoperiod is also a factor that controls the phenology of vegetation. Photoperiod for a given latitude varies in a predictable sinusoidal pattern every year since it is controlled by the Earth's orbit and tilt, but is not very sensitive to climate change except through changes in cloudiness (Jolly *et al.* 2005). In temperate grasslands in Mongolia, water availability controlled the timing of SOS and the temperature controlled when EOS occurred (Ren et al 2017).The growth of grass is directly linked to the arrival of rainfall because the grass is not able to store moisture within its biomass, compared to woody vegetation (Scholes and Archer 1997). The distribution of rain determines the production and development of plants, especially grasses (Hall *et al.* 2000). The effect of an increase or a decrease in the precipitation on the phenology is not known (Chen *et al.* 2014). In prairie grasses in the United States, the primary productivity of these grasslands is controlled by the amount of water that is available. Water availability varies each season and also at the depth of the soil (Nippert and Knapp 2007). The annual cycle of the growth of grasses in savannas is influenced by the soil moisture since grass has shallow roots compared to trees that have access to deeper soil water (Dye and Walker 1987; Baldocchi *et al.* 2004; Archibald and Scholes 2007; Ma *et al.* 2007; February *et al.* 2013).

The phenological pattern of leaf development and loss ('greenness') for most locations is a uni-modal by asymmetrical curve, rising from a low level during the dry and/or cold season, to a high plateau during the moist and warm growing season, then falling again. Zhang *et al.* (2003) developed an idealised mathematical model of phenology (Figure 1.2) based on the following four-parameter double-logistic function (one logistic describes the greenup and the other the brown-down):

$$y(t) = \frac{c}{1+e^{a+bt}} + d \qquad \text{(Equation 1.1)}$$

Where t = time, a and b are fitting parameters, c+d is the maximum value of greenness and d is the minimum wintertime value of greenness. Greenness is typically measured from space, using a 'vegetation index' (VI), of which several exist.

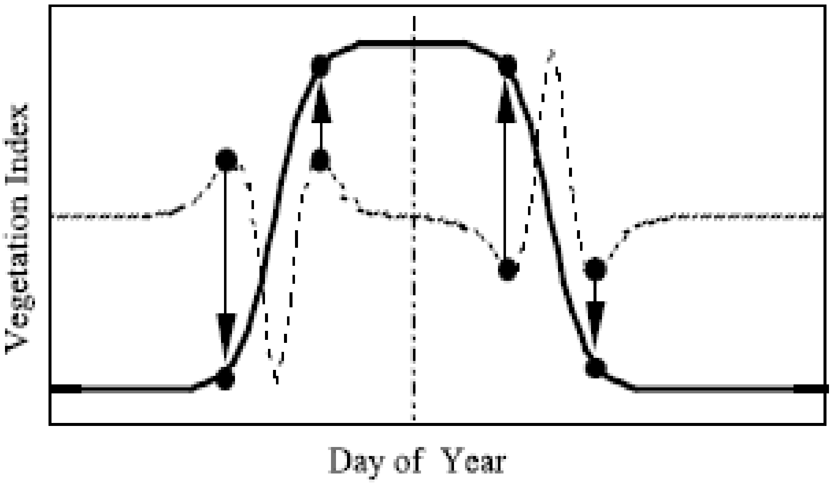


Figure 1.3: A generalised phenological model (Zhang *et al.* 2003). The solid line is the phenological curve showing the ideal time series for VI data. The dashed line represents the first derivative of the phenological curve which represents the rate of change. The dots represent key transition dates; such is the start and end of green-up and brown-down. Note that this is a purely descriptive mathematical model, and the four parameter form is about as simple as possible. Mathematical models are useful to give a general idea of how the phenology changes over time, but the parameter values have little intrinsic ecological meaning – they are just fitting parameters.

It is important to develop a phenological model that will give parameters that have an ecological meaning. Changes in the phenology are a consequence of changes in the climate. With the climate continuing to change (temperatures getting warmer), we need to understand current phenological patterns and future changes in the phenology need to be predicted (Scranton and Amarasekare 2017). Several approaches have been used to create phenological models. Mathematical models are the most common method that is used (Zhang et al 2003; Menzel *et al.*; 2006; Piao *et al.* 2006). These mathematical models can be used to generate predictions that go as far as explaining how temperature influences phenotypic traits (Scranton and Amarasekare 2017).

Growing Season

The growing season in high-altitude African grasslands is defined as the period between the first rains at the end of the dry season and the first frost at the beginning of winter the following year. Due to climate change, the length of the growing season is expected to change. Temperatures have been increasing worldwide and this may have an impact on the growing season. In all climates, the growing season is affected by cold indicators such as snow and frost. Increasing temperatures reduce the amount of snow and frost that occurs meaning theoretically the growing season will lengthen (Linderholm 2006; Cleland 2006). Changes to the length of the growing season will have an impact on other ecosystem processes (Archibald and Scholes 2007).The length of the growing season is linked to the variability in the weather from year to year (Richardson *et al.* 2013). In arid areas, thresholds of greenup and browndown are difficult to detect because of the variability in the vegetation and the rainfall (Vetter 2009). The length of the growing season determines the primary productivity of an ecosystem (Scheiter and Higgins 2009).

Lower precipitation and higher temperatures in grassland ecosystems could conceivably either shorten or lengthen the growing season depending on the trade-offs between evaporation (which shortens it because of higher temperatures), or the frosting effects that may lengthen it. Albedo is the proportion of incident solar radiation that is reflected by the land surface (Richardson *et al.* 2013). There is an increase in the albedo at the end of the season because dead grass reflects more solar radiation than either green grass or bare soil. At the beginning of the growing season, the albedo is reduced because live grass has a low reflectance of solar radiation (Ryu *et al.* 2008; Hollinger *et al.* 2010; Richardson *et al.* 2013).

Spring Phenology

Spring phenology is the “onset of photosynthetic activity” which is controlled by many different factors. In temperate forests, spring phenology is controlled by temperature (Piao *et al.* 2006) and in grasslands; it is controlled by precipitation (soil moisture (Shen *et al.* 2011). The increase in the warming worldwide has been linked to the earlier onset of vegetation activity in spring such as the flowering date which leads to the lengthening of the growing season (Linderholm 2006). It is important to study the link between spring phenology and climate change since spring phenology affects ecosystem processes such as carbon cycling and energy balance (Jeong *et al.* 2009a; Richardson *et al.* 2009a; Cao *et al.* 2015).

Autumn Phenology

There are not many studies on autumn phenology. This is because it is difficult to get exact dates of leaf senescence from remote sensing. Autumn events also happen over a longer period of time making it more difficult to observe (Klosterman *et al.* 2014). Compared to spring phenology, the effects of climate change on autumn phenology are not well understood in temperate ecosystems (Menzel 2003; Estrella and Menzel 2006). Many biological events seem to be happening at a later date (Rosenzweig *et al.* 2008). Autumn phenology is controlled by temperature and precipitation in temperate landscapes (Korner and Basler 2010). One feature of autumn phenology is leaf senescence, which is the final stage in the life of a leaf where it has declined in function. This is shown by a colour change from green to brown or yellow or red (Estiarte and Penuelas 2015; Gallinat *et al.* 2015).

The timing of phenological events, such as the start of the growing season (SOS) and end of the growing season (EOS), is particularly sensitive to climate change (Menzel *et al.*; 2006; Piao *et al.* 2006, 2015). There is uncertainty about how the start of the growing season (SOS) and the end of the growing season (EOS) are determined. Most studies on phenology focus on the factors that control phenology at the SOS (Schwartz *et al.*; 2006; Cleland *et al.* 2007, Morisette *et al.* 2009; White *et al.* 2009; Piao *et al.* 2011; Jeong *et al.* 2011). Fewer studies have focused on the response of EOS to climate change (Gallinat *et al.* 2015). Recent studies report that EOS dynamics may play a critical role in determining the length of vegetation growing season (Garonna *et al.*, 2014), and subsequently regulate terrestrial water, carbon and nutrient cycles (Piao *et al.*, 2007, 2008; Richardson *et al.*, 2013; Estiarte & Penuelas 2015). Determining the SOS is easier because greenup is easier to detect. The process of vegetation browning is very slow and this makes it difficult to establish a clear EOS (Gonsamo *et al.* 2012; Richardson *et al.* 2009b; Garonna *et al.* 2014).

Plant Growth and Weather

In order for plants to grow, several conditions are necessary, such as water, oxygen, nutrients, light and a suitable temperature. Some of these conditions are associated with the weather variables such as temperature and rainfall. Another variable that should be considered when studying plant growth is atmospheric CO_2. These variables have changed over time and are predicted to change in the future (IPCC 2007). Plants are sensitive to low temperatures and most processes in the plant cannot occur below freezing point, and are severely retarded at temperatures of 0-15°C, with a growth optimum around 25-30°C. Water stress causes the stomata to close, which reduces the rate at which leaves grow. If the stress persists, the leaves die and drop from a plant (Jolly *et al.* 2005). Other meteorological factors that have an influence on plant growth are photoperiod and humidity.

In grasslands, it has been suggested that a certain threshold of soil moisture has to be met in order for vegetation to grow. Practical estimates of these thresholds could be based on (1) cumulative precipitation (Gibbens 1991) (2) a proportion of the annual precipitation for that region (White *et al.* 1997) or (3) a soil moisture index (Zhang *et al.* 2005). The onset of the rainy season (ORS) is defined as the first wet day above a given threshold after a spell of receiving a certain amount of rainfall. This wet spell should not be followed by an extended dry period. The end of the rainy season (ERS) has been defined as “the date when the cumulative rainfall reached 99% of the total seasonal rainfall” (Zhang *et al.* 2005, Boyard-Micheau *et al.* 2013).

A study by Dye and Walker (1987) on grasses in Zimbabwe semi-arid savannas showed that the growth of grass depends on the amount of available soil moisture. This means the growth of grass is dependent on the rainfall. Chidumayo (2001) showed that in moist African savannas, the grass starts growing after the significant rainfall and since the time at which the first significant rainfall occurs is not the same, the start of the grass growing season differs every year. Different grass species respond to soil moisture in different ways. *Heteropogon contortus* grows faster after it rains because it is sensitive to the availability of soil moisture. The growth of *Heteropogon contortus* is affected by drought conditions and this leads to a change in phenology due to climate change (Dye and Walker 1987). Other grasses such as *Cymbopogon plurinodis* and *Themeda triandra* are not as highly sensitive to soil moisture but it still plays an important part in their growth. They have a period of quiescence that occurs even if there is enough soil moisture where the grass does not grow; after which the grass starts growing again if the soil moisture is still favourable (Dye and Walker 1987). The greenup date of grass species is specific to a certain location (Chen *et al.* 2014).

The growth of plants in temperate ecosystems is strongly driven by temperature. At higher altitudes, precipitation, frost, snow and radiation (due to cloud cover and increasing Ultraviolet radiation) become important factors. Plant physiological properties also have an influence on the development plants during spring (Studer *et al.* 2007). Low temperatures are not considered an important constraint on ecosystem functions in the tropics, compared to high latitudes (Scholes and van Breemen 1997). The main factors that control plant phenology in the tropics are thought to be the seasonality of water availability and photoperiod (Jolly *et al.* 2005). In savanna systems, water availability is a limiting factor for growth, rather than light (Archibald and Scholes 2007) or low temperatures (Nemani *et al.* 2003). Phenology in tropical ecosystems may be defined by soil moisture rather than temperature in general, but a high altitude (the Enkangala grasslands are above 1600 m); frost is one of the factors that can control the length of the growing season (Huntley 1984).

Remote Sensing

Vegetation monitoring is crucial for environmental management (Zhou *et al.* 2001, Reed *et al.* 2003). Remote sensing products are used to monitor vegetation at different scales. These products are readily available (Zhou *et al.* 2001, Zhang *et al.* 2003). Remote sensing is used for many different applications such as classifying land cover detecting natural and human-induced changes in an environment (Kerr and Ostrovsky 2003). Remote sensing is used to assess large-scale ecosystem features such as phenology and this helps us to be able to infer ecosystem productivity and carbon sequestration (Whitecross *et al.* 2017).

The use of ground-based observation for phenology is useful because it helps us to validate the values of vegetation indices from remote sensing (Fitchett *et al.* 2015). These ground-based observations are limited to species, space and time. In order to study phenology at a larger spatial scale, satellite-based methods are employed as they provide high spatial coverage and fine temporal resolution (White *et al.* 1997). Remote sensing data is easily available through various sensors such as NASA's Advanced Very High-Resolution Radiometer (AVHRR) sensor, Moderate-resolution Imaging Spectroradiometer (MODIS) sensor and ESA's Medium Resolution Imaging Spectrometer (MERIS) sensor, Multi-angle Image SpectroRadiometer (MISR) and several other sensors at a fine temporal resolution (at least one reading every 8 days). These data from these sensors has been used in many different applications worldwide in particular, for studies of phenology (Justice *et al*. 1985; Zhang *et al*. 2006; Jeganathan *et al.* 2010). MISR gives us the Fraction of Absorbed Photosynthetic Active Radiation (FAPAR) directly, rather than by indirect inference from surface greenness. FAPAR is the proportion of incoming solar radiation in the photosynthetically active region (between 400nm and 700nm) which is absorbed by plants during photosynthesis (Pettorelli *et al.* 2005). FAPAR is a reliable and ecologically-meaningful measure for quantifying the presence of vegetation at a global scale (Gobron *et al.* 2000), and is directly relatable to Gross Primary Productivity.

Aim

The aim of this study is to gain a predictive understanding of the phenology of the Enkangala moist, high altitude grassland.

Objectives

1. Use moderate spatial resolution, high time-resolution multi-temporal satellite-derived datasets to describe the phenology of natural high-altitude grassland communities in the Volksrust-Wakkerstroom area through assigning attribute values to a minimal phenometric model, and to relate the phenometric attributes to climate conditions such as soil moisture and air temperature.

2. Determine if there have been changes in the phenometric attributes, such as the date of green-up or brown-down, over the period of satellite records (2000 to present); and by inference using the relationship to climate cues, over the period of climate records (1904 to present).

2.Materials and Methods

Study Area

The grassland biome in South Africa has been mapped and classified into about 50 different plant communities (Mucina and Rutherford 2006). The study area is part of the Wakkerstroom Montane Grassland which is a high altitude grassland (altitude between 1800m and 2250m above sea level) found in KwaZulu Natal and Mpumalanga (Muchai 2002). The vegetation that is found there is mostly montane grassland on the hilltops and valley bottoms. The steep areas increasingly support thickets, typically dominated by *Leucosidea sericea*. The study area has 87% of the natural habitat remaining, unlike adjacent areas which are transformed by agriculture, mining and human settlements (Fourie 2005, WWF-SA 2011). This is because much of the land is steep, underlain by shallow soils, or too cold for most crops to be grown there (Mucina and Rutherford 2006). The Karoo Supergroup sediments underlie most of the study area, capped by basalt or dolerite on the higher mountains. Mudstones, sandstones and shales predominate in the valleys. Dolerite dykes and sills are common. The plant diversity is high (over 1300 species, RJ Scholes *pers com*). There are about 80 endemic plant species such as *Helichrysum aureum var. argentum*, *Bowkeria citrina* and *Lotonis amajubica* (Mucina and Rutherford 2006; WWF-SA 2011). Some of the grass species found in this region include *Themeda triandra, Digitaria thicholaenoides, Tristachya leucothrix, Hetropogon contortus, Loudetia simplex* and *Diheteropogon filifolius* (Muchai 2002).

The study sites that were selected were located between the towns of Volksrust and Wakkerstroom. These towns are among the first settlements that were established in the Old Boer republics of the Oranje Vrystaat and the Zuid-Afrikaanse Republiek. Given the history of these towns, long-term weather records are available (Moyo 2015). These are important in determining if there has been a change in the phenology over a much longer period than the available satellite data.

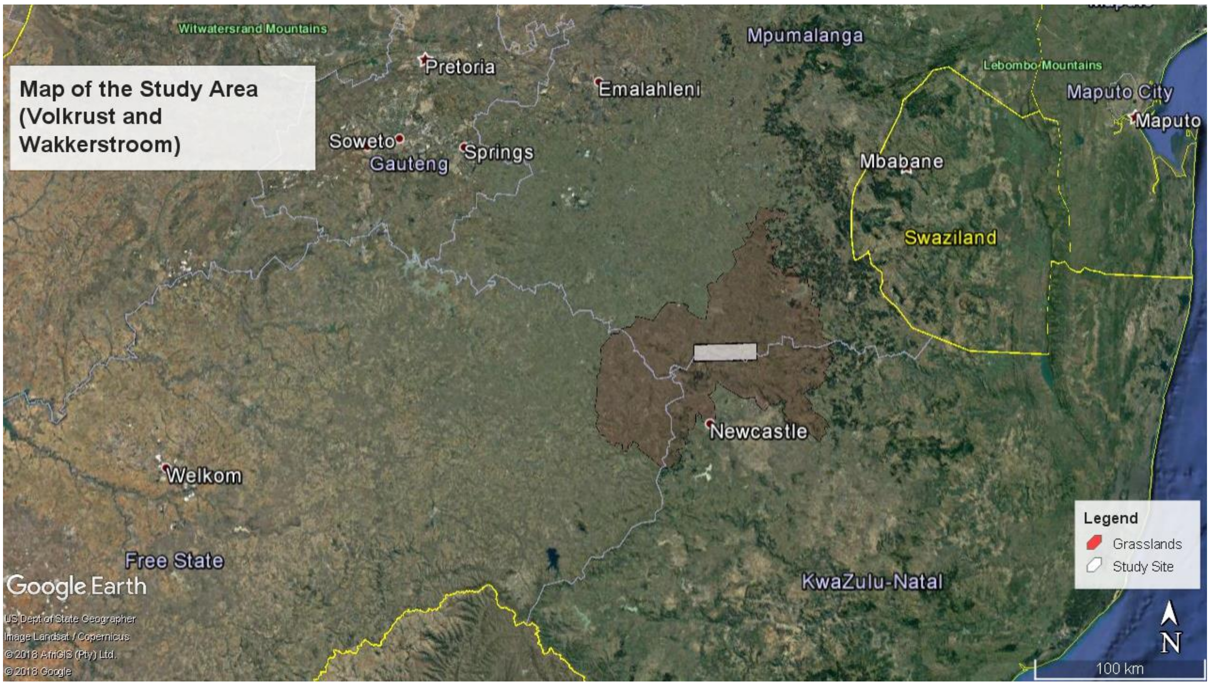


Figure 2.1: Map of the study area, located in the Enkangala grasslands (highlighted in red), which span three provinces (Mpumalanga, KwaZulu Natal and the Free State). The study area is outlined by the thick black box, and is located on the border of Mpumalanga and KwaZulu Natal.

FAPAR

The Fraction of Absorbed Photosynthetic Active Radiation (FAPAR) is the proportion of incoming solar radiation in the photosynthetically active region (between 400nm and 700nm) which is absorbed by plants during photosynthesis (Pettorelli *et al.* 2005). The value of FAPAR is by definition always between 0 and 1. FAPAR can be generated from several different sensors, such as SeaWiFS, MERIS, MODIS and MISR, (Verstraete *et al.* 1999). FAPAR is a reliable and ecologically-meaningful measure for quantifying the presence of vegetation at a global scale (Gobron *et al.* 2000). FAPAR is also used to quantify the photosynthetic capacity of vegetation as it measures the amount of energy (radiation) that is absorbed by the plant (Zhang et al 2017).

