MONITORING THE RE-GROWTH RATE OF ALIEN VEGETATION AFTER FIRE ON AGULHAS PLAIN, SOUTH AFRICA

by
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DECLARATION

I, the undersigned, hereby declare that the work contained in this thesis is my own original work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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ABSTRACT

The Agulhas Plain, an area rich in fynbos, was monitored within six months after the February 2006 fire. The potential of using medium resolution imagery, specifically from the Moderate Resolution Imaging Spectroradiometer (MODIS) in determining the re-growth rates of indigenous and alien vegetation types after fire was explored. Pixels representing dense areas of each vegetation type were selected. There was a significant difference in the pixels selected for each vegetation type. A time series of Normalized Difference Vegetation Index (NDVI) data was derived and fitted to functions, such as Double Logistics and Asymmetric Gaussian as implemented in the TIMESAT software. The results show that alien vegetation grows faster after a fire occurrence than in its absence. Within the specified months of monitoring, it was observed that fynbos grew faster than the alien vegetation. Also, the re-growth rates of vegetation on the coastal soils were higher than those of vegetation on the inland soils. The determination of the re-growth rate was necessary to assist resource managers determine the appropriate time for *follow-up* of clearing invaded sites after fire.

Key words: *alien vegetation, Agulhas Plain, MODIS, fire, fynbos, time-series, NDVI*

OPSOMMING

Die Agulhas-vlakte, ‘n gebied met weelderige fynbosplantegroei, is binne ses maande na die veldbrand in Februarie 2006 gemonitor. Die potensiaal vir die gebruik van medium resolusiebeelde, dit is, Moderate Resolution Imaging Spectroradiometer (MODIS) om die hergroeitempo van in- en uitheemse plantegroeitipes na ‘n brand te bepaal, is ondersoek. Beeldelemente wat digte gebiede van elke soort plantegroei verteenwoordig, is geselekteer. Beduidende verskille in die geselekteerde beeldelemente is waargeneem. ‘n Tydreeks van Normalized Difference Vegetation Index (NDVI) data is afgelei en gepas met funksies soos Double Logistics en Asymmetric Gaussian soos in die TIMESAT-sagteware geïmplementeer. Die resultate toon dat uitheemse plante vinniger na ‘n brand groei as wanneer daar geen brand was nie.Tydens die gespesifiseerde moniteringsmaande is daar waargeneem dat die fynbos vinniger as die uitheemse plante gegroei het. Verder is die hergroeitempo’s van plantegroei in die kusgronde hoër as dié van plantegroei in die binnelandse gronde. Die vasstelling van groeitempo’s was nodig om hulpbronbestuurders te help om die gepaste tyd te bepaal vir die opvolg van die opruiming van gebiede waar indringing plaasgevind het na ‘n brand.

Sleutelwoorde: *uitheemse plantegroei, Agulhas-vlakte, MODIS, veldbrand, fynbos, tydreeks, NDVI*

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CHAPTER 1: STUDY BACKGROUND

The distribution of alien vegetation in South Africa requires monitoring to curb the effects on natural vegetation. In the past, monitoring alien and indigenous vegetation types has been achieved through field surveys at a local scale. Remote sensing, for the first time, provides the capabilities of monitoring vegetation at multiple scales, from local to regional scales. Campbell (2002) has defined remote sensing as ‘‘the science of deriving information about the earth's land and water areas from images acquired at a distance’’. This relies on measurement of electromagnetic energy reflected or emitted from the features of interest. Remotely sensed imagery, such as aerial photographs and satellite imagery, provides data that is needed for mapping and monitoring vegetation dynamics.

Aerial photography, the oldest form of remote sensing, has been used since the inventory of the camera more than 150 years ago to view the earth’s surface. It has also been used extensively to map alien vegetation (e.g. Stow et al. 2000; Kakembo, Palmer, & Rowntree 2006). Since the 1970s, satellite technology has made it possible to obtain constant coverage of the earth’s surface at regular time intervals. Though satellite technology has been applied in many countries to monitor vegetation dynamics, the potential has not been fully explored in South Africa. This research attempts to show that it is possible to effectively utilise satellite remote sensing to monitor the vegetation dynamics in South Africa.

Moreover, considering the spatial extent of alien vegetation in South Africa, utilizing the potential of satellite technology is vital. Satellites provide data at various spatial (i.e, fineness of the spatial detail visible in an image) and temporal (i.e, time intervals between images) resolutions that can be used to achieve this goal. With the remarkable success recorded in other countries (e.g. Zhang et al. 2003; Beck et al. 2006), it is desirable that such a method be adopted in South Africa. In this study, the potential of using medium spatial resolution imagery in monitoring vegetation dynamics will be explored. Specifically, Moderate Resolution Imaging Spectroradiometer (MODIS) data will be used to monitor the re-growth rate of alien vegetation after fire. The study will contribute to the efforts of managing biodiversity in the fynbos biome of South Africa.

1.1 INTRODUCTION

When certain species of plants grow on a land other than their native soil, such plants are referred to as an alien plants. Alien plants such as *Hakea*, *Acacia,* and *Pinus* have been introduced to South Africa from other countries for various reasons, such as forestry, windbreaks, crop species, shade and creation of aesthetic surroundings (Cowling & Richardson 1995). Of the alien plant species in South Africa, 64 species were introduced from South and Central America, 14 from North America, 26 from Australia, 19 from Europe, and 25 from Asia (McQueen & Noemdoe 2000).

Alien vegetation has the ability to rapidly regenerate and spread at an alarming rate to other areas (Ashpole 2001), thereby sometimes becoming an invasive alien plant species. There are 161 species (38 herbaceous, 13 succulent and 110 woody) which have been introduced to South Africa (McQueen & Noemdoe 2000). A basic feature of an invasive alien species is that it usually has no natural enemies to limit its production and spread because the alien vegetation has been introduced into an environment in which it did not evolve (McQueen & Noemdoe 2000). As a result of this, they are strong competitors for resources such as water, nutrients, sunlight, and space. Recently the phenomenon of alien vegetation has become widespread and it is believed that it tends to invade, suppress and eventually replace natural vegetation growth (Low & Rebelo 1996). It has been estimated that alien vegetation occupies more than 10 (ten) million hectares (i.e. 8%) of the total land surface of South Africa (Versfeld, Le Maitre, & Chapman 1998; Ashpole 2001). Of these, *Acacias* are the most widespread (see Table 1.1 below).

Table 1.1 Top 10 invading species or groups of species in South Africa.

Species	**Condensed invaded area (ha)**	**Total invaded area (ha)**	**Density (%)**
Acacia cyclops	339 153	1 855 792	18.28
Prosopis species	173 149	1 809 229	9.57
Acacia mearnsii	131 341	2 477 278	5.3
Acacia saligna	108 004	1 852 155	5.83
Solanum mauritianum	89 374	1 760 978	5.08
Pinus species	76 994	2 953 529	2.61
Opuntia species	75 356	1 816 714	4.15
Melia azedarach	72 625	3 039 002	2.39
Lantana camara	69 211	2 235 395	3.1
Hakea species	64 089	723 449	8.86

Source: Versfeld DB, Le Maitre DC and Chapman RA 1998. Pp 30.

Alien vegetation constitutes several environmental and ecological threats to the natural vegetation, which may eventually have an impact on the economy. For instance, because alien vegetation is known to use more water than natural vegetation, there may be a reduction in water supplies, especially on mountain water catchment areas (Versfeld, Le Maitre, & Chapman 1998). As competitors with the natural vegetation, alien vegetation suppresses and changes the natural landscape, resulting in a decrease of natural vegetation. Additionally, alien vegetation contributes to increasing soil erosion because its root systems are not able to withstand heavy flooding, as evidenced in pine plantations (Cowling 1992). Apart from these problems, alien vegetation alters the fire behaviour of the natural vegetation. Alien vegetation has higher fire loads (biomass) which increases the intensity and frequency of fire occurrence (Ashpole 2001), and which can also cause physical and chemical soil damage. Intense fire occurrences have also resulted in the loss of property, especially properties close to places where alien vegetation is found. The impact of the invasive vegetation on the economy has led to several efforts by the government to monitor and curb the spread of alien vegetation in South Africa.

The monitoring of the distribution of alien vegetatiton and its growth rates in South Africa, through field surveys, can be time consuming and labour intensive. Aerial photographs have been used to map the distribution of alien vegetation. Stow et al. (2000) have examined the possibility of using colour infrared (CIR) digital camera imagery at a spatial resolution of 0.5m to discriminate *Acacia* species from indigenous vegetation (fynbos) in the Cape lowlands. They were able to uniquely identify shrub and tree features using visual or computer-assisted interpretation. Similarly, Kakembo, Palmer, & Rowntree (2006) applied high resolution digital camera imagery to characterize the distribution of *Pteronia incana* species in Ngqushwa District, Eastern Cape. They classified the imagery into different degrees of invasion and other land cover types using remote sensing software (e.g. Idrisi). They applied a range of vegetation indices, such as Perpendicular Vegetation Index (PVI), as opposed to ratio based vegetation indices like Normalized Difference Vegetation Index (NDVI) to determine which best characterizes the spatial distribution of the shrub and the degree of invasion. They found that PVI could be particularly suited for identifying the *Pteronia incana.* PVI is defined as the measure of the distance of a pixel from the soil brightness line (Gibson & Power 2000). It is computed as: $1/\sqrt{(Sr - Vr) - (Sir - Vir)}$

Where s = soil reflectance, V = vegetation reflectance, r = red, and ir = infrared.