Another ecologically-meaningful and measurable vegetation parameter is of Leaf Area Index (LAI), the one-sided leaf area per unit ground area (m^2m^{-2}). There are LAI products based on MODIS and other sensors (Cleland *et al.* 2007). LAI is an indirect measure of the photosynthetic capacity of a plant, and it can be calculated from FAPAR by assuming the leaf orientation (usually assumed to be random or 'spherical'). FAPAR is a better measure of photosynthetic capacity because satellites directly measure it and not LAI. Only one step is required to calculate gross primary production (GPP; units = $kg/m^2/year$) from FAPAR (value between 0 and 1) (Monteith 1972, 1977).

$$GPP = \varepsilon * APAR*FAPAR \qquad \text{(Equation 2.1)}$$

where ε (epsilon, or the radiation use efficiency) is more-or-less constant for a given vegetation (and not very different between vegetation types), and APAR is the available photosynthetically-active radiation, calculated from the time of day, the day of year, latitude and cloud cover.

FAPAR and LAI provide more ecological information than traditional products such as NDVI or EVI. This helps us to be able to tell the subtle ecological differences in an environment (Verstraete *et al.* 2012). FAPAR can be used to estimate the net primary productivity. The net primary productivity (NPP) depends on the amount of water that is available in the system. It also depends on the absorbed radiation (Grarbulsky and Paruelo 2004). NPP has a linear relationship with the integral of the absorbed photosynthetic radiation (APAR) (Monteith 1981). The availability of water controls the amount of radiation absorbed by the canopy (Grarbulsky and Paruelo 2004).

Climate Data

A long term dataset (from 1904-2012) was constructed by Moyo (2015) and then was extended to 2015. Weather data was acquired from various sources such as the South African Weather Service (SAWS) and the Agricultural research council. Daily minimum temperature, daily maximum temperature and daily rainfall were obtained for the town of Volksrust (27°22′S 29°53′E, 1660 m above sea level, Station Number 406/6821, SAWS Municipal station). To fill in the gaps in the Volksrust dataset, data from the nearby towns was used. These towns were Wakkerstroom (27°21′S 30°08′E), 1760 m above sea level, 24.1 km east of Volksrust, Station Number: 407/261, SAWS Municipal station). Other stations that were used to patch the data were from the Agricultural Research Stations of Nooitgedacht (near the town of Ermelo) and the Morgenzon.

Materials and Methods

Selection of Study Sites

The phenological model was calibrated for the Volksrust-Wakkerstroom region by identifying study sites in the area. The study sites were selected to be homogenous at the scale of several MISR pixels (~275 m each) with respect to slope, soils and hydrature and they all had similar vegetation types and were accessible. The plots that were selected had different land uses with some of the plots being farms, commonage, abandoned fields and maize fields. The maize fields were selected in order to distinguish between the greenness signal from the grasslands and the signal from the maize (the greenness signal seems to be similar). These study sites were the plots that were observed using remote sensing. The study sites had to be large enough to be detected by the MISR sensor, taking into consideration a minimum pointing accuracy of about 1 pixel.

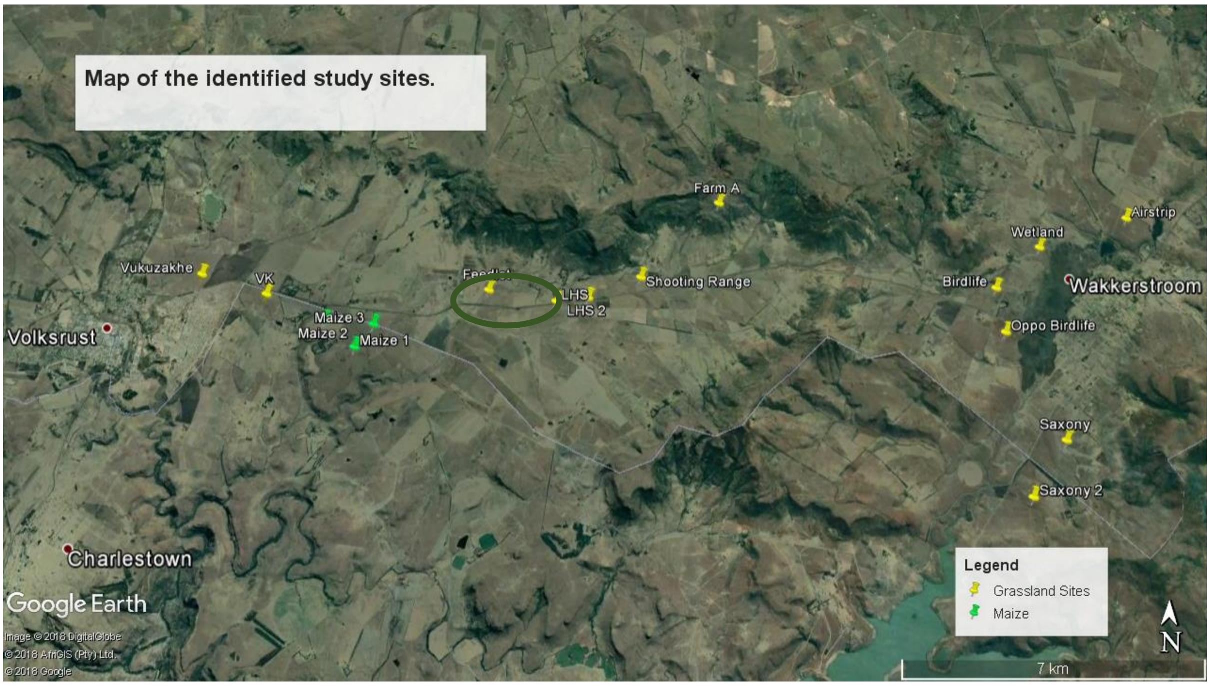


Figure 2.2: Map of the study area and the identified study sites. The jagged white line is the border between Mpumalanga and KwaZulu-Natal. The area is relatively untransformed except for areas around the two towns of Volksrust and Wakkerstroom, and some agricultural activity on flatter land. The darker patches are *Leucosidea* forests on the south slopes of the hills. The Zaihoek Dam (big water body in the south of the figure) is a pumped storage scheme which also supplies water to the Amajuba Power Station. The yellow boundary represents the extent of the Enkangala grasslands. These sites are found along the Volksrust to Wakkerstroom main road. The green ring represents maize fields in that area. The maize fields were selected in order to distinguish between the greenness signal from the grasslands and the signal from the maize (the greenness signal seems to be similar).

MISR Data

The Multi-angle Imaging SpectroRadiometer (MISR) sensor was used. Other sensors like the Moderate Resolution Imaging Spectroradiometer (MODIS) and Medium Resolution Imaging Spectrometer (MERIS) could have been used but there are several advantages of using the MISR dataset. MISR has 9 cameras that take readings at the same time compared to the other sensors. This gives more information during each overpass. MISR has an on board calibrator, spatial resolution of 275m (MISR-HR) and has 36 spectral bands. The MISR dataset also gives us many different biogeophysical products which have several different applications. These include FAPAR that will be used in this study. FAPAR is a direct measure of greenness and provides more ecological information than traditional products such as NDVI or EVI. This helps us to be able to tell the subtle ecological differences in an environment (Verstraete et al. 2012). The other sensors are used to calculate NDVI.

There are several problems with using NDVI, which make it difficult to separate ecosystem variation from interferences. These include calibration uncertainties, satellite and sensor drift, angular and atmospheric effects (Zhou et al. 2001). For instance as the sensor gradually degrades as it spends years in the harsh space environment. Since there is no on-board calibration, measurement errors can lead to an observation of a trend when one may not exist (Kaufmann et al. 2000). The Bidirectional Reflectance Distribution Function (BRDF) is another problem encountered. It is a way of expressing the variation in reflectance that you get from a surface depending on the angle at which you look at it from and its effects must be eliminated. BRDF depends on the wavelength and the structural and optical properties of the surface (Pettorelli et al. 2005). MERIS was also discontinued in 2012.

MISR-HR Data is available at the Global Change Institute (GCI) and it is based on Verstraete et al (2012). The MISR data for the study area, consisting of MISR path 168, 169 and 170; (block 112 in all cases), was obtained for all available dates between the launch of the Terra platform in 2000 and the present (May 2014 is the latest date that we had). The MISR record was “complete” and adequate to carry out this study.

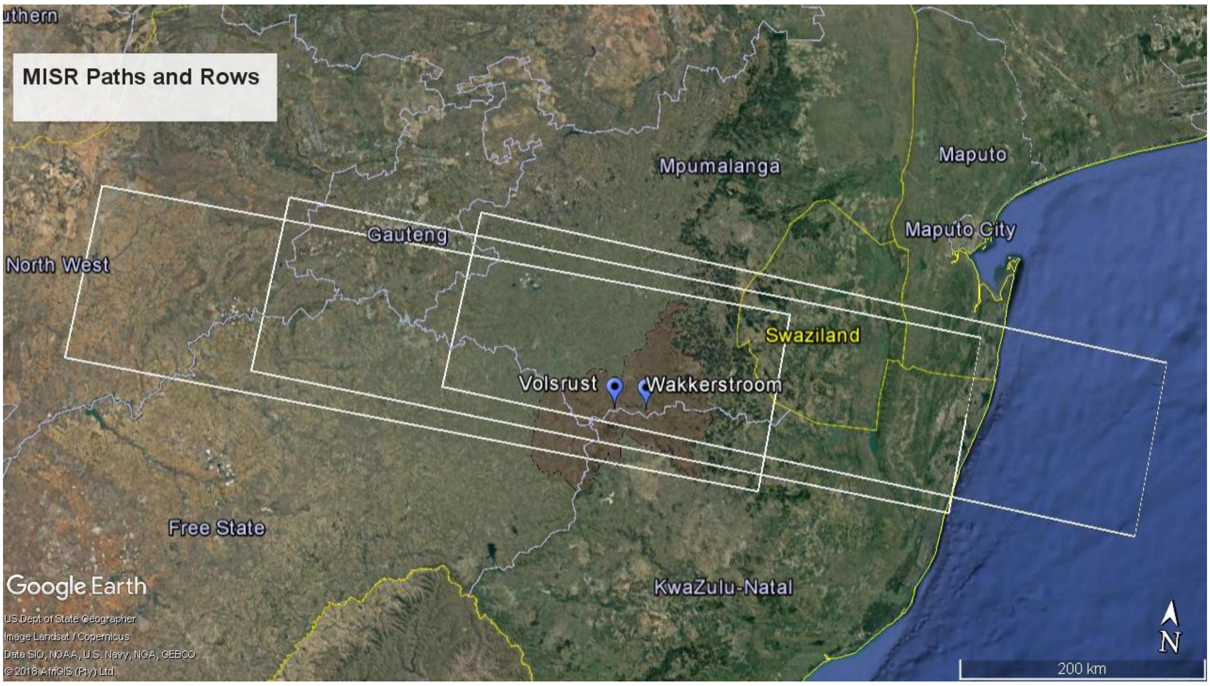


Figure 2.3: The MISR paths and rows overlaid on the study area (area marked in red), showing how most of the locations fall into the overlap of three paths, trebling the frequency of acquisition, which is important for detecting rapid phenological change. Path 170 is the one on the left and path 168 is the one on the right; only row 112 is shown

In order to extract the pixel data from MISR coverages for the identified grassland areas, grids with centres spaced at MISR high-resolution spacing (275 m) were generated and were overlaid on the site polygons. All grids that were more than 250 m from a polygon edge constituted the sample.

Steps to extracting FAPAR from available MISR Data

1. The MISR paths and blocks (path 168, 169 and 170; block 112 in all cases) that pass over the study site were selected. The blocks are overlapping (Figure 2.3) and this overlapping increases the amount of data that is available for the study site which is useful because there are instances where there is missing data. Cloud cover during the summer months means no satellite readings can be taken. The presence of mountains affects the readings as the angle is too steep for the sensor to take any readings. As the Earth rotates, the MISR pass for two different paths may not be recorded on the same day, the passes may occur on different days. There is at least one reading for one path every eight days. It is possible for the data from different paths to be recorded on the same day.

2. The data that is recorded by the MISR instrument has to be converted to high-resolution data (MISR-HR). Verstraete *et al.* (2012) developed a method of converting MISR data to MISR-HR data. MISR-HR data contains several products that have many various applications. These products include FAPAR, LAI and albedo and they are processed at a resolution of 275m (MISR data is processed at 1100m) which is useful for observing changes in the environment such as degradation, damage due to fire and phenology. MISR-HR gives the best estimates of the measurements from the sensor as it takes measurements at a higher spatial resolution.

3. The MISR paths have a particular projection, and thus need to be reprojected to longitude and latitude. The data for the MISR-HR variables (including FAPAR) and the longitude and latitude are stored in two matrices. These matrices have to be georeferenced in order to assign the longitude and the latitude to the MISR-HR blocks.

4. The MISR-HR variables are for each day that the satellite passes for a specific path. We combined all the data from the different days the satellite passes to create an aggregated dataset which is a matrix (MISR-HR variables * Latitude and Longitude * Time).

5. The FAPAR was extracted from the variable matrix that also contained 18 other variables. The values for FAPAR are between 0 and 1 and values outside that range are excluded. There are instances where there will be missing data. Cloud cover is the most common cause for missing data, especially during the summer months. The steepness of mountains in the study area also leads to missing data. If it is too steep, the sensor cannot make all the necessary corrections and conversions. Another satellite may be appropriate for this particular site.

A time series of FAPAR was constructed using the data from the three MISR paths that pass over the study area. A 3x3 grid was constructed around the centre of each of the study sites The FAPAR for each pixel in the 3x3 grid is determined from the MISR-HR Data. The FAPAR values in the 3x3 grids were averaged to give mean FAPAR for the site. In theory, there should be 27 pixels for a particular day (9 pixels for each site that is covered by 3 MISR paths). However, there were not always 27 pixels because sometimes the satellite does not pass on the same day, or some pixels may have been covered by clouds. A phenology dataset which is as continuous and time-resolved as possible was produced. On average, up to half of the pixels are covered by clouds. Using all three overlapping paths means there were more records per pixel. The fraction that was covered by clouds using data from the three paths is much smaller than if only one path was used. More records are available during the drier parts of the year because there are no clouds. During summer months, there are less readings because there are clouds which make it impossible to get any readings. There are on average about 400 records over the 13 year period (401±29 records) for each site.

Extracting the eight parameters of the general phenology model for the Enkangala Grasslands.

The eight parameters (evergreen fraction, greenup date, relative greenup rate (RGR), peak FAPAR, browndown date, relative death rate (RDR), frost date and end of the growing season) of a generalised, minimal grassland phenological response curve (Figure 2.4) were extracted for each year and for each study site.

1. The evergreen fraction is the annual minimum value on the response curve, after elimination of outliers (FAPAR of 0.1).

2. The greenup date is the first day the vegetation starts being green. In this case the greenup start date is defined as the day when the FAPAR was above 0.2. The FAPAR on this date is 10% above the evergreen FAPAR which we think will eliminate any false starts.

3. The peak FAPAR is the maximum value on the response curve, after elimination of outliers (Peak FAPAR of around 0.6).

4. To calculate RGR, an exponential function was fitted to the initial section of the greenup curve. The following equation, appropriate for exponential growth, was used: (t1 – start of growth, t2 – maximum FAPAR)

$$\frac{\ln(FAPAR_{t2}) - \ln(FAPAR_{t1})}{t_2 - t_1} \qquad \text{(Equation 2.2)}$$

5. Determining the browndown date was not as straightforward as determining greenup date. The browndown date is the date when the grass starts dying and is indicated by a drop in the FAPAR by a certain percentage below the peak FAPAR. This percentage was determined by trial-and-error. In this case the browndown start date is defined as the day when the FAPAR dropped by 0.2 below the maximum FAPAR.

6. To calculate RDR, a function was fitted. We assume that the death rate is also exponential. The following equation was used: (t1 – start of browndown, t2 – FAPAR = 0.2 at the end of the season)

$$\frac{\ln(FAPAR_{t2}) - \ln(FAPAR_{t1})}{t_2 - t_1} \qquad \text{(Equation 2.3)}$$

7. To end of the growing season is when the FAPAR returns to the evergreen FAPAR (0.1)

8. A frost event (D_{frost}). This accelerates the browndown. The frost event occurs when the minimum air temperature is below 2.2°C. A frost event occurs when the air temperature measured at standard screen height for that particular day is below 2.2°C noting that the temperature recorded in a screen 1.5m above the ground is higher than the temperature on the ground (Burton 2014).

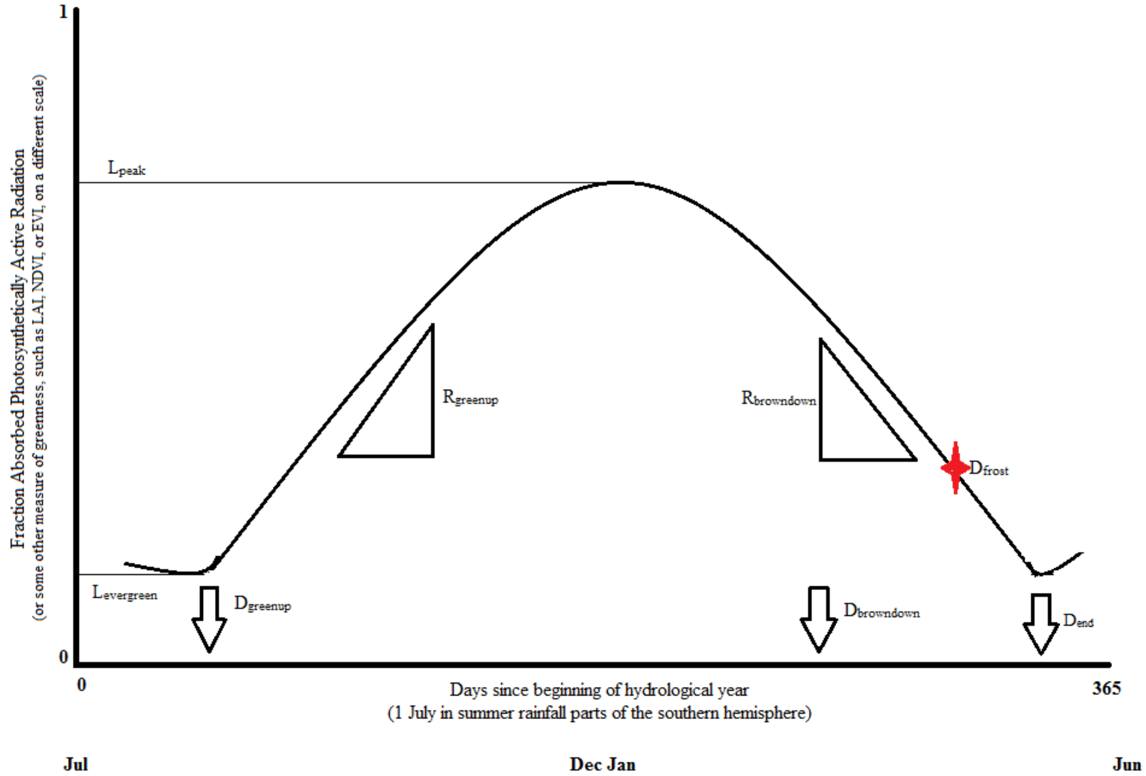


Figure 2.4: A seven-parameter phenological curve based on ecological attributes for a particular year. This model contains interpretable ecological values, as explained below. This is a very simplified version of what a phenology curve would generally look like.

The growing season length is the duration of the period between the greenup and end of browndown dates. It is still possible for growth to occur after start of browndown date but grasslands brown relatively quickly. The area under the FAPAR curve integrated between greenup and browndown, convolved with functions of soil water content and air temperature, and multiplied by the radiation use efficiency, is a proxy for grassland productivity. A temporal trend will be determined over the period of the satellite record. The data will have a lot of noise. Moving averages will be used to reduce the noise.

Calculating soil moisture

From the 110-year daily weather data from Volksrust area, the daily soil available water content using a simple soil water balance model were calculated.

$$\text{Soil moisture} = \text{soil moisture}_{\text{previous day}} + \text{rainfall} - \text{evapotranspiration} \qquad \text{(Equation 2.4)}$$

The initial soil moisture is 0 because the starting date is in winter where there is no rainfall (we assume that is the case, it is not absolute).

The 110-year daily weather dataset was constructed from data from the South African Weather Service (SAWS) and the Agricultural Research Council (ARC) (Moyo 2015). This weather data set was calibrated to the more accurate but data-demanding Penman-Monteith equation (Cai *et al.* 2007) for a nearby site where all data elements are available (Ermelo).

$$\mathrm{ET_o} = \frac{0.408\Delta(R_\mathrm{n} - G) + \gamma(900/(T + 273))u_2(e_\mathrm{s} - e_\mathrm{a})}{\Delta + \gamma(1 + 0.34u_2)} \qquad (1)$$

(Equation 2.5)

where ET is the evapotranspiration (mm/day); R_n is the net radiation (MJ m^{-2}/day); G is the soil heat flux density (MJ m^{-2}/day); T is the temperature (°C); u_2 is the wind speed (m/s); e is the vapour pressure (kPa); γ is a constant (kPa/°C)

Determining thresholds for soil moisture and mean temperature

The thresholds for the heat (mean temperature) and soil moisture were determined for the greenup date and browndown date, and the relationship between peak FAPAR and accumulated growth opportunity, for the period of satellite data availability. A plot of soil water content and mean temperature is used to determine the minimum amount of water in the soil that is required for growth to start. The date of browndown date depends on the temperature (frost) and water stress. The RDR is a result of accumulated stress (dry days, soil water content).The threshold of the soil moisture and mean temperature for the greenup date and browndown date were determined, for the period of satellite data availability (February 2000 – May 2014).The dates for the green up and the browndown were determined during the extraction of the six parameters of the phenology model. The mean soil moisture and mean temperature for the 10 days before those dates was calculated to determine the amount of soil moisture and temperature that is required for growth to start.

Simulating Past Phenology

The relationships that were determined were used to simulate the growing season lengths for each year since 1904 (assuming no change in greenup rate or browndown rate or APAR). The statistical trend for that time period was determined. The thresholds (soil moisture and temperature) that are determined for the greenup and the browndown are used to determine the greenup and browndown dates for the years where satellite data is not available. The greenup rate and browndown rate help us to be able to determine all the parameters of the phenology model. The frost date is determined by the minimum temperature of 2.2°C.

This chapter is intended for submission as a stand-alone paper, and therefore follows that format, including its own Abstract and conclusions. It therefore repeats, in places, some material covered in Chapter 1 and 2.

3. The length of the growing season of South African high-altitude grasslands in relation to climate

Abstract

The phenology of plants is usually cued to climate; therefore climate change is likely to have an effect on the date of events such as greening and browning, and thus the length of the growing season. Since the length of the growing season, the rainfall and the temperature control ecosystem processes such as primary productivity and transpiration, phenological change will lead to changes in the ecosystem services such as forage provision and water yield. We analyse the phenology of high-altitude grasslands near Wakkerstroom, South Africa, using 18 years of Multi-angle Imaging SpectroRadiometer (MISR) derived 8-daily Fraction of Absorbed Photosynthetically Active Radiation (FAPAR) data, and relate the greenup and brown-down timing to climate cues including temperature and soil moisture. We found that the length of the growing season has not changed in the period where satellite data is available.

Key Words: Phenology, Climate Change, Remote Sensing, Multi-angle Imaging SpectroRadiometer (MISR), Growing Season Length

Introduction

Climate controls many aspects of ecosystem process and composition, so understanding the links to climate is crucial for projections of the future supply of ecosystem services such as grazing, water provision and food (Walther *et al.* 2002; IPCC 2007; Grimm *et al.* 2013). One of the first ecosystem attributes to respond to changes in the climate is phenology (Walther *et al.* 2002; Badeck *et al.* 2004; Rosenzweig *et al.* 2007; Stocker and Dahe 2013). An example is the detection of changes in the growing season.

Phenology is "the study of the timing of recurrent biological events, the causes of their timing with regard to biotic and abiotic forces, and the interrelation among phases of the same or different species" (Lieth, 1974). Vegetation phenology is affected by the changes in the environment. Changes in phenology, in turn, affect processes such as water, carbon and nutrient cycling and exchange of energy between the land surface and atmosphere (Gu *et al.* 2003; Chen *et al.* 2005; Piao *et al.* 2007;

Noormets 2009; Penuelas and Filella 2009; White *et al.* 2009). The phenology of the vegetation in a particular area is influenced not only by the climate, but also by the composition of the vegetation, and factors such as soil type and landscape position (Linderholm 2006; Richardson *et al.* 2013).

Most vegetation phenological research has been carried out on trees, and in mid-to-high latitude locations, particularly in the northern hemisphere. Grassland phenology studies have been conducted in in China, Mongolia and Tibet (Xiao *et al.* 1995, Yu *et al.* 2003, Zhou *et al.* 2001, Zhang *et al.* 2004, Chen *et al.* 2014) and in the United States of America (White *et al.* 2009). The high-altitude ('Afromontane') near-tropical grasslands we discuss here are likely to differ in their phenological cues from those described for tree-based, high-latitude systems. For instance, at low latitudes day-length variation is much less prominent, and the winter cold period is much less pronounced. The winter period is characterised by dryness rather than extreme cold. Northern Hemisphere seasonality is out of phase with Southern Hemisphere seasonality. The period in which grass growth is concentrated in these strongly summer-rainfall grasslands is that time following the onset of the first rains around September (by which stage the ambient temperatures are warm enough to allow leaf expansion), and before it is terminated, either by the first frosts of the next year, or by progressive desiccation due to the tapering off of rainfall from about April onward. In Africa, phenology studies have been conducted in the much warmer, lower altitude, tree-containing savanna biome (Scholes and Archibald 2007, Whitecross *et al.* 2016, Whitecross *et al.* 2017).

The temperatures have been rising over the past century in the study region, as in other parts of the world, a change attributed to the rising atmospheric concentrations of greenhouse gases (Kruger and Sekele 2013). This would theoretically extend the growing season (Linderholm 2006, Cleland *et al*. 2006). Observations of changes in precipitation in Southern Africa are more equivocal. Easterling et al. (2000) found that there was an increase in the total amount of precipitation and also in the frequency of heavy precipitation events in South Africa. Other studies (Kniveton et al. 2009, Thomas et al. 2007) have shown that there have been changes in the mean rainfall along with changes in the onset of the rainy season, rainfall intensity and the frequency of dry spells. Thus soil moisture in this location may have been declining, as a combined result of declining rainfall and rising evaporative potential. It is also possible that the rains are coming earlier of later. Thus the duration of the growing season could potentially shorten (Scheiter and Higgins 2009). This study sets out to unravel whether changes have in fact taken place in the start, end and thus duration of the growing season in these grasslands.

High altitude, low latitude grasslands

The grassland biome is one of the most transformed biomes in the world, due to its suitability for cereal crop production, and South African grasslands are no exception., The grassland biome covered approximately 17% of South Africa a century ago (Mucina and Rutherford 2006). The boundaries of the grassland biome are determined by climate (Ellery et al 1991, Rutherford, Mucina and Powrie, 2006,) in interaction with fire and grazing (O'Connor and Bredenkamp 1997, Bond *et al.* 2003). South African grasslands, like other Afromontane grasslands (White 1981), are high in biodiversity and contain many endemic plants and animals (Parr *et al.* 2014). Several important rivers have their source in the area of our study (which have been referred to as the 'Enkangala grasslands, WWF-SA 2011), making the management of the grassland catchments important for both the river ecology and the provision of reliable supplies of fresh water to the industries and cities of South Africa (Nel *et al.* 2007).

Grasslands play an important but underestimated role in the global carbon cycle, particularly through the large carbon store in their soils (Hall and Scurlock 1991; Hall *et al.* 1995; Chen *et al.* 2014). Understanding the responses of vegetation growth, productivity and thus the carbon cycle to environmental changes is thus important (Zhang *et al.* 2013)

Phenology can be used to map different vegetation functional types and biomes. Grasslands can be identified based on their phenology (Wessels et al 2009).

Factors that control the phenology in the Enkangala Grasslands

Phenology can be controlled by different factors at different times of the year. Temperature – averages, extremes or cumulative heat-sums - controls many processes in plants (Korner and Basler 2010, Cleland *et al.* 2007). Temperature triggers leaf colouration in many tree species, even though photoperiod (typically conflated with temperature) may control the start of growth and reproductive events in plants and release from dormancy (Heide 2011). Temperature can also control the vegetation growth in humid and warm climates (Zhang *et al.* 2004).

In semi-arid and arid ecosystems, the pulsed pattern of water availability resulting from episodic rainfall events in a high-evaporation environment determines the timing and duration of plant growth and development opportunities, thus rainfall and evaporation, as well as the water retention capacity of the soil, need to be considered in the phenology of non-humid grasslands (Chen *et al.* 2014). Rainfall triggers germination and the emergence of green leaves in the predominantly perennial grasses. This is well-understood for crops (Penuelas *et al.* 2004, Zhang *et al.* 2005), but less so for grasslands (Chen *et al.* 2014).

Climate Data

Moyo (2015) analyses the daily rainfall and temperature records from the Volksrust-Wakkerstroom area (representative of the Enkangala grasslands), for the period 1904 to 2012. The mean annual rainfall is 770mm, and the mean annual temperature is 14.6ºC. The annual evaporation amounts to 1630 mm. He found that the daily mean temperature in the area has increased by 1.4°C over the past 100 years, which is double the global rate (Collins 2011, Niang *et al*. 2014). The minimum temperature increased almost five times faster than the maximum temperature (2.3°C versus 0.6 °C per century); this is a characteristic of climate change caused by the accumulation of greenhouse gases in the atmosphere (Cubasch *et al.* 2013). All findings were highly statistically-significant. This means there is an increase in warm indices (number of hot days, maximum recorded temperature) and a decrease in extreme cold indices (number of frost days, night-time minimum temperature, Aguilar *et al.* 2009; Kruger and Sekele 2013).

The rainfall during this time period apparently decreased by 10%, but the trend was not statistically significant due to the high interannual coefficient of variation (30%) (Moyo 2015).

Remote sensed data

Satellite observations can be used to estimate the fraction of the photosynthetic radiation (between 400nm and 700nm) absorbed by the canopy (FAPAR, (Pettorelli *et al.* 2005). FAPAR is a reliable and ecologically-meaningful measure for quantifying the presence of vegetation at a global scale (Gobron *et al.* 2000), and is directly relatable to Gross Primary Productivity (Box *et al.* 1989, Grarbulsky and Paruelo 2004).

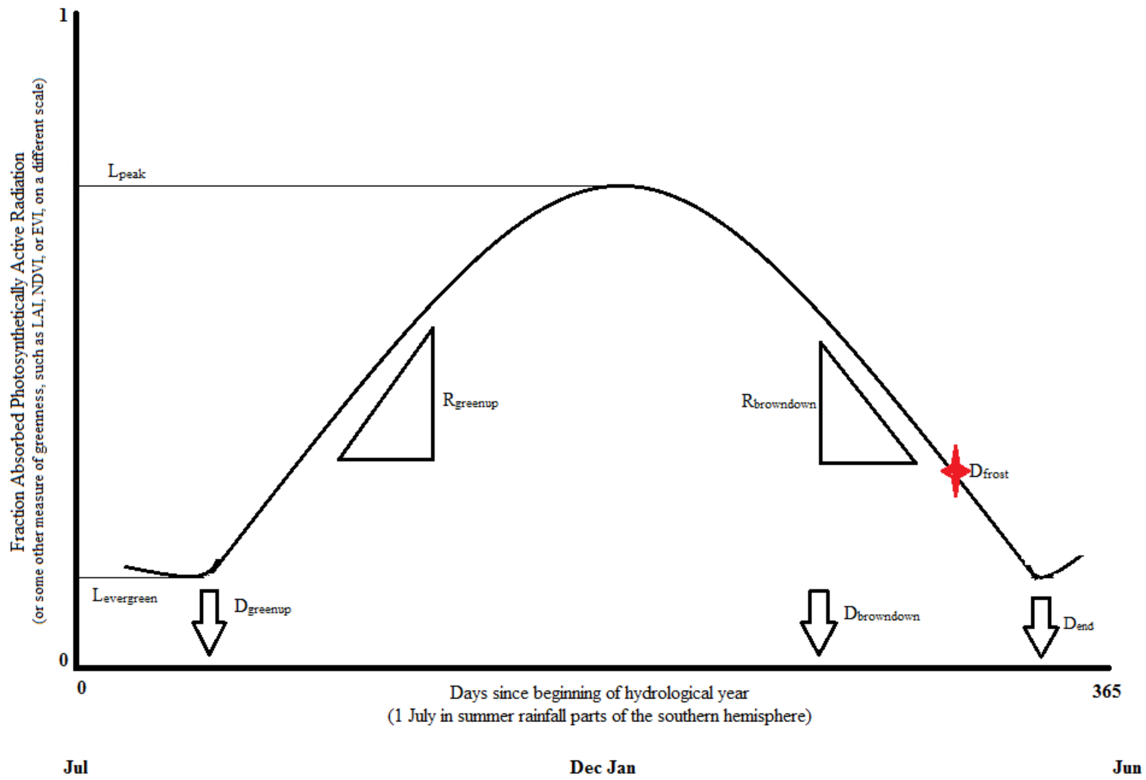
FAPAR is a superior measurement for this purpose than the more widely-used greenness indices (NDVI, EVI and similar) because if it's direct mechanistic association with plant productivity, linearity, sensor-independence and lower signal:noise ratio when correctly extracted (Gobron and Verstraete 2009). We use a unique FAPAR product derived from the Multi-angular Imaging Spectral Radiometer (MISR) sensor carried on the same 'Terra' Earth Observation platform which bears the better-known MODIS sensor. The nine view angles, from 60 º forward to 60º aft, although originally intended for atmospheric studies, allows a very robust and rigorous extraction of a FAPAR product through inversion modelling. MISR used in this way FAPAR directly, rather than correlative inference from surface greenness measure such as NDVI. The workflow we use also improves the spatial resolution to 275 m (Verstraete *et al.* 2012). Because of the relatively narrow swathe of 400 km, nadir overpasses occur only once every 8 days, but by taking advantage of path overlaps, usually three views are potentially available per 8-day period, of which some may be cloud-obscured. The instrument has been in operation since June 2000. We used MISR data from block 122 of paths 168, 169 and 170

The MISR-HR modification (Verstraete *et al.* 2012) was used to bring the resolution from the 1 km of the standard MISR product to 275m.

Most phenology studies that have been carried out have used sensors such as the Advanced Very High-Resolution Radiometer (AVHRR) sensor from NASA, Moderate-resolution Imaging Spectroradiometer (MODIS) sensor and Medium Resolution Imaging Spectrometer (MERIS) sensor from ESA. These sensors have high temporal resolution that makes them perfect for studying phenology (Justice *et al.* 1985, Zhang *et al.* 2006). In this study, the MISR (Multi-angle Imaging SpectroRadiometer) instrument, which is on the same Terra platform as the better-known MODIS was used. The MISR instrument, as the name suggests, it gives nine multi-angular views with its multiple onboard cameras, pointing from 60 ° forward to 60° aft. The multiple angles are most useful in determining a vegetation structural parameter such as leaf area or FAPAR. It has an onboard calibrator which gives a good land surface characterisation which other instruments do not give (Diner *et al.* 1998, Diner *et al.* 2010, Lillesand *et al.* 2008).

An ecologically-informed phenological model

In summer-rainfall, warm locations, the seasonal progression of leaf area is approximately uni-modal (ignoring dips caused by within season droughts), but asymmetrical. Leaf area rises quite rapidly from a low base level (the 'evergreen fraction') following the dry and/or cold season, to a high plateau or peak during the moist and warm growing season, then falls more slowly back to the evergreen fraction. Most studies of the seasonal pattern of leaf display fit one or more arbitrary mathematical functions to the multi-temporal data, in order to smooth over gaps and noise. . Idealised mathematical models, such as that by Zhang *et al.* (2003) use a four-parameter double-logistic function (one logistic describes the greenup, and the other the brown-down) to describe this pattern. The problem is that the parameters have no intrinsic ecological meaning. We propose, instead, a seven parameter, ecologically based model (Figure 1).



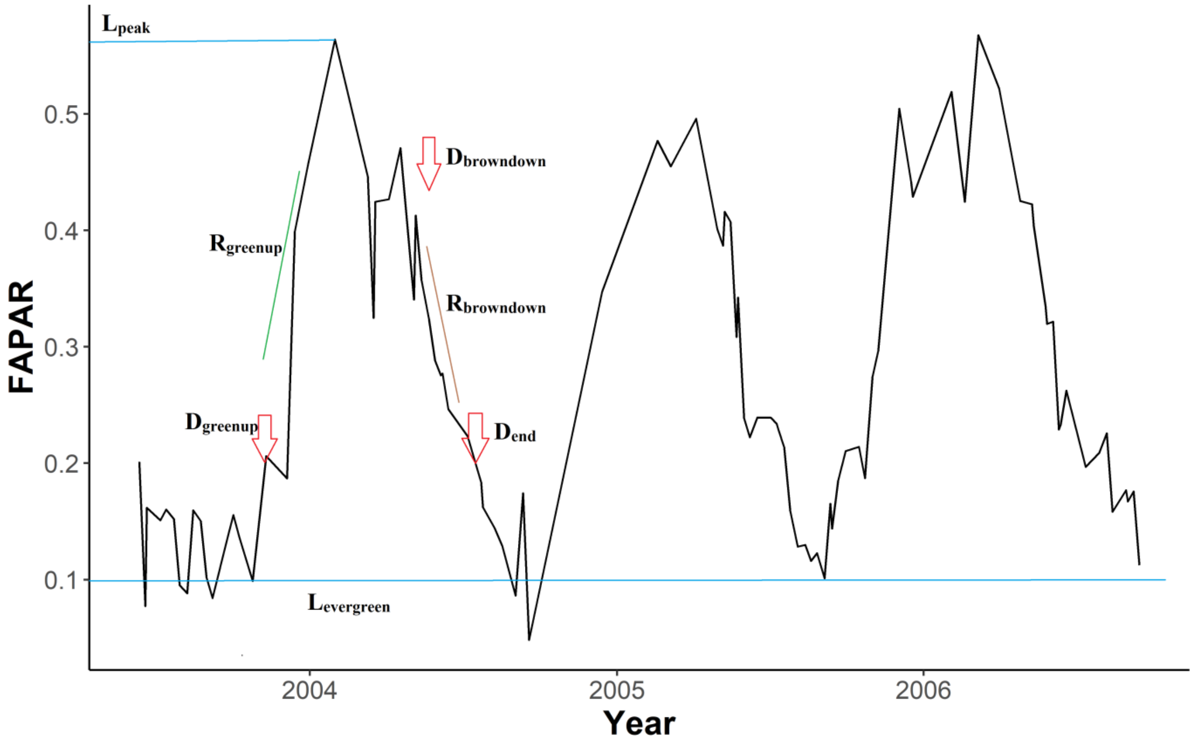


Figure 3.1a and b: (a) A seven-parameter phenological curve based on ecological attributes. The parameters are the evergreen fraction ($L_{evergreen}$), the date of greenup ($D_{greenup}$), the rate of greenup ($R_{greenup}$, the peak leaf level (L_{peak}), the date of when senescence begins ($D_{browndown}$), the date when the growing season ends occurs (D_{end}) and the rate of browning ($R_{browndown}$). This model is flexible and easily interpreted. (b) Shows the same parameters described in (a) extracted from one of the study sites (Birdlife).