Both methods metioned above are suitable for monitoring vegetation growth at a local scale. There is thus a need for a method that can monitor alien vegetation at a regional scale. The potential of medium spatial resolution imagery has been used extensively in other countries to monitor vegetation parameters such as the start and end of growing seasons, and growth rate (e.g. Maselli 2004; Sakamoto et al. 2005; Beck et al. 2006). Hostert, Roder, & Hill (2003) used NDVI data to measure vegetation dynamics at a regional scale in Mediterranean rangelands. They applied a trend analysis on the time series data after selecting reference spectra (or endmembers) which provided a series of vegetation states and change. The magnitude of vegetation increase or decrease was mapped on a per pixel basis.

The potential of monitoring alien vegetation at a regional scale in South Africa needs to be examined. Medium and coarse spatial resolution imagery provide data that can be used to monitor vegetation dynamics at a regional scale. This could assist in determining the appropriate time of taking aerial photographs for monitoring vegetation dynamics at a local scale. Also, for effective planning and management, monitoring the re-growth of alien vegetation after fire will aid in determining the best time, economically, to combat alien vegetation. It is easier and cheaper to clear alien vegetation before it reaches full maturity.

1.2 RATIONALE FOR THE RESEARCH

The aim of this research was to test the capability of high temporal, medium spatial resolution satellite imagery to monitor the re-growth rate of vegetation after fire. An assumption was made that with the 250m spatial resolution of MODIS data products, compared to the much coarser 1000m spatial resolution of the Advanced Very High Resolution Radiometer (AVHRR), is it possible that indigenous and alien vegetation patches can be represented by a single pixel.

The specific objectives were to:

- Investigate various change detection methodologies and make a decision on a change detection method.
- Become familiarised with using MODIS data products.
- Determine whether it is possible to distinguish between plant communities (e.g. alien and indigenous) as represented by MODIS data.
- Determine the re-growth rate of both indigenous and alien vegetation over six months after fire, through time series analysis.

- Make recommendations on the use of medium spatial resolution for the monitoring of vegetation after fire.

It was also necessary to explore the potential of MODIS for monitoring the re-growth of alien vegetation in the South African environment for the following reasons. To begin with, it is made available to the public at no cost other than that of downloading the products. Considering budget constraints, especially in most developing countries in Africa where funds are insufficient for acquiring satellite data for monitoring purposes, MODIS data can be used for the regional monitoring of vegetation. Also, the cost of aerial photographs and high spatial resolution data to be used at local scales after frequent fires may not be realistic. In addition to these reasons, the successful application of MODIS in other countries (Justice & Townshend 2002; Zhang et al. 2003; Doraiswamy et al. 2005; Sakamoto et al.2005; Beck et al. 2006) makes it attractive for use.

In achieving the objectives and testing the significant difference in the re-growth rates of both vegetation types, the research was designed as shown below:

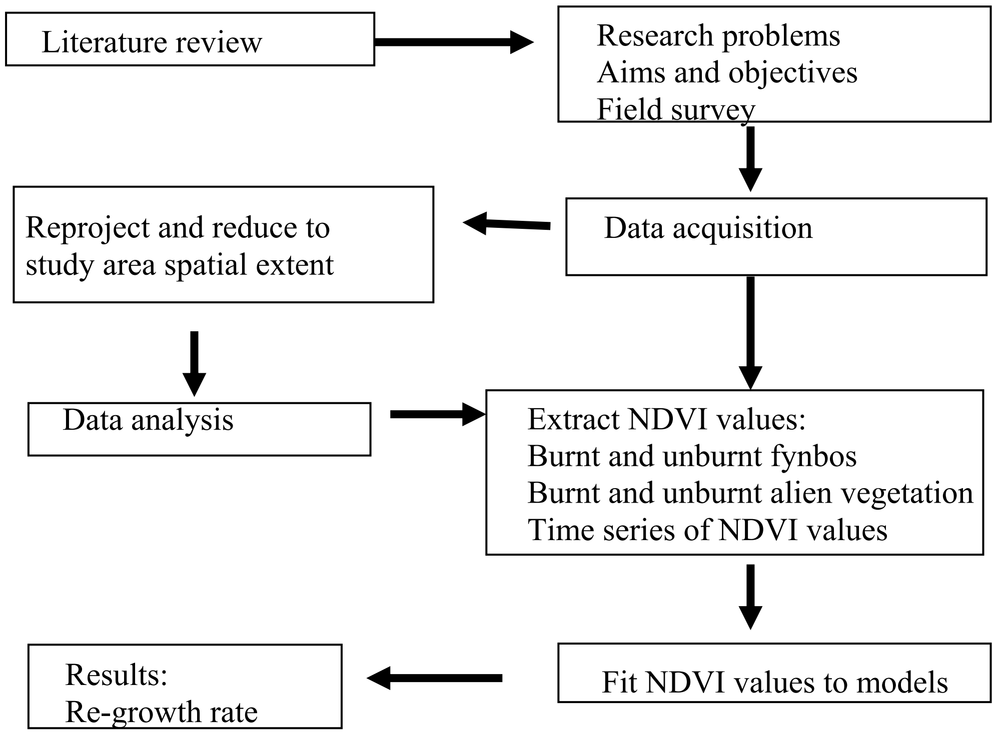


Figure 1.1 Research design

CHAPTER 2: FYNBOS ECOLOGY: BIODIVERSITY AND DYNAMICS

The natural vegetation of South Africa is being threatened by various factors such as urbanization, agriculture, misuse of fire and invasion by alien vegetation. This natural vegetation has been classified into seven biomes, namely, Thicket, Forest, Fynbos, Grasslands, Nama-Karoo, Savanna and Succulent Karoo (Low & Rebelo 1996). Of these, the fynbos biome is considered to have the highest biodiversity with over 7000 plant species, and is facing various threats to its plant diversity (Low & Rebelo 1996). Furthermore, fynbos is the biome most invaded by alien vegetation (Cowling 1992; Versfeld, Le Maitre, & Chapman 1998). For these reasons, the study focused on fynbos and its biodiversity, vegetation dynamics and major threats, discussed below.

2.1 BIODIVERSITY OF THE FYNBOS BIOME

A biome is the highest category of plant community recognised in the world (Cowling & Richardson 1995). McMahon (1992) defined a biome as a collection of vegetation formations sharing certain environmental features, notably similar structures. The fynbos biome (found in an estimated 70,000km^2 area) stretches over a narrow, crescent-shaped arc from the Nieuwoudtville Escarpment, 350km north of the Cape Peninsula, to almost 750km east along the southern Cape coast as far as Port Elizabeth and inland to Grahamstown (McMahon 1992). The fynbos biome occupies about 4% of the land surface (see Figure 2.1) of South Africa (Cowling 1992) and describes both fynbos and renosterveld vegetation types. The fynbos biome, with its large number of endemic vegetation species has earned international recognition as one of the world’s six floral kingdoms. It contains about 9,000 vascular plant species, at least 69% of which are endemic (Low & Rebelo 1996). Other plant kingdoms are the Boreal kingdom: 42%, Paleotropical kingdom: 35%, Neotropical kingdom: 14%, Australian kingdom: 8%, and Patagonian kingdom: 1%.

Fynbos is a Mediterranean-type shrubland as it is found in a Mediterranean climate (Cowling 1992). It refers to a range of vegetation that is uniquely found in Southwestern Cape of South Africa and covers 54% of the region while renosterveld covers 46% (Cowling & Holmes 1992). The Cape fynbos contains essential plant types such as restioids (evergreen reedlike vegetation); ericoids (heathlike small-leafed shrubs); proteoids (tallest fynbos shrubs commonly found at the base of the mountains); and geophytes (bulblike vegetation) (Campbell 1985).

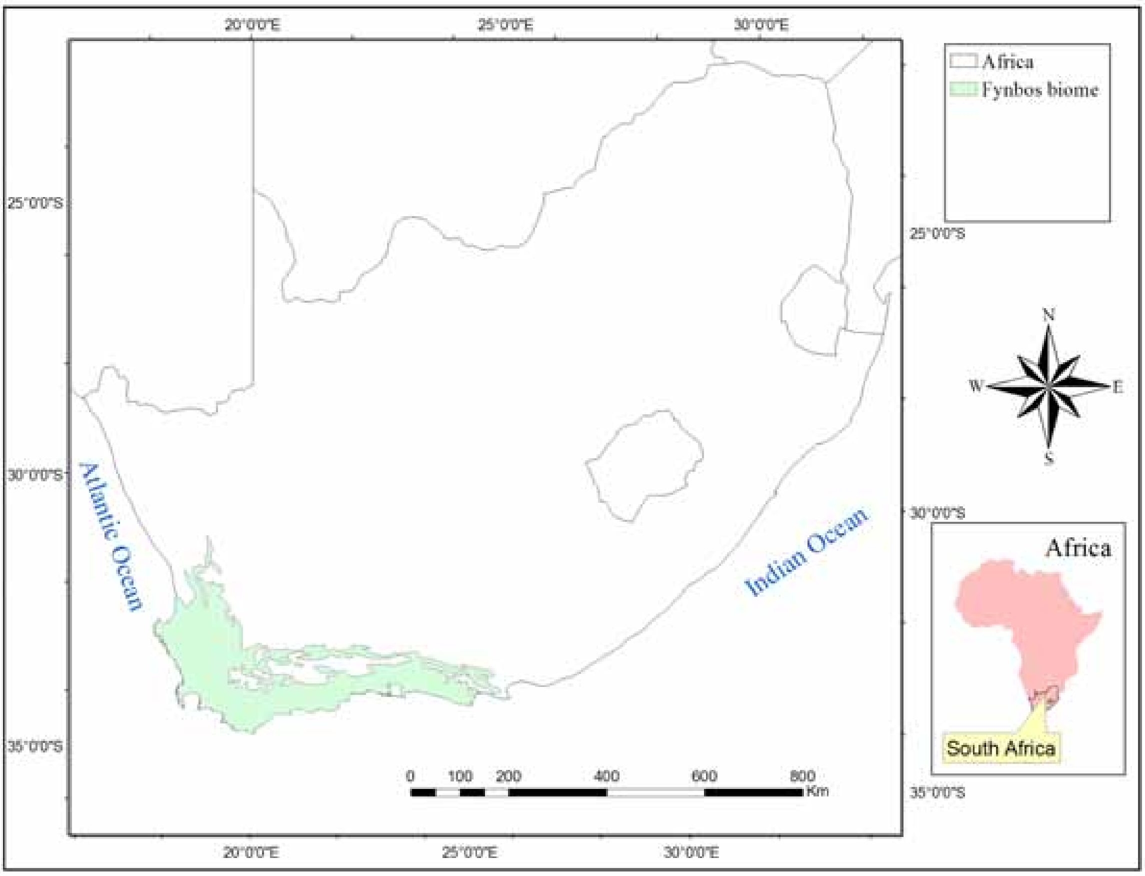


Figure 2.1 The Fynbos biome of South Africa.