Aim

The aim of this study is to gain a predictive understanding of the phenology of the Enkangala moist, high altitude grassland.

Objectives

1. Use moderate spatial resolution, high time-resolution multi-temporal satellite-derived datasets to describe the phenology of natural high-altitude grassland communities in the Volksrust-Wakkerstroom area through assigning attribute values to a minimal phenometric model, and to relate the phenometric attributes to climate conditions such as soil moisture and air temperature.

2. To determine the phenological cues (temperature and soil moisture) that drives the phenological patterns.

Study Area

The grassland biome has many different vegetation types. The study area is part of the Enkangala Grasslands (an informal term referring to a large intact area of high-altitude, moist grassland on the border of Mpumalanga, Free State and KwaZulu Natal). Our particular study locations are in the Wakkerstroom Montane Grassland (Mucina and Rutherford 2006) which is a high-altitude grassland (altitude between 1800m and 2250m above sea level) found in KwaZulu Natal and Mpumalanga (Muchai 2002). The vegetation that is found there is mostly montane grassland in the flat areas. The steep areas have thickets, typically dominated by *Leucosidea sericea*. The study area is 87% covered by natural vegetation, unlike adjacent areas which are transformed by agriculture, mining and human settlements (Fourie 2005, WWF-SA 2011). This is because much of the land is steep, underlain by shallow soils, or too cold for most crops to be grown there (Mucina and Rutherford 2006). The Karoo Supergroup sediments underlie most of the study area, capped by basalt on the higher mountains. Mudstones, sandstones and shales predominate in the valleys. Dolerite dykes and sills are also present. The plant diversity is high (over 1300 species, RJ Scholes *pers com*). There are about 80 endemic plant species such as *Helichrysum aureum var. argentum*, *Bowkeria citrina* and *Lotonis amajubica* (Mucina and Rutherford 2006; WWF-SA 2011). Some of the grass species found in this region include *Themeda triandra, Digitaria thicholaenoides, Tristachya leucothrix, Hetropogon contortus*, *Loudetia simplex* and *Diheteropogon filifolius* (Muchai 2002).

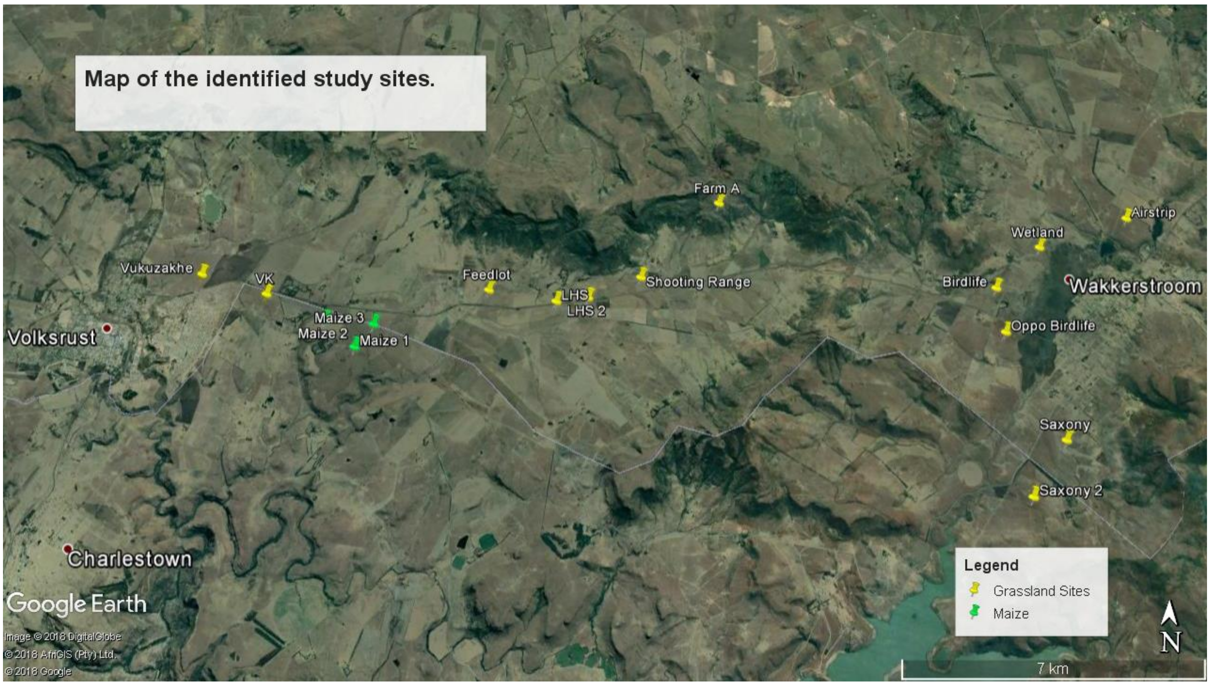


Figure 3.2: Map of the study area, located in the Enkangala grasslands. The identified study sites are found along the Volksrust to Wakkerstroom main road. The yellow represent areas that are grassland. The green represents maize fields in that area. The maize fields were selected in order to distinguish between the greenness signal from the grasslands and the signal from the maize.

Methods

Sample design

Thirteen study locations, each large enough to include at least 3 x 3 MISR pixels (i.e., about 900x900 m, which allows for the MISR pointing accuracy of about one pixel), were using high-resolution satellite data and ground inspection in order to contain pure and homogeneous grassland patches (avoiding current or old fields, roads, wetlands, bush-covered areas etc.) on relatively level ground (slope <15°)

The ten-day running mean temperature was calculated from the daily weather data, rather than the degree-day sums often used in phenological studies, because the temperatures in winter is often warm enough to allow growth. Thus degree-day sums quickly accumulate to large number. Other work suggests that an integration period of about 10 days is optimal. The soil available water content (mm) was calculated using a simple soil water balance model, which is in itself a form of time-integration of rainfall and evaporation observations:

$$\text{Soil moisture} = \text{soil moisture}_{\text{previous day}} + \text{rainfall} - \text{evapotranspiration}$$

where the soil moisture was capped at the profile water holding capacity, about 200 mm. The Penman-Monteith equation was used to calculate the evapotranspiration (Cai *et al.* 2007).

Once the greenup and browndown dates had been established for each of the 14 years in the MISR record (see notes under Figure 1 for the method), the thresholds of 10-day mean temperature and soil moisture associated with them were determined using a graphical method. The growing season length is the difference between the greenup and browndown dates.

Climate Data

Moyo (2015) carried out a long-term climate study of the town of Volksrust. A complete long-term (1904 to 2015) daily record of rainfall and temperature was constructed using data from the South African Weather Service (SAWS), patched where necessary with data from the Agricultural Research Council. This is explained in Chapter 2.

Remote sensed data

MISR data from paths 168, 169 and 170 (block 112) was processed and FAPAR was extracted. A full time series incorporating the three paths was constructed. The MISR instrument passes over the same point every eight days, but the same point may be visible from adjacent paths as well (as in this case, where the sites fall into the overlap). Using all three paths increases the phenological accuracy, since more data is available. This helped us to fill in gaps that may have been caused by a lack of data due to cloud cover and other factors like the steepness of the study site on particular days.

The MISR-HR modification (Verstraete *et al.* 2012) was used to bring the resolution from the 1 km of the standard MISR product to 275m.

Thresholds

The 110-year daily weather data from Volksrust area constructed by Moyo (2015) was used to determine the phenometric thresholds. The ten-day running mean temperature was used to give a measure of temperature instead of the more usual degree-day sums applied in temperate areas, since there is prior work indication this to be a more sensitive variable (White et al. 1999; Jolly et al. 2005). The daily soil available water content was calculated using a simple soil water balance model.

$$\text{Soil moisture} = \text{soil moisture}_{\text{previous day}} + \text{rainfall} - \text{evapotranspiration} \qquad \text{(Equation 3.2)}$$

The initial soil moisture is 0 because the starting date is in winter where there is no rainfall (we assume that is the case, not absolute). The rainfall was obtained from the Moyo (2015) dataset.

The Penman-Monteith equation was used to calculate the evapotranspiration (Cai *et al.* 2007).

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (1) \qquad \text{(Equation 3.3)}$$

where ET is the evapotranspiration (mm/day); R_n is the net radiation (MJ m^{-2}/day); G is the soil heat flux density (MJ m^{-2}/day); T is the temperature (°C); u_2 is the wind speed (m/s); e is the vapour pressure (kPa); γ is a constant (kPa/°C)

The thresholds of mean temperature and soil moisture for the greenup date and browndown date were determined using two different methods. For the greenup date, the instantaneous soil moisture (soil moisture on that particular day) and the 10-day running mean temperature were used. For the browndown date, the minimum temperature was used as it is a much sharper indicator than the 10-day running mean temperature. For soil moisture, the 10-day mean soil moisture was used (notes under Figure 2.2 explain how we determined the greenup dates and browndown dates). A plot of soil water content and mean temperature was used to determine the minimum amount of available soil moisture and temperature in the soil that is required for growth to start. The date of browndown date depends on the temperature (frost) and water stress. The RDR is a calculated as a function of accumulated days of water stress (days for which the soil water content is below a critical value approximating the plant wilting point). The growing season length is the difference between the greenup and browndown dates.

Results

Observed time series of FAPAR

An example of the multi-year phenology for one of the grassland plots is shown below. The rest of the plots are found in the Appendix. The soil moisture and the temperature are the same for all the plots.

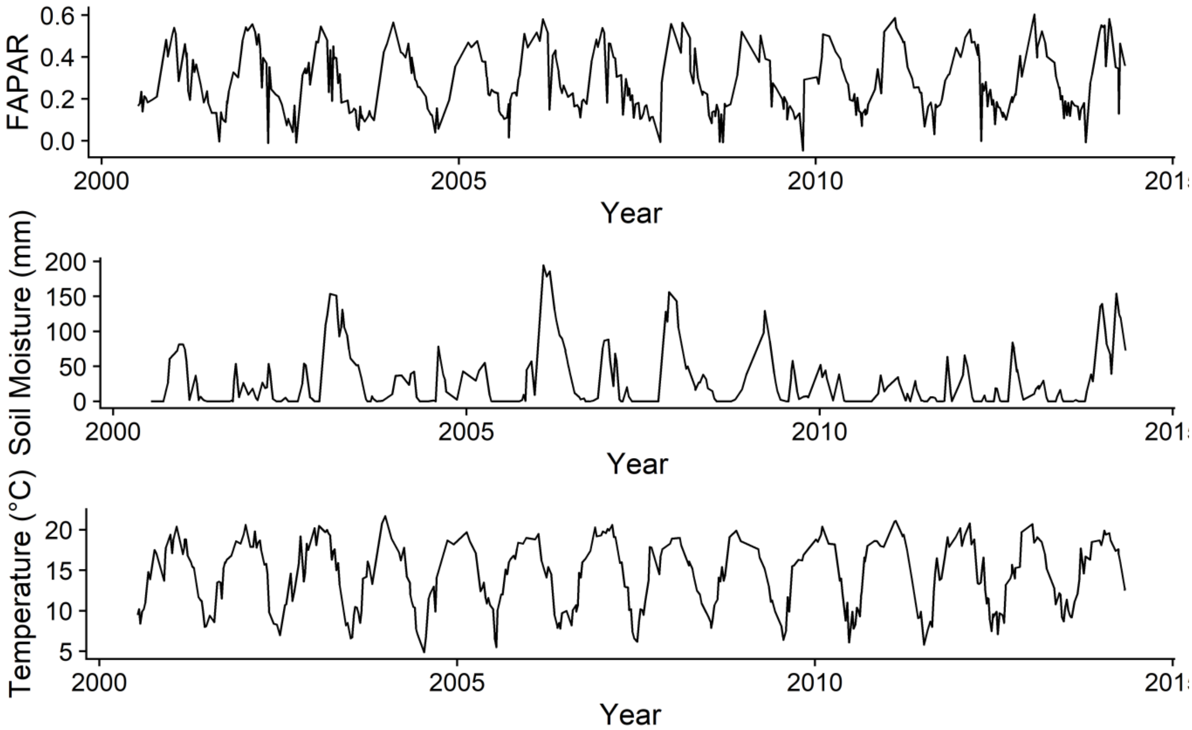


Figure 3.3: The observed FAPAR for a grassland patch at 27.353955ºS, 30.113115ºE from 2000 to 2014. Each point on the graph shows the mean FAPAR value over 9 pixels, on a particular day when the satellite passed and the ground was not obscured by clouds. The inversion procedure provides a measure of the uncertainty in the estimate, as does the variation between the 9 pixels. Both were small (<5% of the mean) and are therefore omitted for clarity. The second and third frame shows the soil moisture and temperature for the corresponding dates when FAPAR readings were taken. The temperature graph has a similar cycle to the FAPAR. The soil moisture is more variable.

The annual seasonality of these grasslands is clear, as is interannual variability in peak leaf cover, the timing of greenup and browndown, and the presence of intro-seasonal droughts. The ‘evergreen fraction’ ($L_{evergreen}$) FAPAR is fairly consistent at around 0.1. The occasional dips to zero are as a result of fires.

In this region, since there is a long dry season in which evaporation greatly exceeds the rainfall and the soil water storage, vegetation can only grow after the first rainfall event, which typically in September or October, whereafter it is rapid. We set the greenup start date to that day of year when the FAPAR, linearly interpolated between observations, is equal to or above 0.2. Setting the trigger a little above the baseline evergreen level helps to eliminate false starts. The greenup is so rapid that the start date is not strongly dependent on exactly what trigger level is set. After the greenup begins the FAPAR increases rapidly and continuously. There are gaps in the FAPAR measurements during the greenup phase of most years due to high cloud cover during spring. The peak can have several causes: it may simply be optimisation by the plants of their carbon assimilation (further leaf area is not justified by the amount of additional radiation that can be intercepted); or it may be due to the determinate growth of individual grass tillers, which stop growing at anthesis. Note that FAPAR, unlike biomass, is self-limiting – it cannot exceed 1.0.

During autumn (from March onward), we defined the browndown start date as the day of year when FAPAR dropped by 0.1 units from the peak FAPAR recorded in that season. The rate of browning was often much faster than greening – contrary to our expectations of gradual desiccation is the major cause (Table 1). It is often observed that there is a distinct shoulder is observed in the brown-down phase. We interpret this to mean that browning commences with gradual drying and senescence of the leaves, suddenly accelerated by a frost event (D_{frost}). The frost event occurs when the minimum air temperature is below 2.2°C. A frost event occurs when the air temperature measured at standard screen height for that particular day is below 2.2°C noting that the temperature recorded in a screen 1.5m above the ground is higher than the temperature on the ground (Burton 2014). There is no standard deviation because the temperature is the same at all the sites. There are fewer gaps in the FAPAR measurements during the browndown phase compared to the greenup phase, since it typically occurs in the drier, less cloudy part of the year.

Table 1: Seven phenological parameters of the ecological phenology model. Note that the date of peak FAPAR is not a parameter, and is only included for interest. These values are the means and standard deviations for 13 grassland plots in each year

Year	**$D_{Greenup}$ (DOY)**	**Peak (DOY)**	**L_{Peak} (FAPAR)**	**$D_{Browndown}$ (DOY)**	**D_{Frost} (DOY)**	**$R_{Greenup}$ (FAPAR FAPAR^{-1} d^{-1})**	**$R_{Browndown}$ (FAPAR FAPAR^{-1} d^{-1})**
2001	93 ± 9	191 ± 5	0.5488 ± 0.0224	259 ± 17	310	0.0104 ± 0.0013	0.0045 ± 0.0043
2002	98 ± 3	226 ± 7	0.5462 ± 0.0067	274 ± 7	311	0.0079 ± 0.0005	0.0065 ± 0.0032
2003	106 ± 9	217 ± 14	0.5128 ± 0.0371	276 ± 11	310	0.0087 ± 0.0017	0.0084 ± 0.0018
2004	126 ±	216 ± 4	0.5540 ± 0.0253	301 ± 10	293	0.0117 ± 0.0024	-0.0042 ± 0.0035
2005	113 ± 20	235 ± 29	0.5140 ± 0.0267	306 ± 12	302	0.0086 ± 0.0032	-0.0016 ± 0.0109
2006	96 ± 7	238 ± 25	0.5580 ± 0.0452	317 ± 3	312	0.0074 ± 0.0013	-0.0051 ± 0.0007
2007	97 ± 8	178 ± 12	0.5180 ± 0.0252	251 ± 8	303	0.0120 ± 0.0024	0.0064 ± 0.0010
2008	120 ± 13	216 ± 36	0.5243 ± 0.0761	302 ± 13	297	0.0111 ± 0.0042	0.0024 ± 0.0065
2009	105 ± 19	204 ± 43	0.4924 ± 0.0531	299 ± 10	290	0.0127 ± 0.0078	-0.0033 ± 0.0041
2010	115 ± 7	236 ± 36	0.4865 ± 0.0442	314 ± 11	316	0.0079 ± 0.0021	-0.0018 ± 0.0052
2011	109 ± 11	216 ± 23	0.5701 ± 0.0258	283 ± 6	302	0.0103 ± 0.0028	-0.0035 ± 0.0050
2012	98 ± 8	235 ± 26	0.5173 ± 0.0198	283 ± 11	285	0.0072 ± 0.0015	0.0031 ± 0.0060
2013	103 ± 18	207 ± 6	0.5899 ± 0.0165	291 ± 12	279	0.0106 ± 0.0022	0.0003 ± 0.0067
2014	113 ± 8	225 ± 5	0.5800 ± 0.0114	292 ± 18	299	0.0095 ± 0.0009	0.0067 ± 0.0101
Overall	107 ± 10	217 ± 18	0.5366 ± 0.0319	289 ± 20	301 ± 11	0.0097 ± 0.0018	0.0013 ± 0.0047

There are several years where the FAPAR decreases and then increases again mid-season. This is because of a dry spell in the middle of the rainy season (a mid-seasonal drought) where the conditions are not ideal for growth and the vegetation starts dying. At some point, the conditions become ideal for growth again and the vegetation grows again. During the 2001/2 season, there were two such events. We set the peak FAPAR for determining the browndown date to the last of these peaks.