According to Van Rensburg (1987) it refers to a large group of evergreen vegetation with small, hard leaves e.g. the Erica family (heathers and false heathers). There are about 526 species in the *Erica* group, 245 in *Aspalathus*, and 138 in *Phylica* (Cowling & Richardson 1995). Van Wilgen et al. (2001) noted that fynbos vegetation types occur predominantly on well-leached, infertile soils which are common in the Cape region. The diversity and unique flora within the fynbos biome is of interest to many ecologists as new species are continuoulsy being discovered.

In Cowling & Richardson's (1995) description of fynbos plant communities, the Proteoids are mostly less than four meters in height, and are easy to identify due to their bushy appearance. They are found mostly at the base of mountains where deep soils accumulate which are usually more fertile than the soils in which other fynbos plants grow. The Ericoids (or heaths) are found mainly in moist and cool environments on the seaward-facing slopes and upper peaks of the coastal moutains. They are found in black, fine-grained, or organic-rich sands. The Restioids are confined to soils that are characterised by total absence of shrubs (espcially tall shrubs). The soils are well drained and shallow, especially on slopes and coastal lowlands. The Grassy fynbos plants are mostly found in the eastern part of the fynbos region (Cowling & Richardson 1995; Kakembo, Palmer, & Rowntree 2006).

It is important to conserve fynbos for several reasons. The fact that it is regarded as a floristic kingdom, endemic to South Africa, gives it enormous economic values (Van Rensburg 1987). Though it is difficult to quantify the value of fynbos in monetary terms, a lot of benefits have been derived from it. The fynbos biome contributes greatly to the economy of South Africa by attracting tourists all over the world, especially to the Cape Peninsula and the Cape of Good Hope. In a year, over 300,000 people use the cable-car to visit the fynbos-covered Table Mountain, while over a million people use the mountain for hiking, strolling and climbing. (McMahon 1992). The tourism industry has been South Africa's fastest growing industry since 2000.

The fynbos biome possesses plant species that have been attested to have great medicinal values and remedies (Van Rensburg 1987*)*. A lot of herbal products are harvested from the vegetation in the fynbos biome, many flowers sold locally and internationally, both dried and fresh, are derived from fynbos (Le Maitre et al. 1997). The popular flowers obtained from fynbos include proteas, ericas and restios. Other products obtained from it include rooibos tea (made from dried *Aspalathus linearis*), honey bush tea and fragrant leaves used in pharmaceutical and cosmetic industries (McMahon 1992).

Although the fynbos biome occupies only 4.4% of the total land area of South Africa, 19% of the country's water catchments fall within its bounds (Van Rensburg 1987; McMahon 1992; Versfeld et al. 1998). As a result, one of the factors considered necessary for the conservation of fynbos is water supply. According to both Le Maitre et al. (2000) and Versfeld, Le Maitre, & Chapman (1998), water supply could be increased by at least 25% if the alien vegetation within the water catchments areas are cleared. Consequently, any threat to the fynbos biome is a threat to the water supply in some parts of South Africa. This has led to several efforts by various governmental organisations to conserve fynbos, and thereby conserving these water catchments. Notable among these is the Department of Water and Forestry's Working for Water program. This program employs people to clear invaded fynbos sites, thereby conserving water and creating jobs which leads to improved social wellbeing for the employees. Apart from eradicating aliens for water supply purposes, the unique plant diversity is also conserved.

Like other Mediterannean climates, fire regimes play an important role in the fynbos biome (Cowling & Richardson 1995). The four main components of fire regimes are, frequency, intensity and spatial extent. Different fire regimes are associated with different vegetation types. Fire causes a regeneration of species in fynbos by stimulating seed release, germination, flowering and returns mineral elements held in the above ground phytomass and litter to the soil (Van Wilgen & Le Maitre 1981; Cowling 1992). Thus fire can be seen as a necessary ecological process in the fynbos lifecycle.

According to Cowling (1992) fire, rather than the Mediterranean-type climate, is the key enviromental factor in the fynbos biome. It does not only initiate regeneration of species, it also preserves the fynbos species. Considering the basis for fire within fynbos, Cowling & Richardson (1995) identified several factors. To start with, fynbos is flammable; and secondly, it experiences weather that is suitable for fire. Fire outbreaks occur mainly in the summer and early autumn. In addition, there can be fire at any time of the year under suitable weather conditions (Van Wilgen 1987). This is dependent on several factors such as climate and the fuel loads of the plant species. The winter rains and summer droughts experienced within the fynbos biome make it susceptible to fire.

Van Rensburg (1987) summarized the life cycle of most fynbos species after a fire occurrence. According to him, certain species start to resprout and the seeds of most species germinate during the first 12 months after a fire. Some sprouting species start flowering and set seed e.g. bulbous or tuberous vegetation such as watsonias. While in four- to- five years after a fire, the vegetation is dominated by grass and reed-like vegetation (graminoids) and the species that sprouted. In the next transitional phase, which may be up to 10 years, all the remaining vegetation reaches maturity and tall shrubs emerge. This is followed by the mature phase (up to 30 years), where tall shrubs attain their maximum heights and produce flowers. Smaller shrubs such as heather begin to die while litter and dead materials accumulate. Lastly (i.e. senescence phase), the mortality among seed-germinating vegetation accelerates. The foliage of surviving vegetation is reduced to tufts at the tips of branches. The canopy becomes more open and germination may occur. Litter accumulates and indigenous forest species may establish on fertile, moist soils.

Since some fynbos plant communities only accumulate enough fuel to sustain a fire under situable conditions after four years, fire cycles of less than four years are rare (Van Rensburg 1987; Cowling & Richardson 1995). However, under extremely hot and dry weather conditions, they may occur under three years. Resource managers use fire as a tool to conserve fynbos species. This is achieved by the intentional ignition of fires within fynbos. However, it has been established that frequent fires (three to four year rotation) may cause the local extinction of slow maturing, non- sprouting fynbos shrubs (Van Wilgen & Kruger 1981; Cowling 1992), so there are physical limits to the frequencies of fire that can be applied to fynbos. On the other hand, if the fire intervals are too long, the vegetation gets old and loses vigour and will eventually die, which is just as detrimental (Daphne 2006).

Non-sprouters (i.e. mostly slow maturing species) are more sensitive to frequent fire and such vegetation therefore dictates the fire frequencies required to maintain species diversity (Van Rensburg 1987; Cowling 1992; Cowling & Richardson 1995). Certain fynbos species are able to sprout after a burn and these species are less affected by fire frequency as they do not have to reach maturity to survive fires; they also generally live longer than non-sprouters.

2.2 THREATS TO THE FYNBOS BIOME AND BIODIVERSITY

The fynbos biome is being threatened by various factors such as urbanisation, poor agricultural practises, invasion by alien vegetation and uncontrolled fires **(**McMahon 1992; Van Wilgen et al. 1997). Urbanisation, particularly around Cape Town, and agricultural practises in the lowland have been attributed to the loss of plant diversity (Low and Rebelo 1996). Of all the factors threatening fynbos, alien vegetation contributes greatly to its reduction (Versfeld, Le Maitre, & Chapman 1998). Due to the low productivity of fynbos on the infertile soils, they are not replaced for agriculture. However, the fynbos biome is replaced with pine plantations and on richer soils where the rainfall is high, fynbos has been converted to fruit orchards and vineyards (Cowling 1992; Van Wilgen et al. 2001).

Cowling (1992) considered how fynbos could support dense stands of alien trees and shrubs within it and found that much of the fynbos biome is climatically suited to tree growth even though indigenous trees are uncommon in fynbos. McMahon (1992) linked the extensive alien plant invasion within fynbos to the fact that most of these woody plants are from climatically and geologically similar environments to fynbos, notably Australia, South America and the Mediterranean regions. An estimated 36% of the remaining Cape fynbos is invaded by this woody alien vegetation, especially Port Jackson Willow (*Acacia saligna*) and Rooikrans (*Acacia cyclops*) (Higgins et al. 1999). Both species were introduced from the sandy coasts of Australia. While Rooikrans thrives on calcareous coastal dunes and limestone, the Port Jackson

Willow is found mostly on acid sands and in wetter sites, along slopes of coastal hills and mountains (Cowling & Richardson 1995). These habitats (i.e. coastal lowlands) are found within the fynbos biome. Alien vegetations such as pines, and hakeas are more visible on the mountains.

Apart from climatic factors contributing to the fynbos vegetation dynamics, disturbance contributes to the invasion of natural vegetation by alien vegetation. The natural disturbance regime in much of the fynbos biome is characterized by intense fires at intervals of between 6 and 30 years (Cowling 1992). The five important climatic parameters contributing to the disturbance regime in an ecosystem are rainfall, temperature, radiation, wind (major factor to fire weather) and periods of drought (Van Wilgen & Hensbergen 1992). Most of these climatic parameters are experienced within the fynbos biome.

As mentioned earlier, alien vegetation has been introduced for various reasons and the absence of the natural enemies of many of the alien species, has resulted in their rapid spread (Cowling 1992; McQueen & Noemdoe 2000). The rapid spread of alien vegetation has attracted attention in the Western Cape, which is the most invaded by alien vegetation of all provinces (see Table 2.1) (Versfeld, Le Maitre, & Chapman 1998).

Table 2.1 Summary by province of the areas invaded by alien vegetation.

Province	**Area (ha)**	**Invaded area (ha)**	**Invaded area (%)**
Eastern Cape	16 739 817	671 958	4.01
Free State	12 993 575	166 129	1.28
Gauteng	1 651 903	22 254	1.35
KwaZulu-Natal	9 459 590	922 012	9.75
Lesotho	3 056 978	2 457	0.08
Mpumalanga	7 957 056	1 277 814	16.06
Northern Cape	36 198 060	1 178 373	3.26
Northern Province	12 214 307	1 702 816	13.94
North West	11 601 008	405 160	3.49
Western Cape	12 931 413	3 727 392	28.82
RSA + Lesotho	124 803 708	10 076 365	8.07

Source: Versfeld DB, Le Maitre DC and Chapman RA 1998. pp 32.

Another threat to the fynbos biome is the misuse of fire. Fire regimes create open spaces in which alien vegetation can grow. Wind dispersal of seeds to these open spaces and less competition from other vegetation contribute significantly to the introduction and spread of alien vegetation after fire. Invasion of the open spaces by an alien vegetation affects the fire behaviour of the plant communities. The higher fuel loads (biomass) of alien vegetation contributes significantly to the frequency and intensity of fires. This can also result in the loss of properties such as buildings and crops.

It is important to distinguish between fuel from dead (dry) and live (wet) vegetation. It is dead fuel that actually carries a fire. A fire will not normally be sustained if there is not enough dead fuel in the vegetation, or should the dead fuel be too moist (Van Wilgen & Van Hensbergen 1992). So once fynbos has gathered enough fuel from the litters (dry leaves) over the years, it burns naturally. However, with the higher fuel in alien vegetation, the natural course of fire within fynbos is altered. Sources of ignition must occur together with sufficient fuel and suitable weather conditions to result in a fire. For instance, the invasion of mountain fynbos by pines could increase biomass by up to 300% (Van Wilgen & Van Hensbergen 1992), leading to frequent fires in such areas, especially around Table Mountain in Cape Town. The intensity of the fire kills the indigenous seeds while stimulating germination of the invading vegetation's seeds (Marshall 2001).

CHAPTER 3: REMOTE SENSING AND VEGETATION MONITORING

The area for monitoring the re-growth rate of alien vegetation in this study is the Agulhas Plain, an area rich in fynbos. Because of its importance, the conservation of the plant species of the biome in this area is driven by various local, national and global organisations. In this chapter, the vegetation and fire regime on the Agulhas Plain will be considered. Furthermore, an overview of the remote sensing process will be given to provide an understanding of remote sensing and how it can be applied to monitor vegetation dynamics. This will include the potential of medium spatial resolution imagery in monitoring alien vegetation and time-series analysis of satellite imagery used in this study.

3.1 STUDY AREA

The Agulhas Plain is the southern most tip of the African continent. It is situated between Bredasdorp and Struisbaai (19°30′ – 20°15′S, 34°30′ – 34°50′E) in southern part of the Western Cape, South Africa. Due to its position, it shares the Mediterranean climate with Australia, Chile, California and the Mediterranean basin. The Mediterranean climate comprises of hot dry summers and cold wet winters (Daphne 2006), with a mean annual rainfall of 500mm (Tertius 2002). The Agulhas Plain, where many of the fynbos species are found, is an important component of the Cape Floral Kingdom.

The Agulhas Plain consists of eight major urban settlements namely: Struisbaai, Stanford, Gansbaai, Bredasdorp, De Kelders, Pearly Beach, Arniston and Agulhas. These, with other rural settlements and four smaller villages, constitute the Overstrand and Agulhas municipalities. The region is also known for its cultural- historical features. The Moravian mission station at Elim has the largest wooden waterwheel in South Africa while the clock in the Elim church dates back to 1764 (Daphne 2006).

3.1.1 Vegetation of Agulhas Plain

The Agulhas Plain (2160km^2) is an area (see Figure 3.1) of exceptional diversity of lowland fynbos and renosterveld habitats (Tertius 2002). It has over 1750 vascular plant species (Cowling and Holmes 1992) and the predominant vegetation types are fynbos (on nutrient-poor soils) and renosterveld (on more fertile soils). Both vegetation types are fire-prone shrublands.

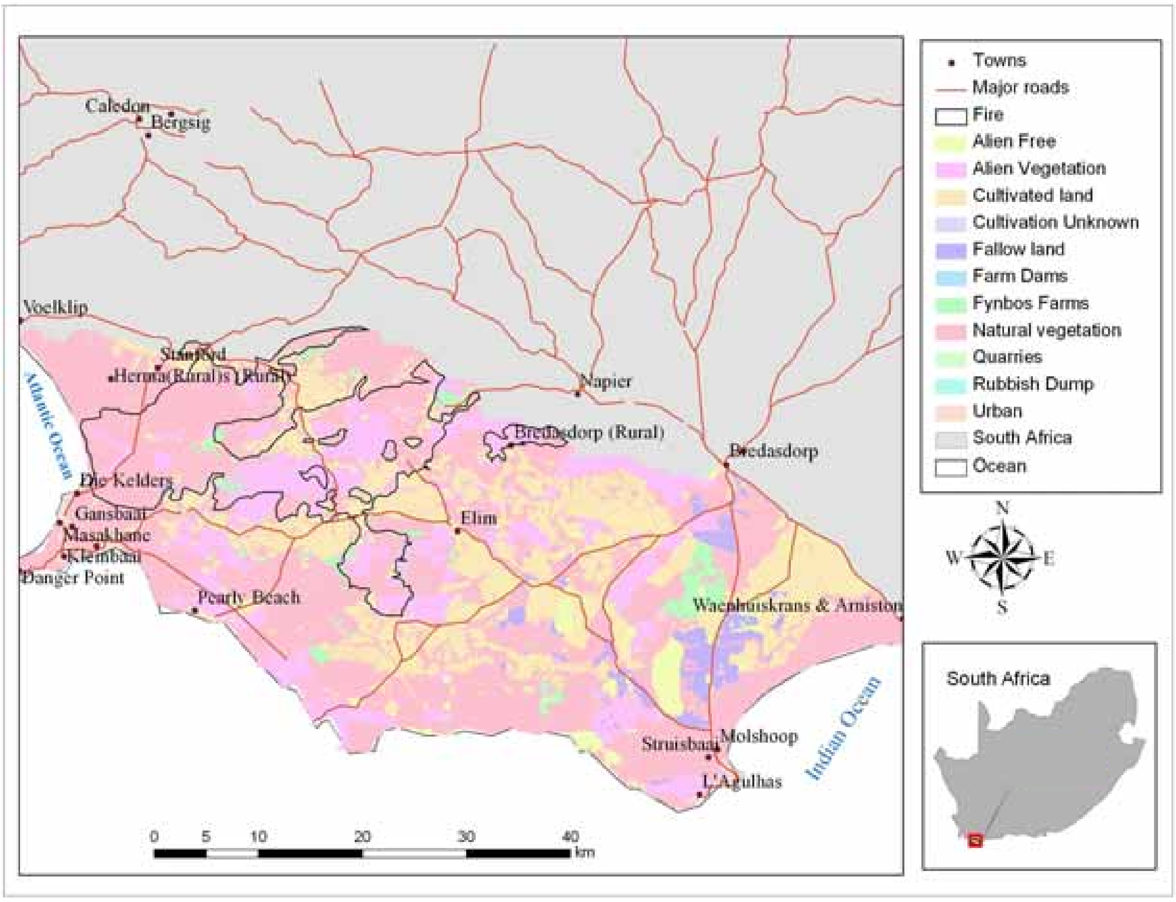


Figure 3.1 The Agulhas Plain

The exceptionally species-rich area of the Agulhas Plain was once covered by many different forms of fynbos and coastal renosterveld vegetation, but it is currently being threatened by alien plant infestation, agriculture and urban development. The natural vegetation on the Agulhas Plain is gradually yielding to the alien vegetation, which is the major threat. Notable among the alien vegetation on Agulhas Plain are Port Jackson Willow and Rooikrans, both introduces from Australia. Natural fire during the summer season (December to January in South Africa) is expected to rejuvenate fynbos on the Agulhas Plain. However, alien vegetation can use the open space created by the fire to spread rapidly.

3.1.2 Fire regimes

The most recent fire on Agulhas Plain occurred on 1 February, 2006. It covered a total area of 669.58km^2 and burned both the fynbos and alien vegetation. It was a natural fire which occurred in the summer drought season of fynbos, which in the Western Cape Province, South Africa, is from December to January. The intensity of the fire was uneven due to variations in fuel loads of the fynbos and alien vegetation. There were areas where the burning was severe and areas which were only slightly affected by the fire. This region is the windiest area yearround along the South African coast (Daphne 2006), which may have contributed to the fires intensity and spread. Fire, as noted by Van Wilgen & Van Hensbergen (1992), is intensified by wind, temperature and fuel loads. The fire burned on different soil types (grey regic Namib and Glenrosa soils).