Climate thresholds for greening and browning

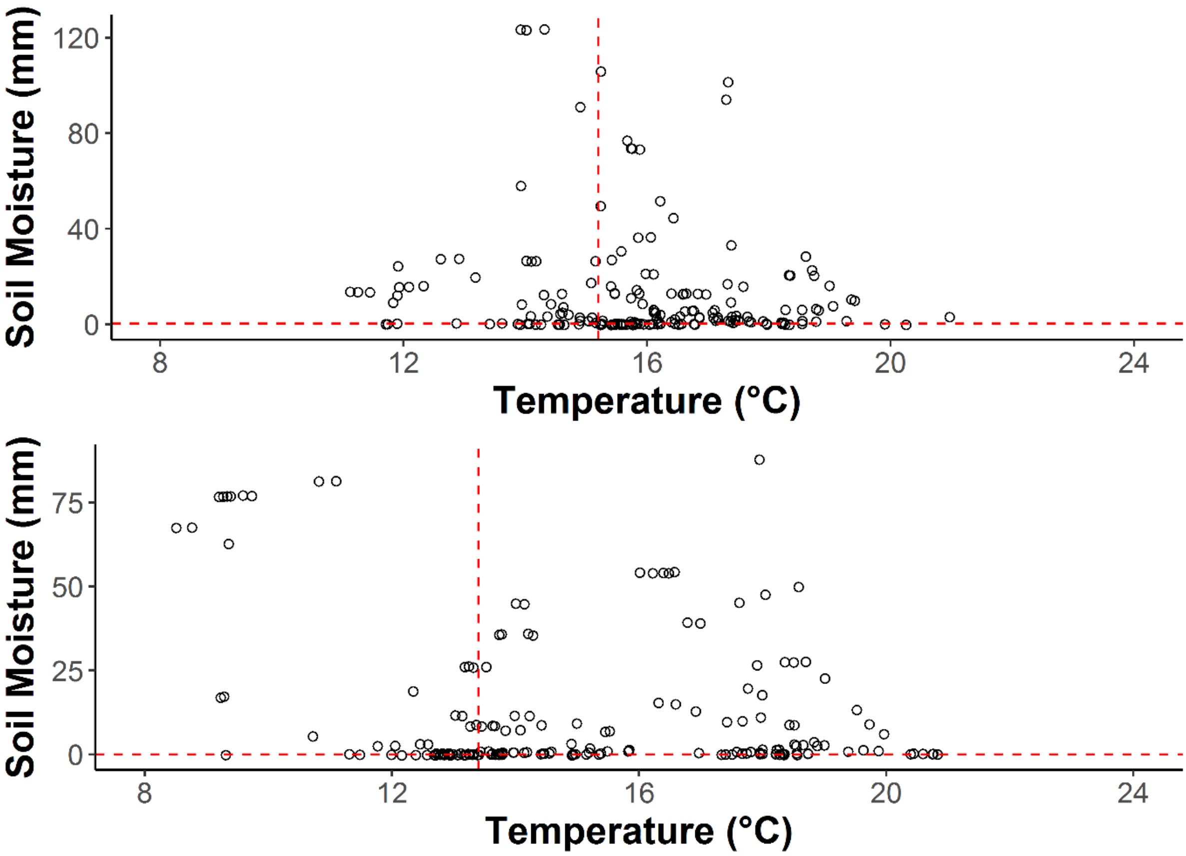


Figure 3.4: The soil moisture content and the preceding 10-day mean temperature on the date when greenup (top panel) and browndown starts (bottom panel). The thresholds represent to 30th percentiles of the distributions (70% of the observations are above the threshold). The open dots represent the 13 plots, in 14 years. The solid dots are the means for all 13 plots in a given year, with the standard deviation shown.

These graphs suggests that greenup starts when the: the soil moisture rises above 0.34mm and the 10-day temperature above 15°C. This is much lower than we expected. We expected the greenup to occur when there is more soil moisture. The greenup occurs after the first major rainfall event of the season and that could explain this trend. There are several points which do not satisfy these criteria. There are points where greenup occurs when the temperature is below the threshold but there is high soil moisture. This suggests that rainfall overrides cool temperatures: thus a greenup during the shoulder months of late or early winter is possible if moisture is present.

Browndown begins in most cases when the soil moisture falls below 10 mm, and often close to 0mm (0.02 mm in this case) while the 10-day running mean temperature is around 13°C. The browndown data shows that temperature is more of a factor during this phase because there are several cases where the soil moisture is high but no growth is possible.

Growing season

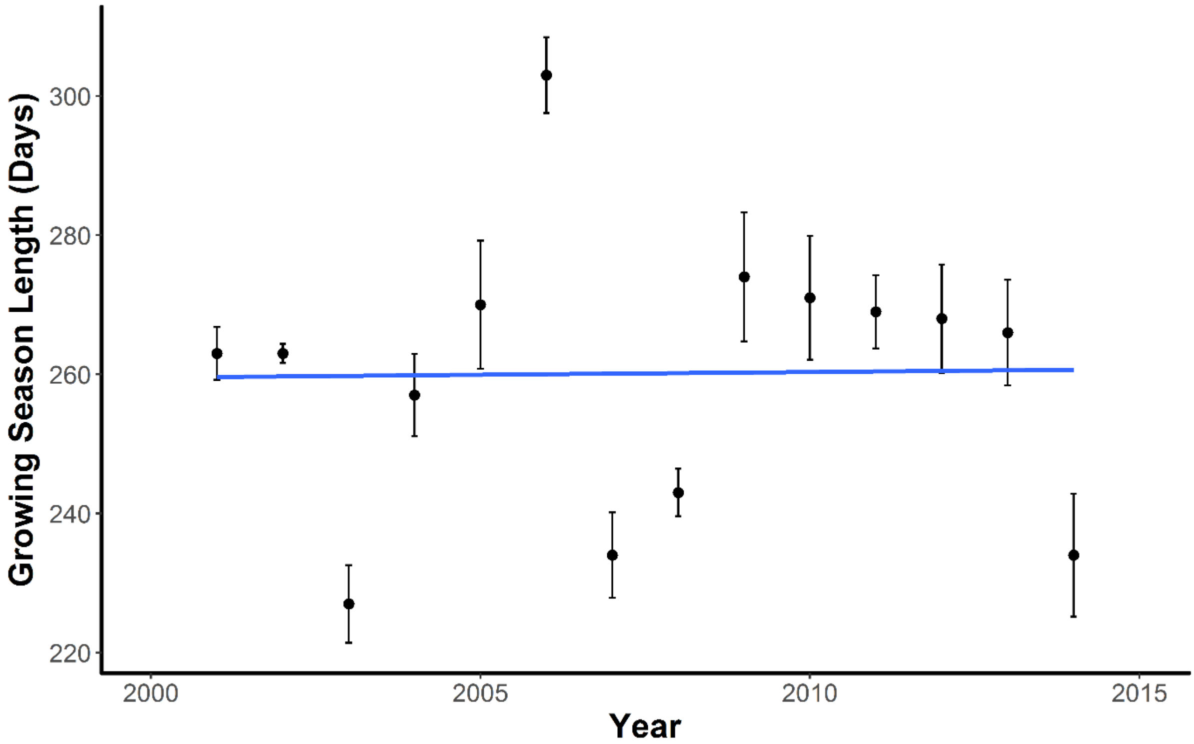


Figure 3.5: The length of the growing season, per July-June year between 2000 and 2015. The bars represent the standard deviation across 13 sites. Equation: GSL = 0.079x + 101.3; n= 14, r^2 = 0.00027, p = 0.955

There is no statistically-significant trend in the annual growing season length over the 14-year period observed by MISR. . The average growing season length in this region, in the period 2000-2014, was 250 days. There are several apparent outlier years 2003, 2007, 2008 and 2014 were 20 to 30 days shorter than the mean, and 2006 was 30 days longer than average. Year 2006, was exceptionally wet, while the 'short' years all had below-average rainfall.

The increase in the length of the growing season over the 14-year period is not significant (p=0.955). It is possible that the length of the growing season is controlled by the amount of rainfall that falls in a particular year. Figure 3.7 shows that there is no relationship between the amount of rainfall and the length of the growing season.

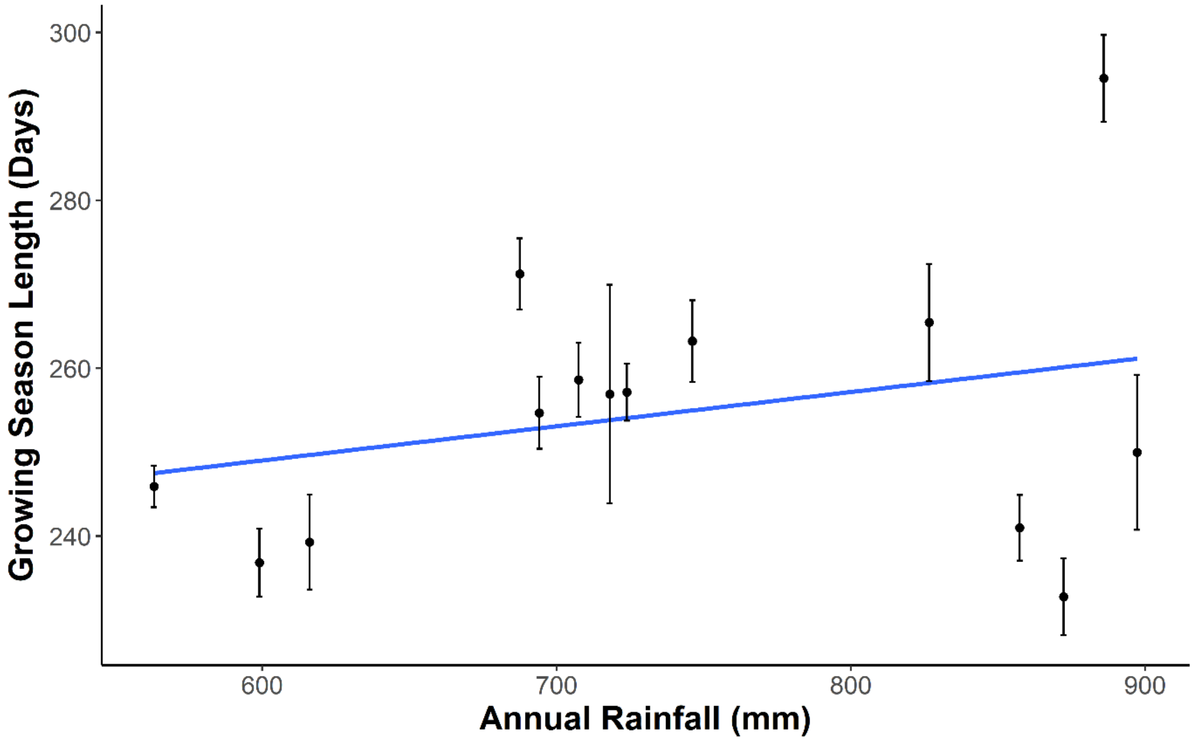


Figure 3.6: Comparing the annual rainfall (July to June year) and the length of the growing season for the years between 2000 and 2015. The bars represent the standard deviation of the length of the growing season across 13 sites. Equation: GSL = 0.040x + 224.6; n= 14, r^2 = 0.07729, p = 0.3359

Discussion

It is more insightful to fit phenological curves based on an understanding of the ecophysiological processes underway, than to simply use an arbitrary mathematical function (Cao *et al.* 2015). In our opinion, the slight increase in the number of parameters is worth the price. We further found that our initial assumption that the phenological curve could be split into just two phases – a greenup and a browndown – was not correct for this location. Two distinct processes are underway in the browndown period: a senescence/desiccation process, with gradual browndown commencing around February, and a sudden browning due to frost, anytime from April onward. This required the introduction of another parameter into our model. We argue that a mathematical model sufficiently detailed to accurately represent the observations would be no more parsimonious.

This study showed that there is no lag in the response of vegetation to the onset of rainfall, contrary to what has been suggested by several studies (Zhang *et al.* 2011; Ji and Peters 2004, 2005; Braswell *et al.* 1997; Wang *et al.* 2003; Potter and Brooks 1998).

Our study confirm that vegetation phenology semiarid ecosystems (even towards the upper end of the semi-arid range, such as the Enkangala grasslands) (Jenerette *et al.* 2010, Zhang *et al.* 2005, Whitecross *et al.* 2016, Dye and Walker, 1987; Archibald and Scholes, 2007; February *et al.*, 2013).

Arbitrary mathematical or statistical models (such as the logistic curve) have been fitted to observed vegetation phenology. It is more insightful to fit curves based on an understanding of the ecophysiological processes underway (Cao *et al.* 2015). From the 14-year observational dataset, vegetation grows almost immediately after the first major rainfall event (>5mm). Vegetation greenup in Africa occurs at the start of the rainy season (Zhang *et al.* 2005). This study showed that there is no lag in the response of vegetation to changes in climatic conditions. This goes against what has been suggested by several studies that there is a lag in the response of vegetation (grasslands) to soil moisture and this depends on the timing of plant growth stages (Zhang *et al.* 2011, Ji and Peters 2004, 2005). There is a lag in the response of vegetation growth to climate change (Braswell *et al.* 1997, Wang *et al.* 2003, Potter and Brooks 1998).

This study found little change in the growing season length over a 14-year period – there was an apparent increasing trend, but not statistically significant. Most studies before this just focused on the trend in the change in the greenness of vegetation (Piao *et al.* 2006, Chen *et al.* 2014). Zhao *et al.* (2011) found that there was an increase in the vegetation growth was attributed to the change in the precipitation and evapotranspiration. In semi-arid and arid ecosystems, phenological patterns are influenced by the accumulated preceding rainfall. The study tends to confirm that vegetation phenology in arid and semiarid ecosystems depends on rainfall, even towards the upper end of the semi-arid range (Jenerette *et al.* 2010, Zhang *et al.* 2005, Whitecross *et al.* 2016, Dye and Walker, 1987; Archibald and Scholes, 2007; February *et al.*, 2013).

In places with a high altitude such as the Enkangala grasslands, the greenup start date is expected to advance because of increasing temperatures (Jeong *et al.* 2011). Other studies using satellite data show that there is a general regional trend, especially at high latitudes, with spring coming at an earlier date. At a local scale, the extent to which the early spring date arrives depends on the methods and the instruments used. High-quality satellite data have only been available for about two decades which makes it difficult to determine a trend (Settele *et al.* 2014). Most studies have reported a trend of spring coming at an earlier date because of increased temperatures (Menzel *et al.*, 2006; Cleland *et al.*, 2007; Primack *et al.*, 2009; Ibanez *et al.*, 2010). The length of the study period is important (White *et al.* 2009). With a longer study period, determining if spring has advanced or not would be much easier.

The phenology model of the Enkangala grasslands is similar to the model of the dystrophic savanna described by Hoare and Frost (2004) where there is a peak in the activity during the summer months. The vegetation activity ceases during the winter months. Wu *et al.* (2016) showed that simple climate data could not be used to describe changes in the landscape phenology because there are several interactions at the SOS in spring and EOS in autumn that are not taken into account. It is possible for a change in the climate of a particular region to lead to a one-way change in phenology. The type of vegetation that is found in the region can have an influence on the phenology of that region.

Conclusion

The annual phenological pattern of a low-latitude, high altitude grassland could be observed over a 14 year period and characterised using a moderate- spatial resolution, high-temporal resolution satellite sensor, using FAPAR is the metric of greenness. The observed season pattern could be well-represented using an ecologically-based, 7 parameter model. The greenup data coincided with the presence of at least 20mm of plant-available water in the soil profile (after a major rainfall event), and a 10-day temperature above 15ºC. Leaf browning began when the soil moisture close to 0 mm, or when the minimum temperature dropped below 0ºC. The length of the growing season averaged 260 days, with standard deviation of 20 days and a range from 234 to 303 days. There was no observable trend in growing season length over the observation period.

The following chapter has been prepared in a format suitable for submission as a paper. It therefore contains material which may duplicate some material in Chapters 1 and 2.

4. Inferred Phenological over the Past Century in a High Altitude, Low Latitude grassland

Abstract

The climate of the Volksrust-Wakkerstroom area has changed in the past 100 years, with a highly-significant increase in the daily minimum temperatures (2.2 °C/century) and daily maximum temperatures (0.6 °C/century). The rainfall decreased by 70 mm (10%) during this period, but the trend was not statistically significant due to the high inter-annual variability. The aim of this study was to hindcast grassland phenological changes over the 20th century based on a phenological model calibrated over the period 2000-2015. The length of the growing season is inferred to have increased over the past 100 years, due to the greenup start date occurring earlier and the browndown date being delayed.

Key Words: Phenology, Climate Change, Remote Sensing, MISR, Growing Season Length

Introduction

Climate change has had an impact on ecosystems, water resources, agriculture, food security and health (Niang *et al.* 2014). Phenology – the study of the timing of biological events (with the dates the start and end of the growing season occur being the focus of this study) - is one of the ecosystem processes shown to have been affected by climate change (Walther *et al.* 2002). The response of vegetation to climate change depends on the type of vegetation that is growing in the area (Donohue *et al.* 2009); no studies have been published to date for low latitude, high altitude grasslands, such as the one reported here.

In this study, temperature and soil moisture triggers derived from an associated study (Chapter 3) are used to determine the start and end of the grassland growing season. Rainfall influences the amount of moisture that is available in the soil and that is one of the factors that control the growth of plants (including grasses and crops) and whether they are able to maintain photosynthetic activity for the duration of the growing season. In this situation, temperature is important especially at the end of the growing season as it determines when the vegetation starts dying due to frost kill. Long-term climate and phenology analysis is required to understand the effects of climate change on the phenology; in turn, this requires long-term weather data to understand slow trends in the inherently-variable climate signal and other subtle changes in the presence of inter-annual variability (DEA 2013; Moyo 2015). The relationship between the changes in the temperature and rainfall is apparently inverse in the summer-rainfall parts of South Africa: periods with higher temperatures tend to have lower rainfall and the opposite is also true (Tyson *et al.* 1975), though this is not necessarily true at the century timescale of climate change. It remains unclear whether rainfall is increasing or decreasing on the north-east escarpment since 1900. It is often difficult to detect trends and shifts in rainfall patterns because of inhomogeneities in the time series (Fauchereau *et al.* 2003), and also because of the high inter-annual variability (nearly 30%).

There are several factors that affect the growth of plants. The main drivers are the amount of carbon that the plant takes in (photosynthetic CO_2 uptake), water availability and temperature (Körner 2015). The growth of plants depends on water availability. The main drivers of water availability are the supply (rainfall) and the demand (evapotranspiration). Changes in the onset and the cessation of rainfall have an effect on the length of the growing season (Simelton *et al.* 2013). Estes *et al.* (2014) conducted a study on the changes in the water availability during the growing season of maize in Southern Africa and showed that changes in the amount of water that is available during the growing season were apparent. This may have an impact in the timing of the growing season. To calculate the evapotranspiration, temperature, humidity, radiation and wind speed data is required (Sheffield *et al.* 2012).It is difficult to assess the effects of water availability on the growth of plants because of the many drivers that control water availability.

For plants to grow they need resources and appropriate conditions that these resources are converted into biomass. While acknowledging the importance of co-drivers, the classical view is still that carbon, that is, photosynthetic CO2 uptake, ranks above any other drivers of plant growth. Hence, theory and modelling of growth traditionally is carbon centric. Here, I suggest that this view is not reflecting reality, but emerged from the availability of methods and process understanding at leaf level. In most cases, poorly understood processes of tissue formation and cell growth are governing carbon demand, and thus, CO2 uptake. Carbon can only be converted into biomass to the extent chemical elements other than carbon, temperature or cell turgor permit.

There are several bioclimatic indicators that can be extracted from annual precipitation. These include the onset of the rainy season, the end of the rainy season, the duration of dry and wet periods and the number of extreme heavy rainfall events (DEA 2013). Many definitions have been used to define the onset of the rainy season (Smith *et al.* 2008): for instance, when a certain threshold-sized event, not be followed by a dry spell in subsequent days, occurs (Moron *et al.* 2009). In order to determine the empirical threshold, the requirements for that crop are taken into account and so are the local climatic conditions. These local conditions cannot be applied to other areas and crops (Boyard-Micheau *et al.* 2013).

Phenological parameters are important in crop and grazing management. These parameters include the start and the end of the growing season (greenup and browndown), the length of the growing season, the growth rate and the death rate (de Beurs and Brown 2013).

The Thermal Growing Season (TGS) starts when the daily mean temperature is higher than a certain threshold in spring, and the season ends when the daily mean temperature is lower than a certain threshold in autumn (Ruosteenoja *et al.* 2016). Growing Degree Days sum (GDD) is often used to trigger phenological events, and is calculated by adding the daily mean temperature excesses above a certain threshold (Ruosteenoja *et al.* 2016).

A method of estimating the length of the growing season independent of climate data is to use multi-temporal remote sensing data, which provides information on the start of greenup and the senescence dates of vegetation. These are used to estimate the length of the growing season (Vrieling *et al.* 2013). This approach was used in the associated study (Chapter 3) to calibrate the climatic triggers, over a 14-year period for which high temporal resolution data were available for the grasslands of the study region.