3.2 THE REMOTE SENSING PROCESS

Remote sensing can be defined as the acquisition and recording of information about an object without being in contact with that object (Gibson & Power 2000). An understanding of the remote sensing process is essential before discussing its applications in monitoring vegetation dynamics. An overview of this process is given in this section.

The energy source is the first requirement to illuminate the earth's surface features (object of interest). The illumination from the sun is a good example of energy source for remote sensing. This energy is in the form of electromagnetic radiation. A full range of electromagnetic energy referred to as electromagnetic spectrum (EMS) is released from the sun towards the earth (Lillesand & Kiefer 2001; Campbell 2002). The longer the wavelength, the lower the frequency of energy in the EMS. However, not all portions of the EMS are useful for remote sensing purposes, but the ultraviolet, visible, infrared and microwaves can be used.

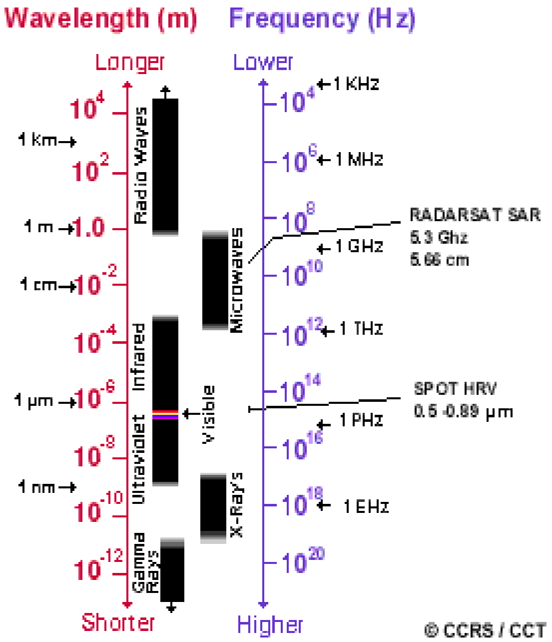


Figure 3.2 The electromagnetic spectrum. Source: CCRS 2002.

The radiation from the energy source to the earth passes through the atmosphere and interacts with the particles and gasses such as dust, ash, oxygen, water vapour and ozone. This interaction leads to processes called scattering and absorption. Scattering is the process in which the energy is re-directed from the original path by atmospheric gasses. Absorption on the other hand, is the loss of energy to atmospheric constituents (Lillesand & Kiefer 2001). Atmospheric particles absorb or scatter electromagnetic energy in different proportions of the EMS. These have impact on the image quality. Scattering and absorption can occur at two stages in the remote sensing process. First, during the transfer of radiation from the sun to the earth and secondly, during the transfer of reflected or emitted energy from the earth to the sensor.

The radiation that is not absorbed or scattered by the atmosphere reaches the earth. The reaction of the earth's surface feature to the radiation can be in any of these three forms: reflection, absorption or transmission. Absorption occurs when the radiation is absorbed by the object. Transmission occurs when the radiation passes through the object, while reflection occurs when the radiation is redirected back to the atmosphere. In remote sensing, it is the energy reflected or emitted from the earth's surface features that is recorded by the sensor. However, the response of earth's surface features differ with the radiation involved. It is the spectral response of the earth's surface features to different portion of the radiation that distinguishes it from other features.

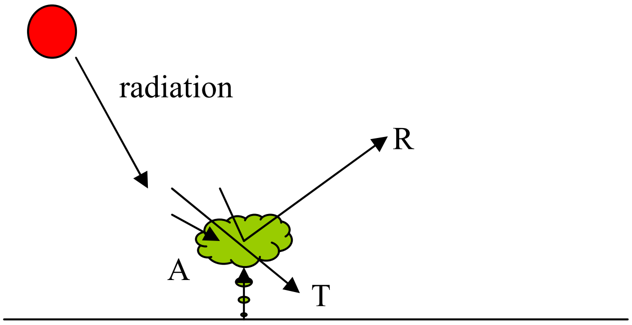


Figure 3.3 Interaction with the object.

Where A = Absorption, R = Reflection, and T = Transmission.

Sensors must be placed on platforms that are not in contact with the object, to allow the recording of reflected energy. These platforms can be placed on the ground, on aircraft and more recently on spacecraft or satellites outside the atmosphere. Most remotely sensed images are obtained from sensors placed on the satellites in space (Campbell 2002). This has the advantage of repetitive coverage of the earth’s surface at regular intervals as they orbit around the earth.

Remotely sensed images, for example, consist of aerial photographs and satellite imagery. The two are not the same. A photograph is a record of a scene captured by a film that is sensitive to ultraviolet, visible or infrared electromagnetic radiation (Gibson & Power 2000). It is mostly taken with cameras from aircrafts flown over the earth. An image is a record of a scene obtained by a scanning system from satellite, which can also be sensitive to the visible, infrared and microwave electromagnetic radiations. Images of the Earth’s surface can be captured periodically as the satelite orbits around the Earth.

With the successful launch of the first Earth Resources Technology Satellites (now referred to as Landsat) in 1972 and the quality of data recorded, several satellites such as SPOT, Terra (latin word for land) and NOAA (National Oceanic and Atmospheric Administration) have been launched for monitoring the earth’s surface, ocean, atmosphere, etc (Gibson & Power 2000). The data recorded cannot be used on the satellite, thus they are transmitted electronically to the earth to receiving stations. The ground receiving stations must be in the line of sight of the satellite to receive such data. The Satellite Application Centre close to Pretoria, South Africa is a ground receiving station for the southern African region. At reception, the data are processed before it can be used for analysis by the end user.

Data analysis is required in order to extract meaningful information about the earth’s surface features. Analysis can be done visually or digitally by remote sensing software such as ERDAS, Idrisi, PCI, TNTmips. Digital processing involves the enhancement, classification or transformation of the data to extract useful information for application to various areas of interest. Remote sensing applications include vegetation monitoring, weather forecasting and sea colour and level monitoring, among others.

3.3 VEGETATION MONITORING

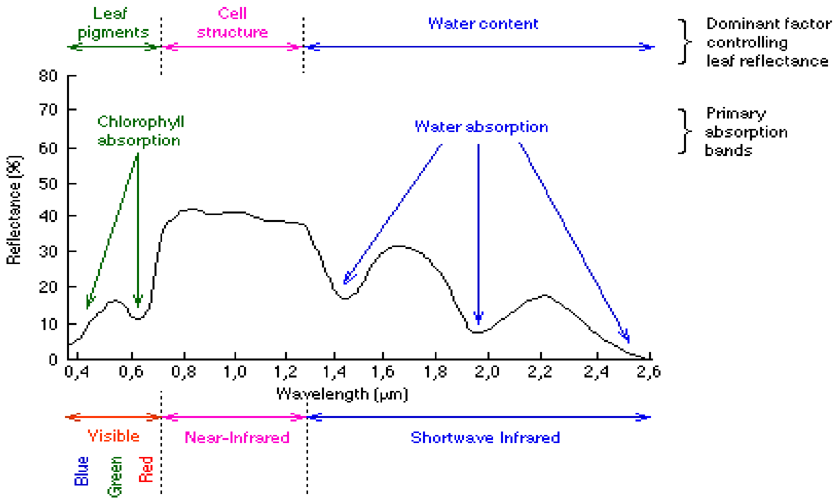
Vegetation cover has been an early focus of research in natural resources management using space-borne satellite imagery with the release of the Landsat satellite in 1972. The application of satellite technology to vegetation studies range from crop yield estimation (Doraiswamy et al. 2005), crop condition (Maselli 2004), to fire mapping (Roy et al. 2005). Its use for monitoring vegetation dynamics requires vegetation indices derived from satellite imagery.

Vegetation indices (VIs) are combinations of several spectral values that are added, divided, or multiplied, to yield a single value that measures biomass or vegetative vigor (Campbell 2002). VIs are mainly derived from reflectance data from discrete red (R) and near-infrared (NIR) bands (Gibson & Power 2000; Maselli 2004), because these bands contain about 90% of the vegetation information.

Vegetation has a characteristic spectral response pattern in which visible blue (450nm i.e. wavelength – see Figure 3.4) and red (670nm) energy is absorbed strongly. The visible green (550nm) light is weakly reflected and near infrared energy is strongly reflected (Lillesand & Kiefer 2001) by vegetation. In the visible portion (400 – 700nm) of the electromagnetic spectrum, the spectral response is determined by chlorophyll. Chlorophyll a and b (green pigments) in leaves absorb the blue and red light for use in photosynthesis and reflect the green light (Gibson and Power 2000). This is why most vegetation is seen as green in the visible light by human eyes. Photosynthesis is the process whereby vegetation converts light and carbon dioxide to organic compounds required for maintenance and growth. Photosynthesis can be represented by the equation below:

$$CO_2 + 2\ H_2O \xrightarrow{\text{light}} [CH_2O] + O_2 + H_2O$$

In the infrared portion (700 – 1300nm), the structure of the leaf (spongy mesophy layer) is responsible for the spectral response of vegetation (Gibson & Power 2000). The shortwave infrared wavelengths (1350 -2600nm) is characterized by water absorption bands (1450, 1950, and 2500nm), as water strongly absorbs the light in the shortwave infrared. This spectral response of vegetation distinguishes it from other land cover types such as bare soil and water.



Source: RSCC website.

Figure 3.4 Typical spectral response characteristics of green vegetation

As vegetation matures, the reflectance in green energy is slightly increased while reflectance in the near-infrared strongly increases. At senescence (old age) or when subjected to stress or moisture shortage, the reverse is observed. This is because under these conditions, the chlorophyll breaks down which leads to a marked increase in reflectance in the red wavelength (Gibson & Power 2000; Lillesand & Kiefer 2001). This results in vegetation being seen as a yellow or brown colour. Also, the tissues of the leaves collapse, resulting in a remarkable decrease of near-infrared reflectance. This spectral response from satellite imagery has been applied to determine the growth stage, health condition and other parameters of vegetation.