The length of the growing season is important in modelling processes such as net primary productivity and the carbon cycle (Pedlar *et al.* 2015), and thus also for economies that depend on agriculture (Ngongodo *et al.* 2014). In Africa, the length of the growing season has been determined either by precipitation-only models, or by precipitation-potential evapotranspiration (PET) models (water balance models). In precipitation-only models, the growing season is defined using precipitation thresholds. In the water balance model, the precipitation is compared to the PET, with the start of the growing season defined as the day when precipitation exceeds one half of the PET. The end of the growing season is defined as the day when precipitation remains below 0.5 PET for a specified amount of time (Cook *et al.* 2012).

In South Africa, there are few studies of long-term historical climate trends (Moyo 2015). The ones which exist mostly focus on the 1960-2010 for which digital data are readily available (Hughes and Balling 1995; Mason *et al.* 1999; Easterling *et al.* 2000a; New *et al.* 2006; Kruger 2006; Nel 2009; Kruger and Sekele 2013). A more recent study by Kruger and Nxumalo (2017) focused on the period between 1931 and 2015. Remote sensing studies have also been carried out for short time periods only, because satellite datasets are only available for at most 30 years (the longest is the coarse AVHRR NDVI dataset). This time is too short to draw robust conclusions about climate change. In Chapter 3, I documented the phenology of the Enkangala grasslands using remote sensing for the period 2000 to 2015. Over this period, trends were not statistically significant. This chapter sets out to extend that record to the period 1904 to 2015.

It is projected that the temperature will increase in southern Africa by between 4 and 6°C by the end of the 21st century (Engelbrecht et al 2015; Archer et al 2018). Rainfall trends are more difficult to project, especially over the study region in north-eastern South Africa, where the rainfall is overwhelmingly convective, and which sits on the border of a region which is projected to become drier (the interior of South Africa) and one projected to become wetter (the eastern seaboard) . It has been projected that some parts of the grassland biome will be 10-15% drier (DEA 2015). A better grasp of future changes in the climate and the growing season allow for better planning, especially for places which rely on agriculture.

Aim

The aim of this study is to determine if the onset, cessation and growing season length of a high-altitude, low-latitude grassland in the north-eastern part of South Africa have changed over the period 1904 to the present (2015) . This is determined by the phenological cues derived in Chapter 3.

Methods

The climate data from the town of Volksrust (method on how this climate data was obtained is explained in Chapter 2) was used to determine the climatic cues for the phenological attributes in Chapter 3. The temperatures were obtained from the climate data and the soil moisture was calculated using the method that is explained in Chapter 2. In this chapter, these climate cues are used to determine the timing of phenological events for the period preceding satellite data (1904-2000 then extended to the period where satellite data is available (2001-2015)), but for which daily temperature and rainfall data are available.

Greenup Start Date

For greenup to occur, several conditions have to be met. Greenup usually occurs between the months of September and November (Chapter 3). Greenup is triggered by a temperature and soil moisture cue. The greenup start date comes after the first major rainfall event (<15mm) and the temperature average for the 10 days before growth starts must exceed 15 °C.

Browndown Date

The browndown start date occurs between the months of March and May (Chapter 3). In Chapter 3, it was shown that for browndown to occur, the soil moisture has to be below 1mm and the temperature has to be below 10°C. These are the thresholds that were used.

Growing Season Length

The length of the growing season for each year was calculated by taking the difference between the greenup and browndown dates for each year.

Results

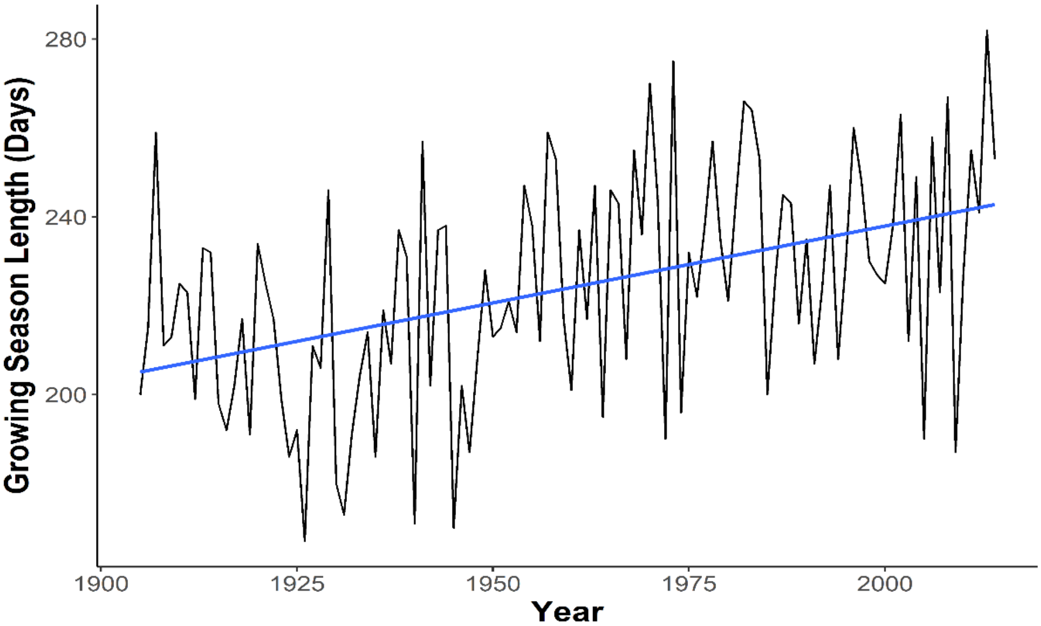


Figure 4.1: The estimated length of the growing season for the year 1904-2015. The trend is indicated by the blue line, which as the equation GSL = 0.345x – 452.96; $p < 0.001$, n=110.

The length of the growing season has increased in the past 100 years by 35 days, a highly significant result ($p<0.001$). Figure 4.1 shows that the growing season length varies greatly from year-to-year. The length of the growing season is increasing because the start of greenup comes at an earlier date while the browndown comes at a later date (Figure 4.2 and 4.3). The greenup start date has advanced by 14 days in the past 100 years while the browndown date has come 15 days later.

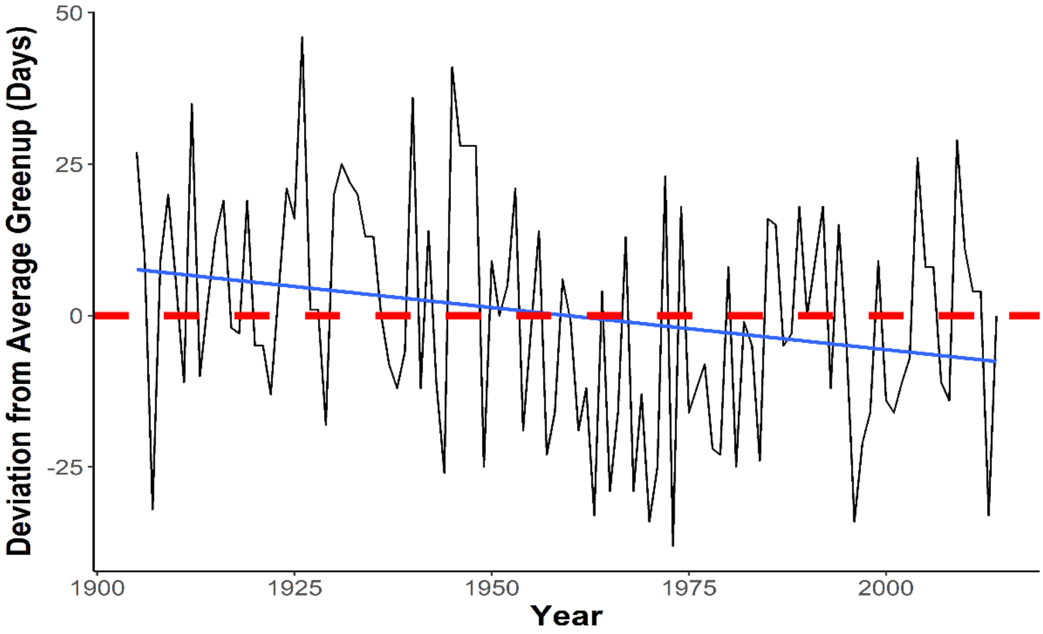


Figure 4.2: The change in the greenup start date for every year from 1904 to 2015 compared to the average for that time period (the average is DOY 107, which corresponds to 10 October). The long-term trend is shown by the blue line (Deviation = -0.139x + 272.77, p= 0.012).

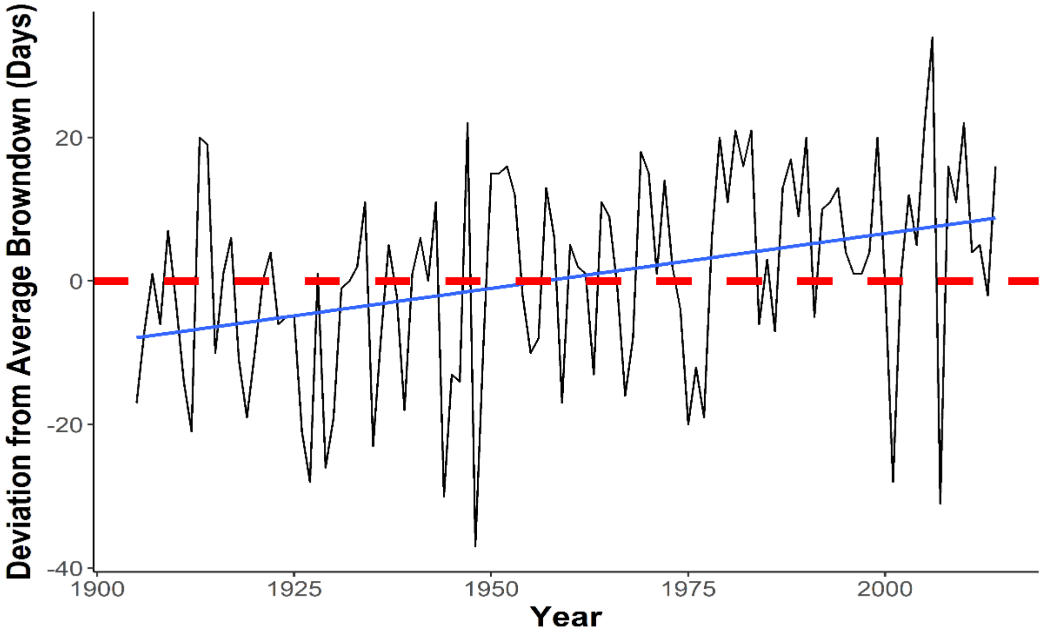


Figure 4.3: Deviation of the browndown date for every year from 1904 to 2015 compared to the average for that time period, which was DOY = 289, which corresponds to 15 April. The long-term trend is shown by the blue line (deviation = 0.153x -299.35, p <0.001).

Discussion

The length of the grassland growing season in the study area is inferred to have has increased over the past 100 years. This is consistent with other phenology studies, most of which have been carried out in the Northern Hemisphere, on high-latitude grasslands. Many previous studies in the northern hemisphere have shown that the growing season has lengthened mainly because spring comes earlier; there is a delay in the decline of autumn activity (Zhou *et al.* 2001; Linderholm 2006; Gornall *et al.* 2010). A study by Ngongodo *et al.* (2014) in Malawi found that there has not been a change in the length of the growing season even though there was a shift in the rainfall onset and cessation dates (both of which are trending later).The length of the growing season is expected to increase as the climate warms up (IPCC 2007). This means crops that are planted in spring can be planted earlier (Potopova *et al.* 2015).

In Europe, the length of the growing season increases because spring comes at an earlier date than anticipated rather than autumn coming at a later date (Menzel *et al.* 2003). This has been shown through satellite data, phenological and climate observations (Linderholm 2006). The variability in the length of the growing season is an indicator of climate change (Santos *et al.* 2015). There also has been an increase in the photosynthetic activity of vegetation in the Northern Hemisphere and that has been linked to the increase in the length of the growing season (Myneni *et al.* 1997). .

It is not clear how productivity (crop yields) responds to a change in the growing season length (Mueller *et al.* 2015), since productivity also depends on the temperature and moisture during the growing season. So, for instance, if the season starts earlier and ends later, but the mean soil moisture is too low during the growing season, or the temperatures are too high, production could decrease.

It is easier to determine the changes in the temperature compared to changes in the rainfall. Rainfall has a higher spatial variability compared to temperature (Kruger 2006; Rowell 2012). Several studies on the long-term trends in the rainfall have yielded different results. A study by New *et al.* (2006) on climate extremes in South and West Africa argued that the length of the rainy season has decreased. Nel (2009) found that there hasn't been a change in the mean annual rainfall, but rather a change in the distribution of rainfall each month. Other studies (Easterling *et al.* 2000a; Thomas *et al.* 2007; Kniveton *et al.* 2009) have shown that there have been changes in the mean annual rainfall with an increase in the total amount of precipitation and in the frequency of heavy precipitation events in South Africa (Easterling *et al.* 2000a). Changes in the onset of the rainy season, rainfall intensity and the frequency of dry spells were reported and these are controlled by the El Niño/Southern Oscillation (ENSO) phenomenon (Thomas *et al.* 2007; Kniveton *et al.* 2009). Many regions in Africa are likely to experience an increase in the inter-annual variability of precipitation (James and Washington 2013). The rainfall in the Enkangala grasslands has apparently decreased by about 10% in the past 100 years, though the change is not statistically significant (Moyo 2015). This goes against many model projections that suggest that rainfall in the eastern side of the country will increase in future. Delays and advances in the start of the rainy season can be attributed to El Nino events. This delay also means the growth and development of vegetation will also be delayed (WFP 2015).

Temperature is the main factor that controls the phenology at the end of the season. In the Enkangala grasslands, the temperature has increased over the past 100 years with the minimum temperature increasing at a faster rate than the maximum temperature. This pattern is what is expected from climate change due to increasing greenhouse gasses, since night-time outgoing re-radiation is more affected by absorption in the greenhouse gas spectrum than daytime inward solar radiation. If climate change was driven by other factors such as a rebound from a medieval cool period, the minimum temperature and the maximum temperature would increase at the same rate. Due to this warming trend, there has been a decrease in cold indices (cold days, cold nights, frost days) and an increase in warm indices (hot days) (Easterling *et al.* 2000b; Aguilar *et al.* 2009; Moyo 2015). Minimum temperatures have increased in the past 50 years and that has led to fewer days having frost (Menzel *et al.* 2003). Frost determines when browndown starts.in the Enkangala grasslands.

Several studies in South Africa show an increase in temperature over the past century, consistent with the global trends (Kruger and Shongwe 2004; Zhou *et al.* 2010; Collins 2011; Kruger and Sekele 2013). The number of warm days has increased while the number of cold days has increased (New *et al.* 2006).

Cook and Vizy (2012), in a study of southern Africa at 90km resolution predicted that length of the growing season will decrease in the 21st century: a different outcome from the finding of this study for the 20th century.

Conclusion

The length of the growing season in the high-altitude, low latitude grasslands of the Volksrust-Wakkerstoom area in South Africa is inferred to have increased over the past 100 years by about 35 days. This is due to an advance in the start of the growing season which comes 14 days earlier than usual and the end of the growing season coming at a much later date (15 days later). An increase in the temperature seems to be the reason for this change. This study gives an idea of how grassland phenology may change in the future in the presence of ongoing, accelerating climate change. The growing season could continue to increase and this has an effect on many other ecosystem processes. Further studies should be conducted on these processes to understand the effect of an increase in the phenology.

5.Summary

The aim of this study was to gain a predictive understanding of the phenology of the Enkangala moist, high altitude grassland. This was done under the following objectives:

1. Using moderate spatial resolution, high time-resolution multi-temporal satellite-derived datasets to describe the phenology of natural high-altitude grassland communities in the Volksrust-Wakkerstroom area through assigning attribute values to a minimal phenometric model, and to relate the phenometric attributes to climate conditions such as soil moisture and air temperature.

2. Determining if there have been changes in the phenometric attributes, such as the date of green-up or brown-down, over the period of satellite records (2000 to present); and by inference using the relationship to climate cues, over the period of climate records (1904 to present).

There has been climate change in the past 100 years with the temperature increasing and the rainfall decreasing. The change in the climate has affected many ecosystem processes, including phenology which has responded to these changes. The way phenology responds to these changes depends on the ecosystem and the climate in that particular place. In this study, we focused on the high altitude, low latitude grasslands in South Africa.

Many studies on the phenology of the grasslands have been carried out in the Northern Hemisphere (high latitude) which have a different climate from ours. Grasslands in the Northern Hemisphere have different environmental cues that control the phenology of those grasslands. This study is the first one to be carried out looking at low latitude montane grasslands (Afromontane). We developed a phenology model for this region using ecological values instead of mathematical methods. The model is described in more detail in Chapter 2 and 3. In the Enkangala grasslands, the soil moisture and temperature are the main factors that control the phenology of the region. These were used to determine the thresholds for the greenup and the browndown phases.

The model was developed using satellite data and climate data. This fulfils the first objective that talks about describing the phenology of the region. Vegetation grows almost immediately after the first rainfall event. There are some gaps (FAPAR readings) in the greenup phase due to cloud cover as there is a lot of rainfall during this time. There is a point that is reached where growth does not occur even though the ideal conditions of growth are met. This is because grass has determinate growth, their growth stops when the grass reaches physiological maturity (Yin *et al.* 2002). There are fewer gaps in the FAPAR during the browndown phase because it occurs when there are (mostly) no clouds.

Growth will not occur unless the soil moisture on the day of growth is above 5mm and the temperature for the 10 days before the first day of growth is 15°C. There are periods where there are dry spells in the middle of the growing season. This is due to a change in the ideal conditions for growth. For the browndown phase, the temperature is the most important factor. Browndown occurs when the mean temperature is below 10°C. Models have been used that use accumulations of temperature and soil moisture over a season to determine phenological events (Schwartz et al 2006). We attempted to determine the thresholds for the greenup and the browndown. The thresholds do not match the predictions that we had. This could be because there are many other environmental cues that govern a phenological event that are not easily detectable in a climate model (temperature and rainfall/soil moisture). An example of such a cue is photoperiod which is static across space (Pau et al 2011).

For the second objective, we set out to determine if there have any changes in the phenometric attributes described in the first objective (above). We found that during the 15 year period where satellite data was available, the length of the growing season did not increased in the past 15 years as suggested by the theory. The cues (thresholds) that were determined from the satellite data and the climate data were then used to model the phenology for the past 100 years (1904-2015). Our modelling work indicates that the growing season has increased in the past 100 years, increasing by 35 days. The increase is because the greenup start date comes at an earlier date (14 days early) and the start of the browndown is delayed (15 days late). Menzel et al (2006) conducted a study showing how the length of the growing season would change if the temperature increased by 1°C. They found that the start of the growing season would advance by 2.5 days$°C^{-1}$ and the end of the growing season would delay by 1.0 day$°C^{-1}$. Increased temperatures during that time period are responsible for this change in the length of the growing season. Temperatures affect the browndown more because usually frost is what accelerates browndown but with temperatures increasing, the likelihood of frost occurring decreases. This study gives an idea of how grassland phenology may change in the future in the presence of ongoing, accelerating climate change.

It is possible that the growing season will continue to increase in the future due to accelerated climate change. This may have several implications on many other processes that occur in the grasslands. Further studies can be carried out to find out if the increases in the temperature and changes in the phenology could affect the occurrence of fires. Other aspects to study include what effect changes in the phenology have on the species composition of the Enkangala grasslands and the effect on the pollination and seed germination in the region.