Though different indices exist to model the amount of vegetation, the index most appropriate for use in a particular environment can be determined through calibration with sample measurements of vegetation vigor. Examples are Enhanced Vegetation Index (EVI), Ratio Vegetation Index (RVI) and Normalized Difference Vegetation Index (NDVI). Vegetation indices have been used to monitor seasonal and inter-annual variations in vegetation at local, regional and global scales. Each of these VIs is discussed below.

As mentioneded above, vegetation has a low reflectance in the red wavelength and high reflectance in the near infrared and the ratio of these reflectances can indicate the amount of vegetation vigor. The ratio vegetation index (RVI) is the simplest index, and it is computed as:

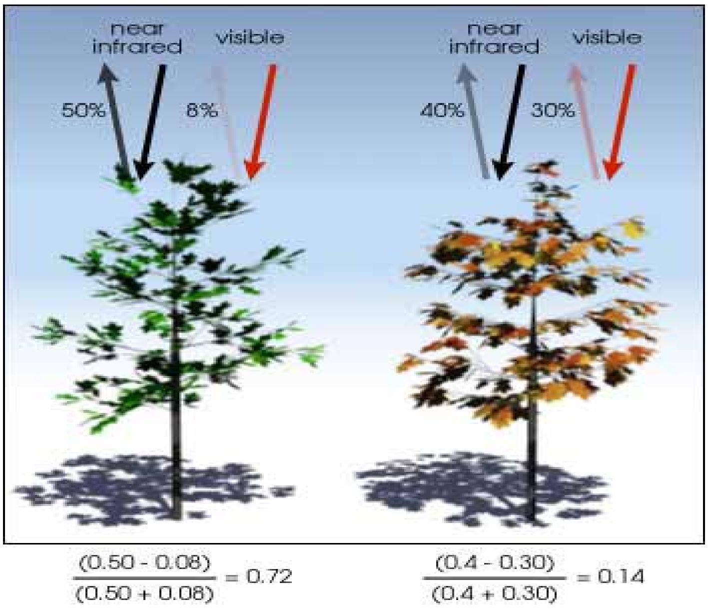
$\mathrm{RVI} = NIR/RED$

The index gives a value from zero (0) to infinity. A zero value represents no vegetation while infinity represents healthy vegetation. RVI can also be used to minimize the effect of differences in illumination due to topography.

One of the most widely used vegetation indices is the Normalized Difference Vegetation Index (NDVI). It is similar to the Ratio Vegetation Index but gives desirable statistical characteristics of various parameters associated with vegetation growth, type and ecosystem environment (Gibson & Power 2000). It is also computed from the combination of two spectral bands (i.e. the difference between the Near Infrared and Red bands) as:

$$\mathrm{NDVI} = NIR - RED \big/ NIR + RED$$

NDVI values vary from -1 to +1, where values near +1 indicate the presence of healthy vegetation and values near -1 indicate the absence of or low vegetation (see Figure 3.5).



Source: Earthobservatory website.

Figure 3.5 Relation of NDVI values to vegetation vigor.

Some of the NDVI data are prepared by satellite administration teams and are made available to the public. Notable among these is the AVHRR NDVI prepared by the NOAA satellite system for regional and global monitoring on a daily basis. The AVHRR instrument provides data at a spatial resolution of one to four kilometers (Campbell 2002). The preparation process involves selecting data based upon viewing geometry, solar illumination, sensor calibration and cloud cover, to prepare geometrically registered NDVI composites (Campbell 2000). Numerous studies have applied the NDVI to monitor vegetation dynamics (e.g. Maselli 2004; Jiang et al. 2006).

Like Ratio Vegetation Index, the NDVI has its disadvantages too. A main disadvantage of the NDVI is the inherent non-linearity of ratio-based indices and the problem in scaling ratios (Gibson & Power 2000). The NDVI also exhibits saturated signals over high biomass conditions and is very sensitive to atmosphere and canopy background variations. Over densely vegetated surfaces, the NDVI responds primarily to red reflectances and is relatively insensitive to NIR variations (Campbell 2002). NDVI data approach their maximum values at fractional vegetation covers between 80% and 90% (Jiang et al. 2006). This does not depict the real state of the vegetation, rather it underestimates the vegetation over high biomass areas.

Lastly, the EVI data is prepared by the MODIS Science team. It is called an Enhanced Vegetation Index since it corrects for some distortions in reflected light caused by particles in the air and ground cover, below the vegetation (Herring 1998). This makes it an improvement of the NDVI product. The EVI data product also does not become saturated as easily as the

NDVI (e.g. when viewing rainforests high biomass regions). Since it optimizes the vegetation signal with improved sensitivity in high biomass areas (Herring 1998), through a decoupling of the canopy background signal and a reduction in atmosphere influences (Gao et al. 2003), it can represent high biomass areas better.

The EVI is computed from the Blue, Red, and Near Infrared bands as:

$$\mathrm{EVI} = \mathrm{G} \;\; \mathrm{X} \; {NIR - RED} \Big/ {L + NIR + C1xRED - C2xBLUE}$$

where C1 and C2 = Atmosphere Resistances from Red and Blue Correction Coefficients respectively. G = Gain power. L = Canopy background brightness correction factor.
The coeficients adopted in the EVI algorithm are L = 1, C1 = 6, C2 = 7.5, and G = 2.5.

3.3.1 MEDIUM RESOLUTION IMAGERY

The potential of using medium resolution imagery, that provides data with a high temporal resolution, for monitoring vegetation dynamics at a regional scale will be explored. The Moderate Resolution Imaging Spectroradiometer (MODIS) on NASA's (National Aeronautics and Space Administration) Terra spacecraft (10:30 AM equator crossing time, descending) was launched 18 December, 1999. On 4 May, 2002, a similar instrument was launched on the EOS-Aqua satellite (1:30 PM equator crossing time, ascending) (Barnes et al. 1998). The MODIS instruments, on both the Terra and EOS-Aqua satellites, were designed to provide long-term observations of global dynamics and processes occurring on the surface of the Earth. Other instruments on the NASA EOS satellite include ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer), CERES (Clouds and the Earth's Radiant Energy System), MISR (Multi-angle Imaging Spectroradiometer) and MOPITT (Measurements of Pollution in the Troposphere).

MODIS is a whisk broom scanning imaging radiometer consisting of a cross-track scan mirror (Barnes et al. 1998). It provides images of daylight reflected solar illumination and day/night thermal emissions over all regions of the globe. It has one of the most comprehensive onboard calibration systems ever flown on a remote sensing instrument (Herring 1998). It operates continuously during the day (collecting data from all bands) and night (collecting only the thermal infrared bands).

With the atmospheric correction and radiometric properties of MODIS (Barnes et al. 1998; Zhang et al. 2003), it has greatly improved the measurement and monitoring of plant growth on both regional and global scales. Radiometric resolution refers to the number of digital levels (e.g. 8 bit, 16 bit) used to represent the data recorded by the sensor. MODIS, with its 36 bands, makes it a multispectral scanning instrument (See Table 3.1 and Appendix A). A multispectral scanning instrument registers reflectance in a number of spectral bands (up to tens) throughout the visible, near- to far- infrared electromagnetic spectrum. Though the spectral width of these bands are similar to the bands on the Landsat Thematic Mapper, the spatial resolutions are different (Barnes et al. 1998). While Landsat has spatial resolution of 30m, MODIS ranges from 250m to 1km (land application bands).

Table 3.1 MODIS specifications

Orbit	705km, 10:30 am descending mode or 1:30pm ascending mode
Swath width and length	2330km by 10km
Weight	250kg
Spectral bands	36
Area	10^0 by 10^0 lat/long
Spectral width	0.4 -14.4 µm
Spatial Resoulutions	250m (bands 1-2), 500m (bands 3-7), 1000m (bands 8-36)

Source: Barnes WL, Pagano TS, and Salomonson VV 1998, (pg 1089).

MODIS provides improved data for vegetation studies on a regional scale at a one- to- two day temporal resolution. This and other characteristics make MODIS data attractive for high temporal resolution monitoring. With the introduction of MODIS, studies on monitoring vegetation dynamics (Zhang et al. 2003; Sakamoto et al. 2005), mapping fire-affected areas (Roy et al. 2005), snow cover and surface temperature have been carried out in several parts of the world. MODIS has bands selected specifically for fire monitoring and is currently the only satellite providing systematic daily global active fire coverage (Rong-Rong et al. 2004).

Roy et al. (2005) developed a global algorithm for mapping fire-affected area The global algorithm was actually an improvement of their previous MODIS algorithm. In the previous MODIS algorithm, a bi-directional reflectance model, (i.e. change detection approach) was used to map 500m locations, and approximate day of burning in Southern Africa. The MODIS algorithm was improved to function for systematic global application which was illustrated for Southern African, Australian, South American and Boreal fire regimes. The four study regions were chosen to encompass tropical, sub-tropical, boreal, temperate and arid environments. The study regions also capture a range of the major factors influencing the accuracy of fire-affected area products derived from satellite data (e.g. spatial characteristics, degree of spectral change from unburnt to burnt vegetation). In this algorithm developed by Roy et al. (2005), MODIS bands that are sensitive and insensitive to biomass burning are used to detect changes due to fire and to differentiate them from other types of change, respectively. The global algorithm can map the location and approximate date of burning for fires obscured by cloud or thick smoke.

The launch of MODIS was an important milestone in moderate resolution remote sensing, providing a marked increase in observational capabilities. According to Justice and Townshend (2002), the investment in MODIS is starting to pay off through the generation of products for global change research, which are now being validated. Studies such as Doraiswamy et al. (2005) have evaluated the potential of the MODIS 250m data product for classication and a qualitative assessment of the MODIS-based classification was made by comparing it with the Landsat Thematic Mapper classification.

MODIS data are provided as Hierarchical Data Format-Earth Observing System (HDF-EOS) files in different levels. Levels 1 and 2 swath data must be projected by users to a projection of their choice, while Levels 3 and 4 grid data are already mapped to a Cylindrical Equiangle projection (Sedano et al. 2005). MODIS data are also available in raw daily images and processed composites for various applications. Like other vegetation data, MODIS NDVI and EVI are provided (as composite data) for monitor vegetation dynamics.

3.3.2 TIME SERIES ANALYSIS TECHNIQUES

A time series is an ordered sequence of observations made at regular intervals over a period of time (Prins 2005). Scientists are interested in using time series analyses so that they may analyse the probabilistic and structural inference about a sequence of data evolving over time (Wegman 1996). With an understanding of the underlying forces and structure that produced the observed data, the data can be fitted to a model for forecasting and monitoring purposes (Prins 2005).

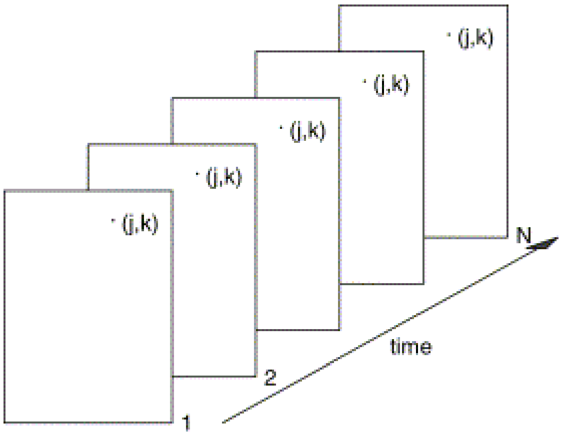


Figure 3.6 Time series of NDVI data

Time series of NDVI data can be used to gain information on seasonal variations of vegetation, since variations of NDVI values are closely related to vegetation phenology. Phenology is the study of the relationship between vegetation growth and the environment (Gibson & Power 2000). A common method for extracting seasonality parameters from time series of NDVI data is the application of thresholds. Here, values above specified thresholds denote the start of a season. Other methods include fitting NDVI data to a model. Examples of such models are Fourier Transforms, principal component analysis, wavelength filter (Sakamoto et al. 2005) and asymmetric Gaussian. It should be noted that each method is suitable for different situations.

For monitoring vegetation dynamics at high latitudes, Beck et al. (2006) have tested a method using a double logistic function, to see if it is more suitable than the approaches based on Fourier series or asymmetric Gaussian functions. Due to the short growing seasons at high latitudes, most algorithms cannot adequately model the vegetation phenology. The double logistic method applied to the MODIS NDVI revealed the growth- senescence cycle, such as the start, the peak and the end of a growing season. Apart from applying the double logistic model to the NDVI, the Fourier series (second order) and asymmetric Gaussian functions, as implemented on TIMESAT software (Jonsson & Eklundh 2004) were applied for comparison. The results showed the double logistic function described the NDVI data better than the Fourier series and slightly better than the asymmetric Gaussian. They concluded that the double logistic function or asymmetric Gaussian function would be appropriate for monitoring vegetation dynamics at high latitudes. Other methods cannot adequately model the short growing seasons associated with high latitude environments.

Also, Zhang et al. (2003) have characterized vegetation phenology by fitting MODIS EVI data to a logistic function. This was to identify the phenological transition for an area centered over

New England. The methodology they employed provided a flexible means of monitoring vegetation dynamics over large areas. Individual pixels were used without applying thresholds, therefore this can be applied to global scales. The methodology can also identify phenology characterized by multiple growth and senescence periods. However, no comparisons were made between ground observations and the remote sensing- based results.

Sakamoto et al. (2005) developed a new systematic method called the Wavelet based Filter for determining Crop Phenology (WFCP), for detecting phenological stages in rice paddies from time series MODIS EVI data. To reduce noise or fit the satellite data to a model, wavelet and Fourier transforms were used for comparison. Three types of wavelets were used: Order, Coiflet and Symlet. Though wavelet transform has been used for other studies, few studies have used it for transforming and detecting crop phenological stages. According to Samamoto et al. (2005), wavelet transform retains time components when transforming time series data, and can reproduce seasonal changes of vegetation without losing the temporal characteristics. They defined a wavelet as a small, localized wave in time or space that satisfies the orthogonal condition. Since a wavelet has compact support, which means that its value becomes zero outside a certain interval of time, the time components of time-series data can be maintained during wavelet transformation. Their results illustrated that there was no significant difference between using the wavelet and Fourier transforms in the heading and harvesting dates. The date of the maximum EVI in the time profile was defined as the estimated heading date. However, in determining the planting date, the wavelet performance was superior to that of the Fourier transform. Also, the method using wavelet transform (Coiflet) showed the best result compared to other types. As Beck et al (2006) noted, Fourier transforms do not give remarkable results for vegetation dynamics.

Although various remotely sensed time series data are available for monitoring vegetation seasons, only a limited number of software for exploring vegetation seasonal parameters from such data series have been developed. Jonsson & Eklundh (2002) have developed a FORTRAN90 program, TIMESAT, for extracting seasonal parameters. This program uses an adaptive Savitzky–Golay filtering method and, optionally, newly developed methods based on upper envelope weighted fits to harmonic and asymmetric Gaussian model functions. The program was tested with the 8 × 8 km pixel resolution Pathfinder AVHRR Land (PAL) data set generated by NOAA.

In the program, NDVI data are fitted to local nonlinear model functions to build global functions, which correctly describe the NDVI variation of full vegetational seasons. The method can be used on both daily and composite NDVI datasets. It can also work with other vegetation indices apart from NDVI. It makes use of algorithms to select set of maxima (highest NDVI values) and minima (lowest NDVI values) from smoothed NDVI values. In TIMESAT, seasonal parameters that can be extracted include start and end of seasons, number of seasons, peak of season, rate of increase and decrease of growth.

According to Jonsson & Eklundh (2004) the start of a season is defined from the global model function as the point in time for which the value has increased by a specified value, of the distance between the base level and the maximum, above the base level/minima (and vice versa for end of season). The rate of increase is determined as the speed of increase between the minimum and the maximum NDVI values. The rate of decrease is determined in a similar way. The amplitude is defined as the difference between the peak value and the average of the left and right minimum values. The length of the season is estimated to be the time over the growing season, i.e. the time between the start and the end of the season. The methods employed by TIMESAT makes it attractive for analyzing time series of NDVI data, as various vegetation parameters can be determined. The double logistic and asymmetric Gaussian functions have been used with great success in fitting NDVI data to models (e.g. Beck et al. 2006). Both functions represent the NDVI data as accurately as possible.

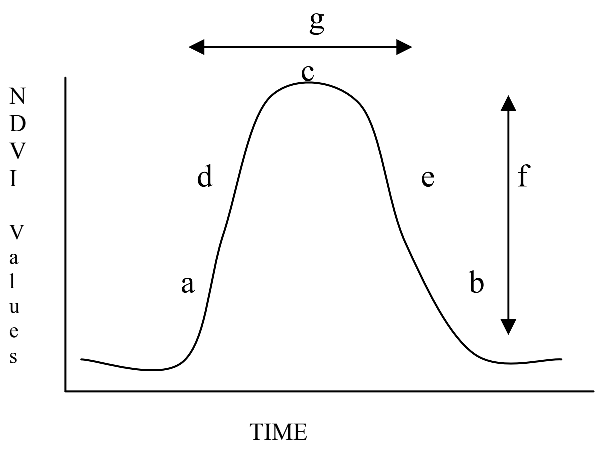


Figure 3.7 Seasonality parameters in TIMESAT.
Where a – Start of season, b - End of season, c - Peak of season, d - Rate of increase, e – Rate of decrease, f – Amplitude , and g - Length of season.

CHAPTER 4: DATA ANALYSIS AND RESULTS

The methodology and the results of monitoring the re-growth of the alien vegetation will be discussed in this chapter. The results include the extent of the alien vegetation before and after the fire, and the re-growth rate. The extent of vegetation before the fire was determined from the vegetation map compiled by the Agricultural Research Council (ARC), while the re-growth rate was determined from the acquired satellite data. The re-growth rate on different soil types was also determined for comparison.

4.1 METHODOLOGY

For the purpose of monitoring the re-growth rate of vegetation in this study, it was necessary to fit the NDVI time series data to a model. Literature has shown that vegetation parameters of NDVI values can better be analyzed using asymetric Gaussian or Double Logistic functions (Zhang et al. 2003; Beck et al. 2006). These functions have been incorporated into the TIMESAT software (Jonsson & Eklundh 2004) and was employed for this study. The methodology is outlined below:

- Acquire satellite NDVI data products.
- Identify pixels representing each vegetation type.
- Time series analysis of NDVI values on a per pixel basis.
- Extract phenological parameters such as the growth-rate, by fitting time series data to models such as Double logistics, asymmetric Gaussians, Savitzky-Golay (Jonsson & Eklundh 2002).
- Analyze results of phenological parameters.
- Test the significance of the results.

Twenty three MODIS NDVI products from August 2005 to August 2006 were obtained (See Appendix A for information on MODIS products). The fire occurred in February 2006, therefore the re-growth rate of alien vegetation was determined over six months. The 2005 products were included to complete the full season. This was necessary to complete the time series data for a year of observations so that the seasonal variation of the vegetation may be highlighted. The MODIS 16-day NDVI composite was chosen over the daily data, for several reasons discussed below.