6.Appendices

Map of Study Sites

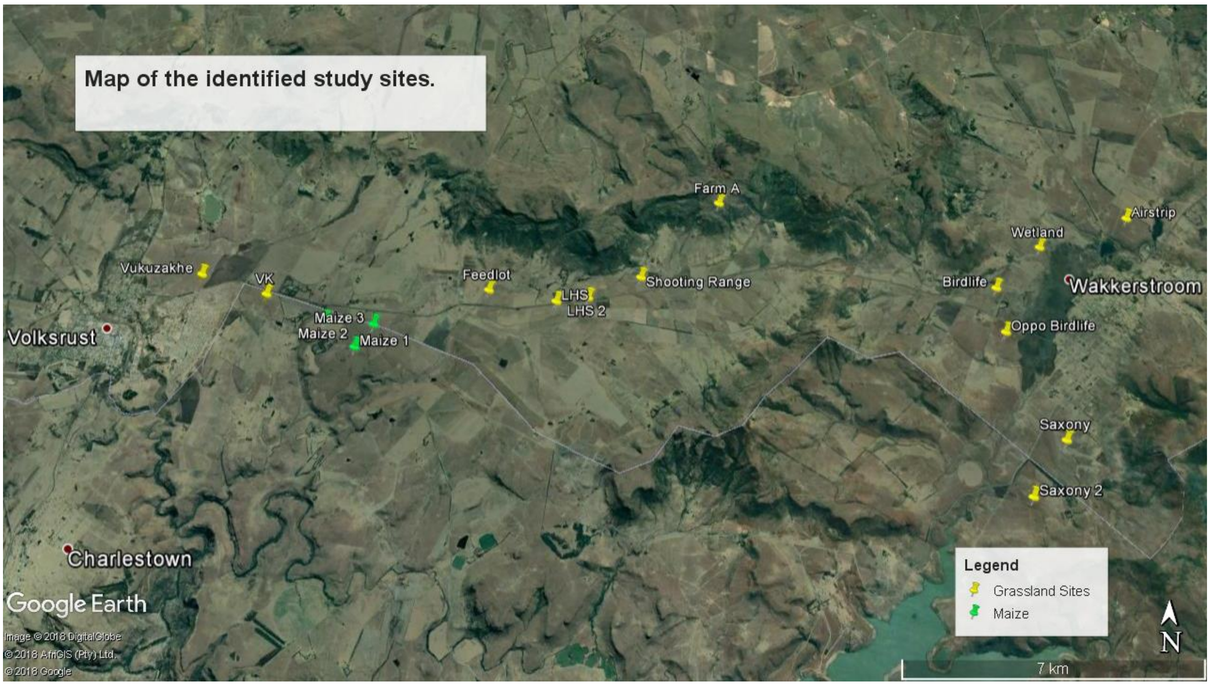


Figure 6.1: Map of the identified study sites. These sites are found along the Volksrust to Wakkerstroom main road. The yellow represent areas that are grassland. The green represents maize fields in that area. The maize fields were selected in order to distinguish between the greenness signal from the grasslands and the signal from the maize.

Table 2: Coordinates for the 13 study sites.

Site	Longitude (°)	Latitude (°)
Vukuzakhe	29.905432	-27.354332
VK	29.923039	-27.358994
Feedlot	29.980858	-27.357001
LHS	29.998535	-27.359522
LHS 2	30.006780	-27.358423
Shooting Range	30.020419	-27.353204
Farm A	30.040787	-27.334855
Birdlife	30.113115	-27.353955
Oppo Birdlife	30.114448	-27.364704
Wetland	30.125648	-27.343468

Saxony	30.126894	-27.389635
Saxony 2	30.117152	-27.402424
Airstrip	30.149638	-27.335610

Section 1: Six phenological parameters from the general phenology model for each study site (The date of the peak is not a parameter, and is only included for interest)

Table 3: ***Airstrip Site***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	107	192	0.5336	236	353	0.0115	0.0061
2002	99	211	0.5597	269	364	0.0092	0.0067
2003	110	243	0.4764	276	346	0.0065	0.0084
2004	135	214	0.574	309	32	0.0133	-0.0058
2005	85	218	0.5258	316	42	0.0073	-0.0055
2006	94	221	0.5479	316	13	0.0079	-0.0048
2007	116	163	0.4908	265	338	0.0191	0.0051
2008	107	276	0.5039	302	357	0.0055	0.0114
2009	94	180	0.4139	305	9	0.0085	-0.0043
2010	123	221	0.4088	327	302	0.0073	0.0088
2011	97	240	0.5362	287	364	0.0069	0.0080
2012	99	221	0.5102	287	24	0.0077	-0.0048
2013	91	211	0.6169	302	38	0.0094	-0.0065
2014	108	221	0.5896	254	353	0.0096	0.0082

Table 4: ***Birdlife Site***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	91	196	0.536	254	329	0.0094	0.0074
2002	98	225	0.5508	283	359	0.0080	0.0076
2003	100	207	0.5441	294	312	0.0094	0.0095

2004	132	218	0.5643	287	16	0.0121	-0.0051
2005	113	280	0.4765	280	305	0.0052	0.0347
2006	115	251	0.5792	316	8	0.0078	-0.0044
2007	96	185	0.5387	251	319	0.0111	0.0074
2008	93	178	0.5603	298	360	0.0121	0.0057
2009	136	167	0.5198	293	323	0.0308	0.0061
2010	119	218	0.5076	304	345	0.0094	0.0073
2011	111	229	0.5846	286	1	0.0091	-0.0047
2012	111	240	0.5292	287	352	0.0075	0.0087
2013	74	203	0.6035	280	356	0.0086	0.0072
2014	107	222	0.5549	298	360	0.0089	0.0074

Table 5: ***Farm A Site***

Year	**Greenup (DOY)**	**Peak (DOY)**	**Peak FAPAR**	**Browndown (DOY)**	**Senescence (DOY)**	**Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}**	**Death Rate FAPAR $FAPAR^{-1}$ d^{-1}**
2001	81	189	0.5309	258	2	0.0090	-0.0052
2002	100	229	0.5527	265	364	0.0079	0.0075
2003	100	200	0.4644	269	349	0.0084	0.0057
2004	100	214	0.5539	313	23	0.0089	-0.0053
2005	81	229	0.4746	316	23	0.0058	-0.0042
2006	81	229	0.4746	324	41	0.0058	-0.0046
2007	90	158	0.4721	258	344	0.0126	0.0046
2008	133	273	0.3582	342	364	0.0042	0.0064
2009	74	225	0.3902	316	31	0.0044	-0.0034
2010	108	316	0.4094	346	23	0.0034	-0.0024
2011	103	165	0.5207	265	39	0.0154	-0.0076
2012	85	280	0.4746	287	32	0.0044	-0.0035
2013	154	214	0.577	284	9	0.0177	-0.0052
2014	102	221	0.568	251	258	0.0088	0.0282

Table 6: ***Feedlot Site***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	85	200	0.5261	254	6	0.0084	-0.0050
2002	102	240	0.5453	283	3	0.0073	-0.0042
2003	110	196	0.5531	294	353	0.0118	0.0065
2004	107	225	0.4728	287	32	0.0073	-0.0045
2005	85	225	0.5035	304	32	0.0066	-0.0048
2006	93	163	0.4448	316	50	0.0114	-0.0071
2007	90	159	0.4691	251	258	0.0124	0.0086
2008	136	269	0.3556	298	364	0.0043	0.0061
2009	74	298	0.4004	293	32	0.0031	-0.0026
2010	110	316	0.4094	304	28	0.0035	-0.0025
2011	113	170	0.5231	286	43	0.0169	-0.0076
2012	85	284	0.4773	287	35	0.0044	-0.0035
2013	103	207	0.5731	280	3	0.0101	-0.0052
2014	102	229	0.5668	298	280	0.0082	0.0204

Table 7: ***<u>LHS Site</u>***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	92	181	0.5745	251	360	0.0119	0.0059
2002	100	221	0.549	273	357	0.0083	0.0074
2003	110	214	0.5452	269	335	0.0096	0.0083
2004	132	211	0.5554	302	13	0.0129	-0.0052
2005	112	276	0.4981	305	17	0.0056	-0.0035
2006	96	240	0.5771	313	39	0.0074	-0.0053
2007	92	176	0.5312	236	331	0.0116	0.0063
2008	129	196	0.5529	291	360	0.0152	0.0062
2009	120	200	0.507	287	21	0.0116	-0.0052
2010	112	221	0.5147	309	32	0.0087	-0.0050
2011	110	225	0.5847	287	17	0.0093	-0.0052

2012	99	203	0.5147	280	338	0.0091	0.0070
2013	102	200	0.5783	287	342	0.0108	0.0075
2014	115	214	0.5834	294	20	0.0108	-0.0055

Table 8: ***<u>LHS2 Site</u>***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	91	196	0.5623	287	360	0.0098	0.0063
2002	98	229	0.5427	280	360	0.0076	0.0076
2003	108	225	0.5349	280	349	0.0084	0.0079
2004	159	218	0.561	309	17	0.0175	-0.0051
2005	123	265	0.4933	316	21	0.0064	-0.0037
2006	97	247	0.5636	320	43	0.0069	-0.0051
2007	92	176	0.5284	243	331	0.0116	0.0063
2008	127	229	0.5753	298	364	0.0104	0.0078
2009	120	162	0.5063	294	21	0.0221	-0.0066
2010	113	229	0.5089	313	32	0.0081	-0.0047
2011	121	232	0.5883	284	13	0.0097	-0.0049
2012	105	214	0.5245	287	349	0.0088	0.0071
2013	102	203	0.5792	302	346	0.0105	0.0074
2014	119	229	0.5766	298	10	0.0096	-0.0048

Table 9: ***<u>OppoBirdlife Site</u>***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	101	189	0.5219	251	360	0.0109	0.0056
2002	101	225	0.5444	280	364	0.0081	0.0072
2003	105	207	0.4768	276	346	0.0085	0.0063
2004	109	211	0.5563	280	13	0.0100	-0.0052
2005	138	214	0.5192	309	21	0.0126	-0.0049

2006	95	251	0.5788	316	35	0.0068	-0.0049
2007	96	176	0.5364	258	353	0.0123	0.0056
2008	126	207	0.5576	291	1	0.0127	-0.0050
2009	113	173	0.5166	287	24	0.0158	-0.0064
2010	123	232	0.5046	309	39	0.0085	-0.0048
2011	101	229	0.5828	287	6	0.0084	-0.0048
2012	105	247	0.5272	280	21	0.0068	-0.0043
2013	97	211	0.5921	287	39	0.0095	-0.0063
2014	127	225	0.5868	305	364	0.0110	0.0077

Table 10: ***Saxony Site***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	89	196	0.5431	287	349	0.0093	0.0065
2002	97	225	0.5472	265	357	0.0079	0.0076
2003	105	221	0.4808	258	313	0.0076	0.0095
2004	132	218	0.5634	302	17	0.0120	-0.0052
2005	120	214	0.5323	302	24	0.0104	-0.0052
2006	98	251	0.5824	316	54	0.0070	-0.0054
2007	107	176	0.5187	258	338	0.0138	0.0059
2008	127	232	0.5621	305	364	0.0098	0.0078
2009	113	216	0.5215	302	13	0.0093	-0.0047
2010	123	225	0.5133	316	39	0.0092	-0.0051
2011	121	229	0.5892	287	3	0.0100	-0.0048
2012	105	251	0.5391	294	360	0.0068	0.0091
2013	94	211	0.6094	302	6	0.0095	-0.0054
2014	116	232	0.5919	302	3	0.0094	-0.0047

Table 11: ***Saxony2 Site***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}

						FAPAR FAPAR^{-1} d^{-1}	
2001	113	189	0.5426	287	364	0.0131	0.0057
2002	102	225	0.5412	265	364	0.0081	0.0072
2003	133	203	0.4702	258	313	0.0122	0.0078
2004	134	218	0.5617	309	17	0.0123	-0.0051
2005	129	214	0.5344	313	24	0.0116	-0.0052
2006	95	240	0.5822	320	54	0.0074	-0.0057
2007	107	196	0.5071	258	342	0.0105	0.0064
2008	127	192	0.5617	305	1	0.0159	-0.0054
2009	111	165	0.5194	305	13	0.0177	-0.0063
2010	123	225	0.503	316	39	0.0090	-0.0050
2011	120	229	0.5932	287	3	0.0100	-0.0048
2012	97	247	0.5317	294	386	0.0065	0.0070
2013	97	211	0.6109	313	6	0.0098	-0.0054
2014	127	225	0.5879	302	3	0.0110	-0.0049

Table 12: ***<u>Shooting Range Site</u>***

Year	**Greenup (DOY)**	**Peak (DOY)**	**Peak FAPAR**	**Browndown (DOY)**	**Senescence (DOY)**	**Growth Rate FAPAR FAPAR^{-1} d^{-1}**	**Death Rate FAPAR FAPAR^{-1} d^{-1}**
2001	92	189	0.5686	254	360	0.0108	0.0061
2002	96	221	0.5399	276	360	0.0079	0.0071
2003	94	225	0.5373	280	320	0.0075	0.0104
2004	128	218	0.5529	305	13	0.0113	-0.0050
2005	113	284	0.4941	316	24	0.0053	-0.0035
2006	96	243	0.5725	316	35	0.0072	-0.0051
2007	92	192	0.5307	247	338	0.0098	0.0067
2008	122	185	0.549	298	1	0.0160	-0.0055
2009	112	181	0.5137	294	382	0.0137	0.0047
2010	122	221	0.5137	313	397	0.0095	0.0054
2011	110	225	0.5804	284	12	0.0093	-0.0050
2012	100	214	0.5254	284	353	0.0085	0.0069
2013	112	218	0.5922	302	35	0.0102	-0.0059

2014	115	229	0.5922	302	349	0.0095	0.0090

Table 13: ***VK Site***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	85	189	0.5745	254	346	0.0101	0.0067
2002	92	229	0.5516	276	360	0.0074	0.0077
2003	103	221	0.5503	276	346	0.0086	0.0081
2004	128	211	0.5554	309	10	0.0123	-0.0051
2005	111	214	0.5503	316	21	0.0098	-0.0052
2006	95	254	0.586	316	24	0.0068	-0.0047
2007	91	192	0.5363	247	331	0.0098	0.0071
2008	107	196	0.5618	302	3	0.0116	-0.0054
2009	81	265	0.5439	313	17	0.0054	-0.0040
2010	107	214	0.5108	313	32	0.0088	-0.0052
2011	92	211	0.577	284	13	0.0089	-0.0054
2012	100	221	0.5261	265	342	0.0080	0.0080
2013	101	200	0.5757	294	346	0.0107	0.0072
2014	110	221	0.5821	302	349	0.0096	0.0083

Table 14: ***Vukuzakhe Site***

Year	Greenup (DOY)	Peak (DOY)	Peak FAPAR	Browndown (DOY)	Senescence (DOY)	Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}	Death Rate FAPAR $FAPAR^{-1}$ d^{-1}
2001	85	189	0.5907	240	346	0.0104	0.0069
2002	92	229	0.5339	276	364	0.0072	0.0073
2003	103	221	0.5524	276	346	0.0086	0.0081
2004	119	218	0.5722	305	43	0.0106	-0.0060
2005	147	214	0.5603	305	28	0.0154	-0.0055
2006	98	247	0.5881	316	35	0.0072	-0.0051
2007	92	185	0.5392	243	335	0.0107	0.0066

2008	107	189	0.5618	302	1	0.0126	-0.0055
2009	111	243	0.5352	309	13	0.0075	-0.0043
2010	107	207	0.5141	309	32	0.0094	-0.0054
2011	92	207	0.5841	280	17	0.0093	-0.0056
2012	96	207	0.5273	254	338	0.0087	0.0074
2013	104	203	0.5656	284	364	0.0105	0.0065
2014	108	229	0.5735	298	338	0.0087	0.0097

Table 15: ***Wetland Site***

Year	**Greenup (DOY)**	**Peak (DOY)**	**Peak FAPAR**	**Browndown (DOY)**	**Senescence (DOY)**	**Growth Rate FAPAR $FAPAR^{-1}$ d^{-1}**	**Death Rate FAPAR $FAPAR^{-1}$ d^{-1}**
2001	92	189	0.5298	254	353	0.0100	0.0059
2002	101	229	0.5417	265	353	0.0078	0.0080
2003	100	240	0.4808	276	309	0.0063	0.0127
2004	125	218	0.5589	298	357	0.0111	0.0074
2005	113	214	0.5192	284	13	0.0094	-0.0047
2006	97	254	0.5762	313	13	0.0067	-0.0044
2007	96	185	0.5351	247	335	0.0111	0.0066
2008	119	189	0.5563	298	360	0.0146	0.0060
2009	111	174	0.5139	291	21	0.0150	-0.0062
2010	111	229	0.506	305	32	0.0079	-0.0047
2011	120	218	0.5669	280	364	0.0106	0.0071
2012	92	232	0.5179	287	13	0.0068	-0.0043
2013	102	200	0.5947	269	346	0.0111	0.0075
2014	107	229	0.5868	294	357	0.0088	0.0084

Section 2: The observed FAPAR for each study site from 2000 to 2014. Each point on the graph shows the FAPAR value on each particular day when the satellite passed and took readings.

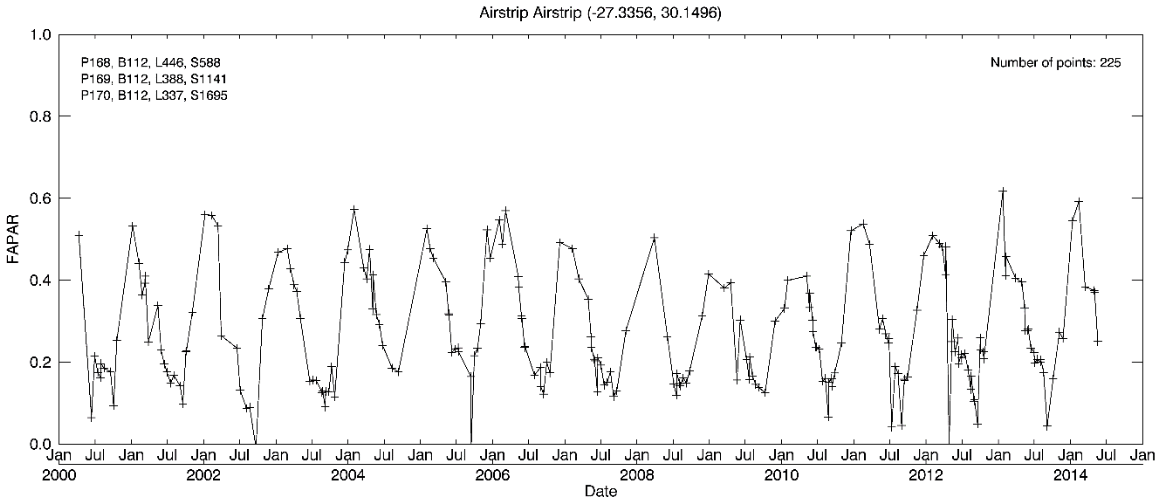


Figure 6.2: Observed FAPAR for the Airstrip site.

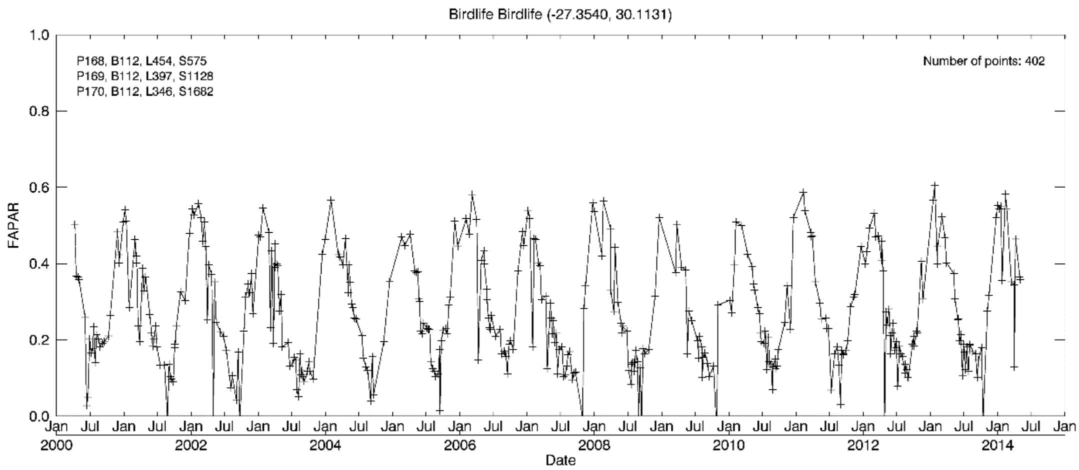


Figure 6.3: Observed FAPAR for the Birdlife site.

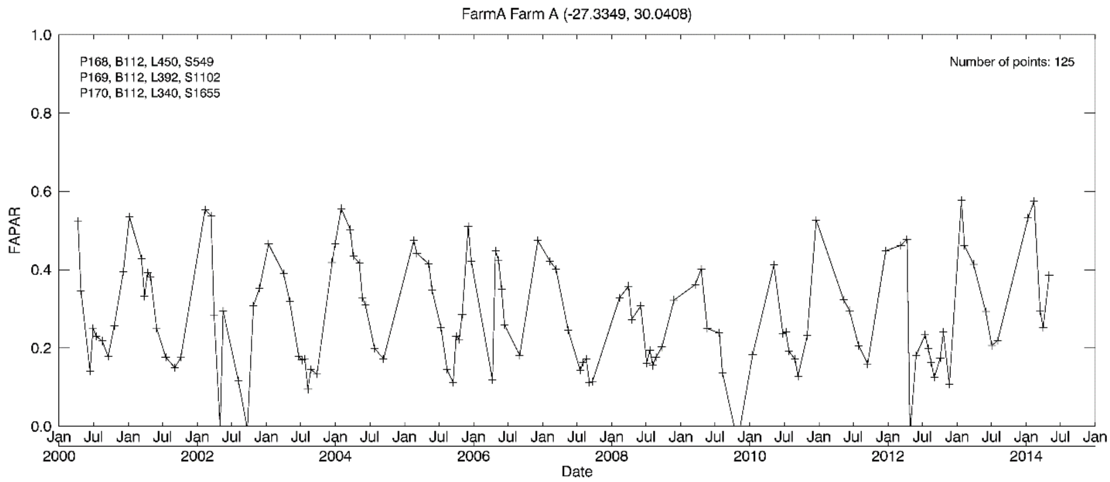


Figure 6.4 Observed FAPAR for the Farm A site.

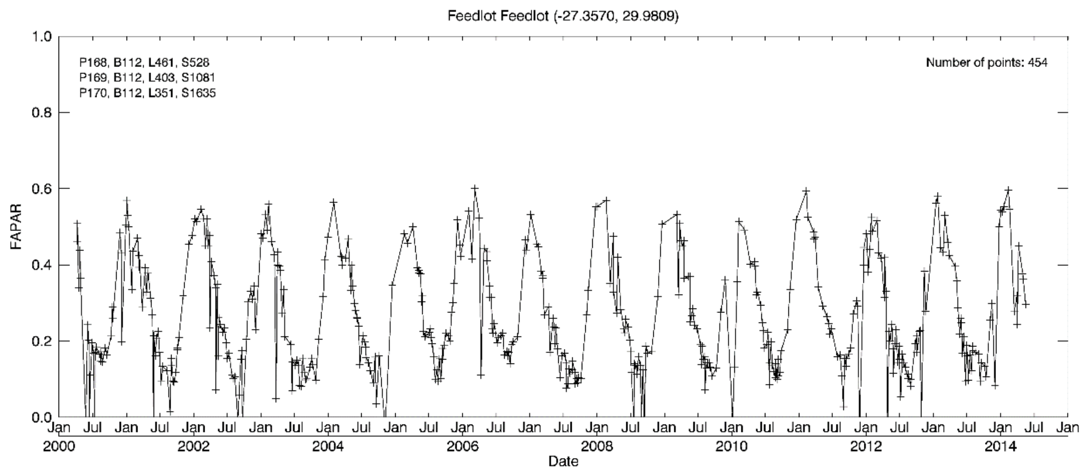


Figure 6.5: Observed FAPAR for the Feedlot site.

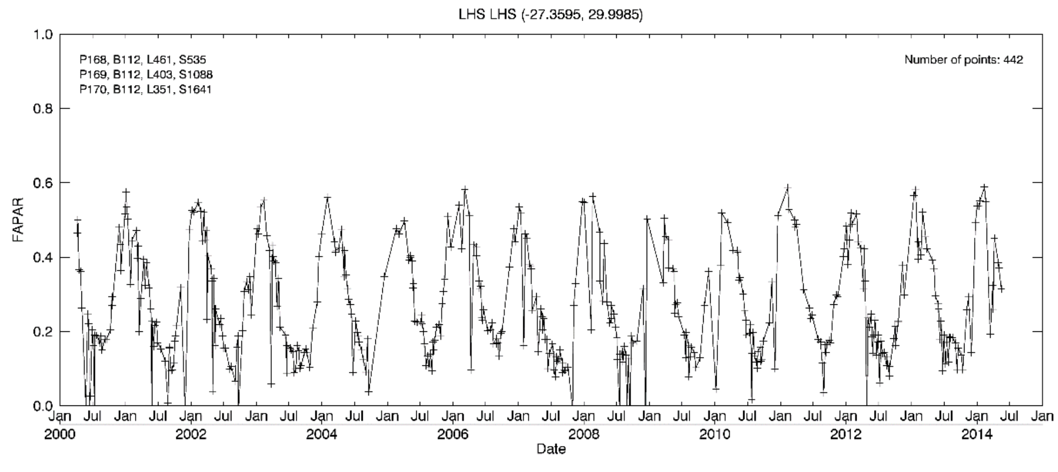


Figure 6.6: Observed FAPAR for the LHS site.

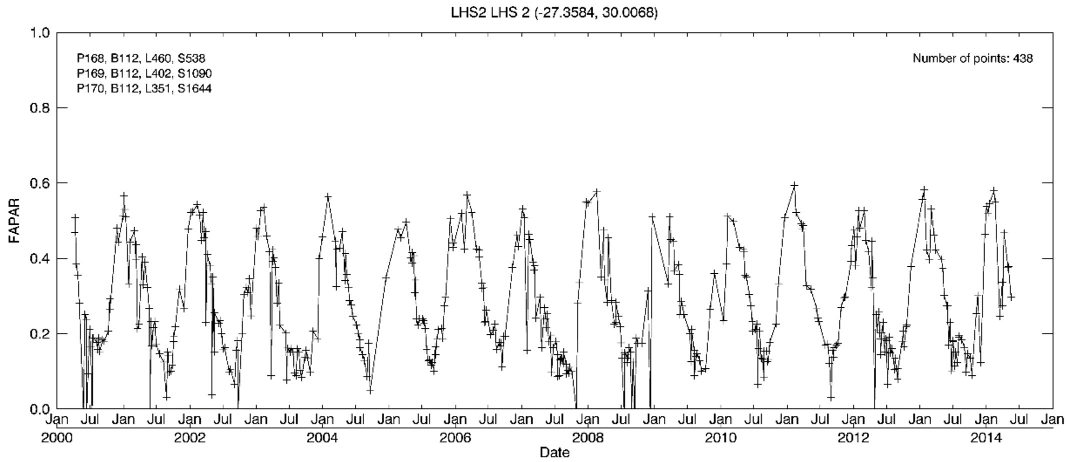


Figure 6.7: Observed FAPAR for the LHS2 site.

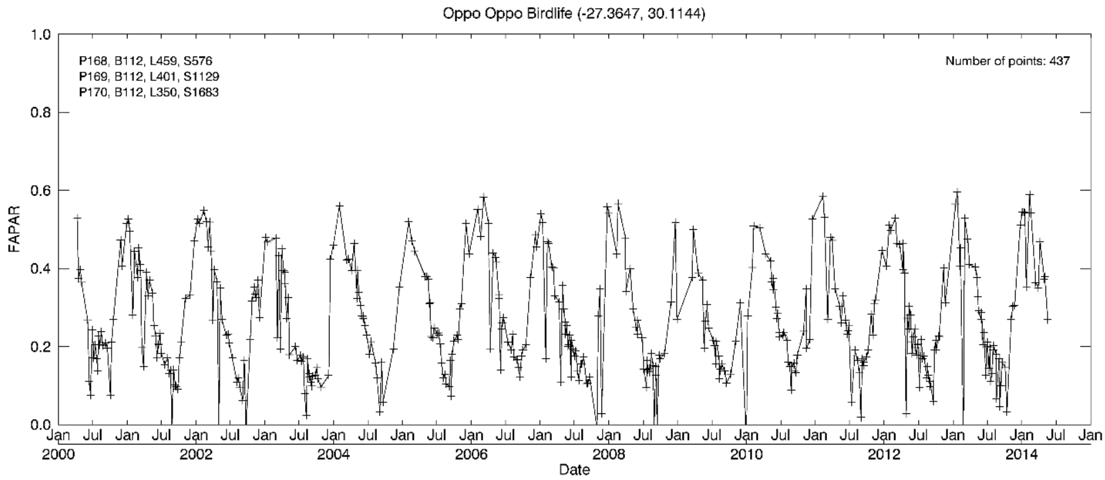


Figure 6.8: Observed FAPAR for the OppoBirdlife site.

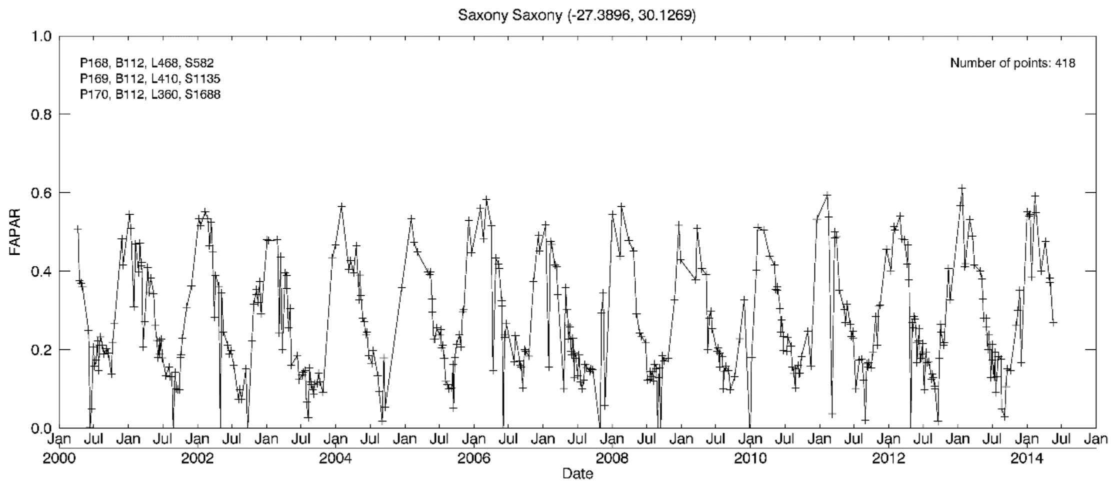


Figure 6.9: Observed FAPAR for the Saxony site.

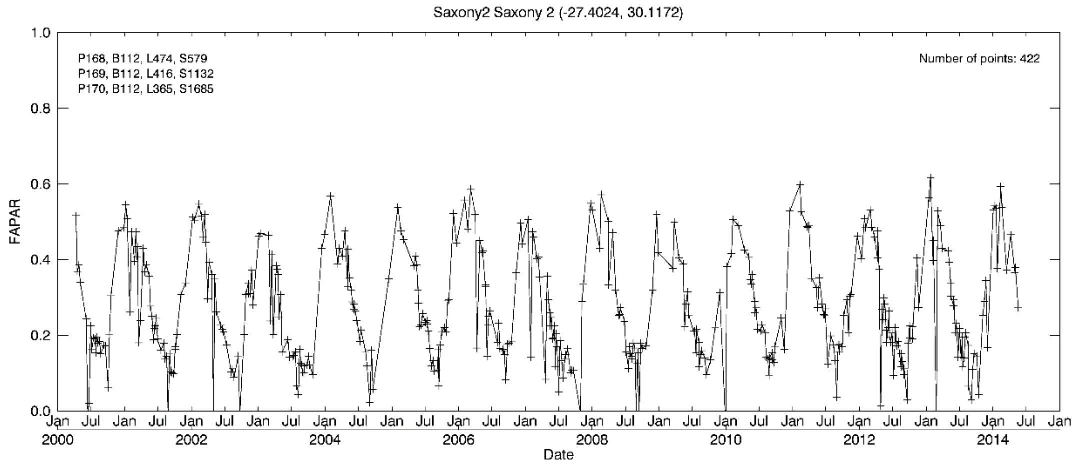


Figure 6.10: Observed FAPAR for the Saxony2 site.

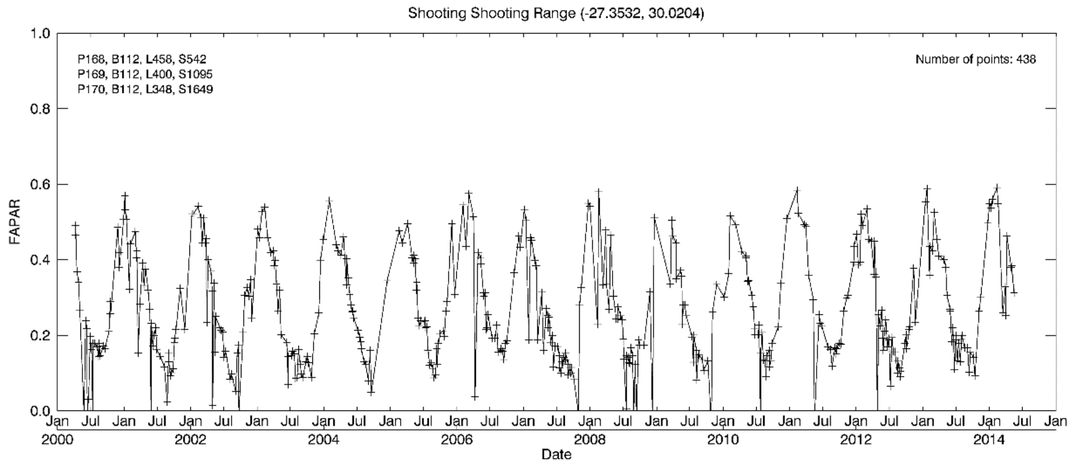


Figure 6.11: Observed FAPAR for the Shooting Range site.

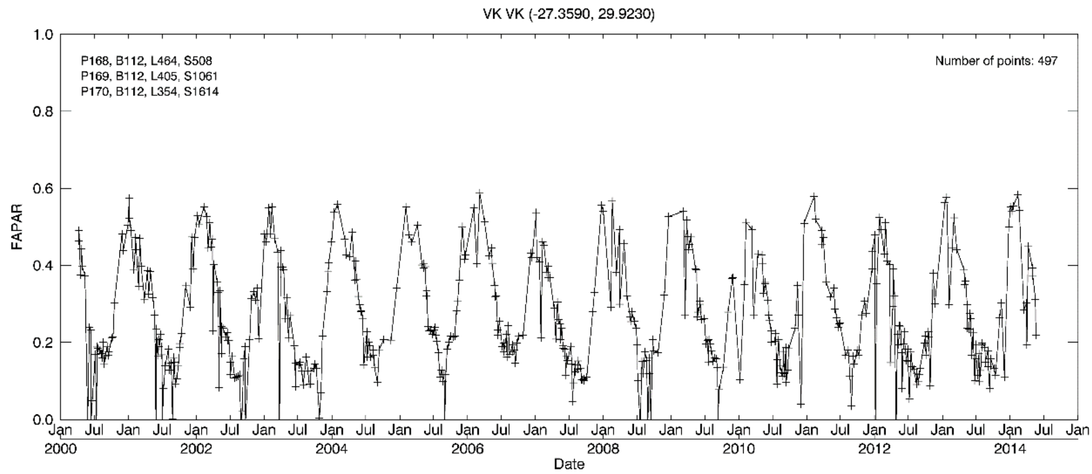


Figure 6.12: Observed FAPAR for the VK site.

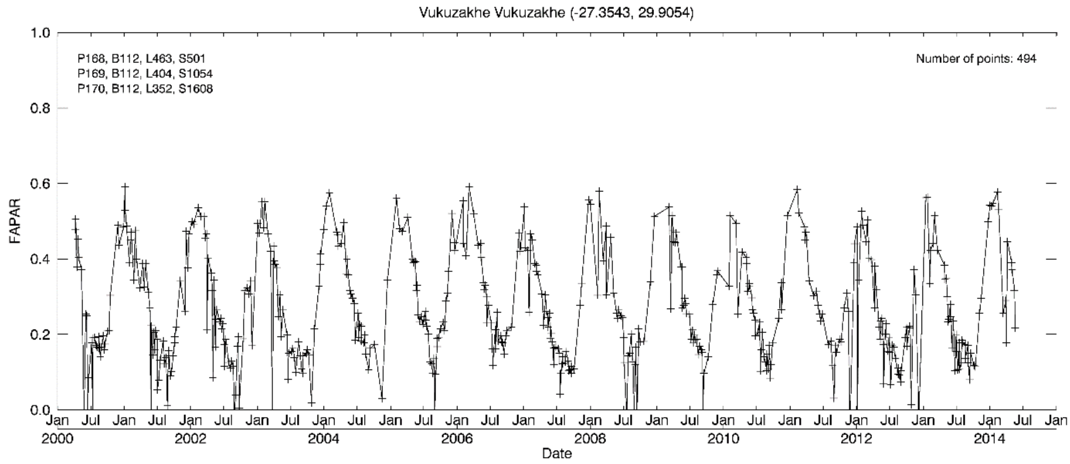


Figure 6.13: Observed FAPAR for the Vukuzakhe site.

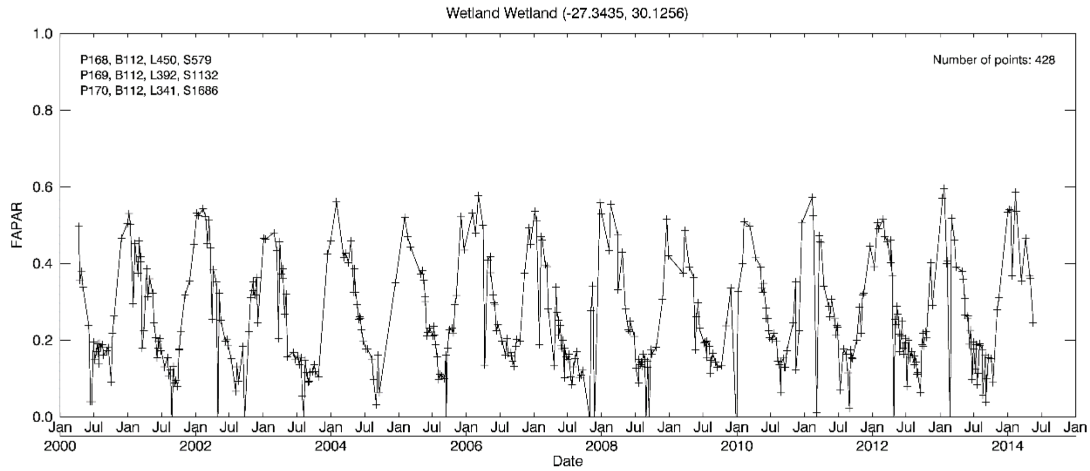


Figure 6.14: Observed FAPAR for the Wetland site.

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