The daily data contain cloud effects and noise, while the composite product (MOD13Q1) has been corrected for molecular scattering, ozone absorption and aerosols (Huete et al. 2002). The composite products are derived from the daily datasets. During the compositing process, effects of clouds are filtered and the highest NDVI values from the daily dataset are selected (Campbell 2002). This is unlike the Landsat 16-day data, which is obtained once in 16 days and may therefore be cloud contaminated. In other words, cloud contamination is removed from MODIS NDVI products during the compositing process, which is not the case with Landsat data. Also, in a recent research by Van Leeuwen et al. (2006), the quality of NDVI values from high temporal sensors were evaluated. They found that the MODIS NDVI data are minimally affected by the atmospheric water vapour, while AVHRR NDVI data are substantially reduced by water vapour.

Other data acquired include:

- Vegetation map of Agulhas Plain (Compiled by ARC for Agulhas Plain Cape Action Program for the Environment project).
- Fire-scar map of 2006 (Compiled by ARC).
- Soil map of Agulhas plain (Department of Geography and Environmental Studies GIS server, University of Stellenbosch).

The MODIS product of February 2006 is shown in a false colour RGB (Red Green Blue) bands composite, below. The near infrared, red, and blue bands (NIR/Red/Blue) are displayed according to the RGB composite. The fire- affected area (black outline – see Figure 4.1) and the extent of the study area (white outline), are also shown. Vegetation is represented by the red colour in the composite. Sparse vegetation can be seen within the fire affected area, showing the part of the vegetation that was not burned by the fire. However, dense vegetation can be seen in the fire-affected area in the MODIS imagery of August 2006 (Figure 4.2), representing the re-growth of vegetation within six months after the fire.

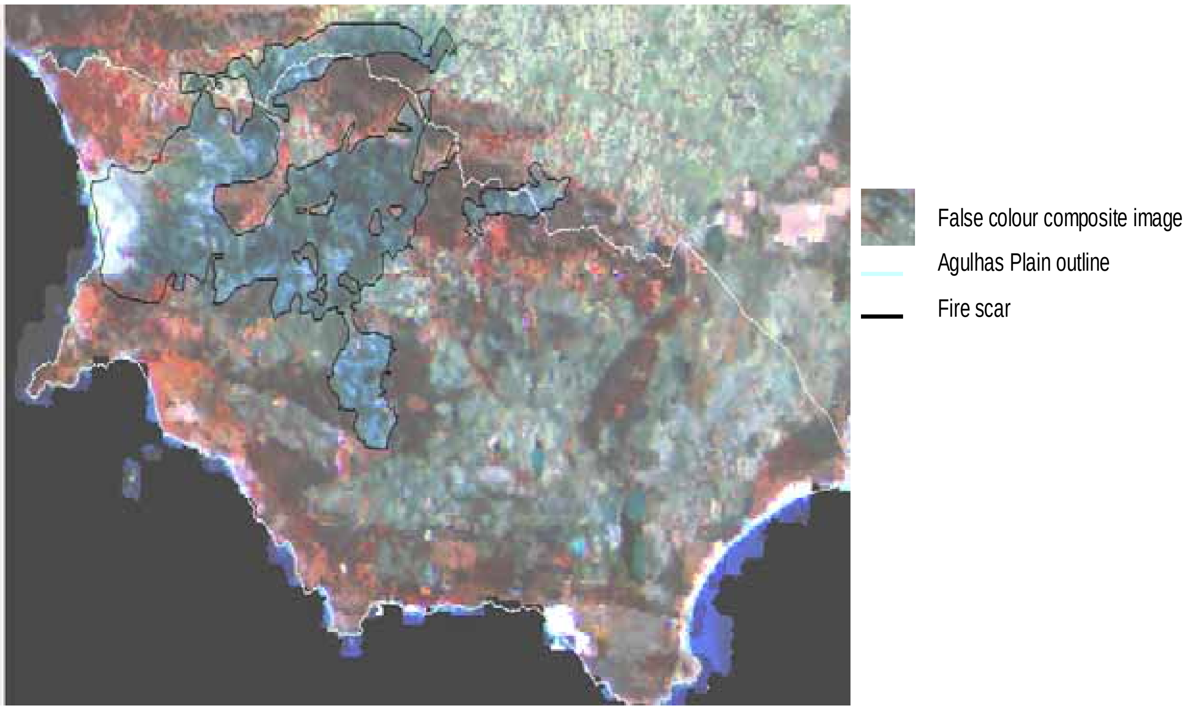


Figure 4.1 Agulhas Plain MODIS data of 2 – 17 February, 2006

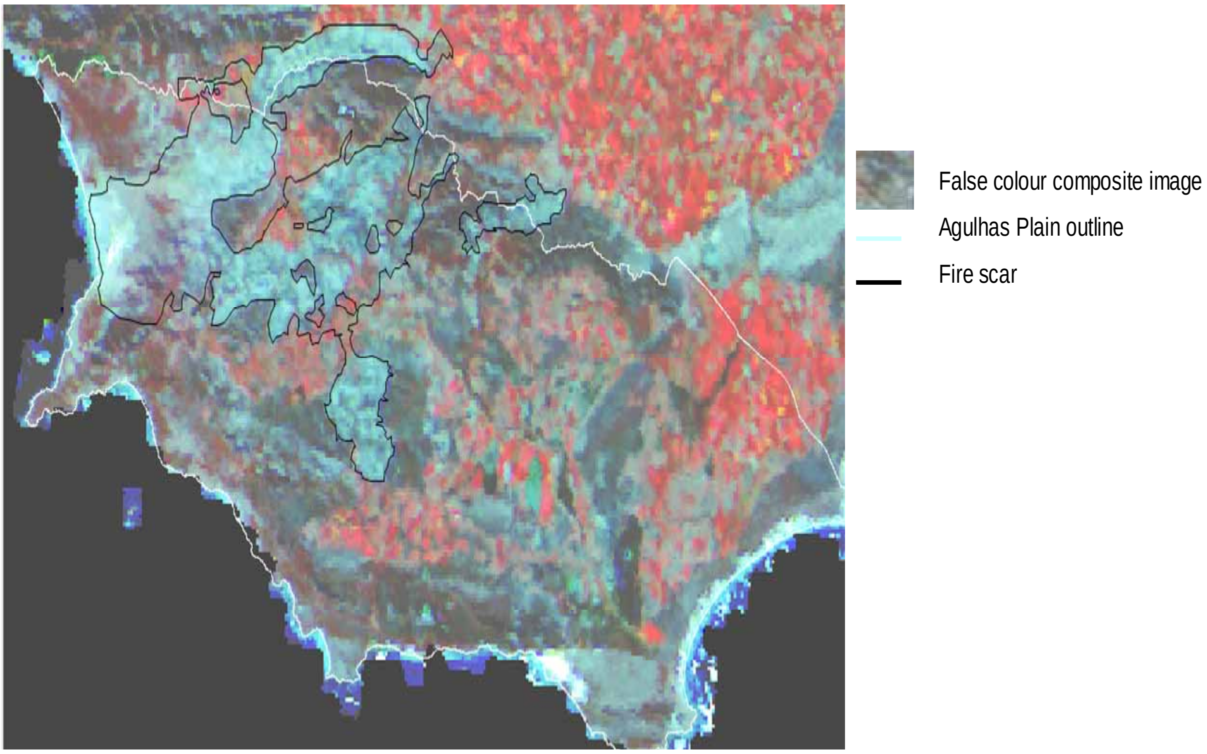


Figure 4.2 Agulhas Plain MODIS data of 13 – 28 August, 2006

Though the EVI data minimizes much of the contamination problems present in the NDVI, such as those associated with canopy background, the NDVI data was sufficient for monitoring alien vegetation at the scale in this study since the high biomass or canopy is not common within the fynbos biome.

MODIS products are provided in HDF format and were converted using the MODIS Reprojecting Tool (available from http://lpdaac.usgs.gov/landdaac/tools/modis/index.asp) to GEOTIFF format that is compatible with many commercial types of software. The MODIS products were clipped to the extent of the study area (See Appendix B for download, conversion and reprojection information). The MODIS NDVI values in 16-bit signed integer (-2000 to 10000) were converted to NDVI ratios (-1 to +1). This was achieved by dividing the values by a scale factor of 10,000. The vector data (vegetation, fire scar and soils) obtained were also projected to the Transverse Mecator and assigned the World Geodatic System 1984 (WGS 1984) datum.

The vegetation map was used to identify the vegetation types in the image. A field trip to the study area was made to validate the data. Areas having at least 70-80% of fynbos or alien vegetation were each identified during the field survey and their geographical coordinates recorded with the aid of the Global Positioning System (GPS). Selecting areas dominated by a single vegetation type was important so as to avoid working with mixed pixels in the data as much as possible. Mixed pixels are pixels representing more than one land cover type. The field trip was made in the first week of September, 2006, in order to get a true picture of the vegetation as shown on the data. This was a week after the date of the last composite in August was obtained (13th to28th August, 2006). Samples of sites visited and selected are shown below for each vegetation types:

Figure 4.3 Burnt alien vegetation

Figure 4.4 Burnt fynbos

Figure 4.5 Unburnt alien vegetation

Figure 4.6 Unburnt fynbos

The researcher was accompanied by a professor of plant ecology , a remote sensing researcher and the supervisor, who all contributed to the effort of selecting the right areas for each plant types. Hereafter, pixels representing the GPS coordinates were identified on the MODIS product. NDVI values of 5-6 pixels representing alien vegetation were averaged for; (a) burnt area, and (b) unburnt area. Time-series of NDVI values were derived for the average burnt and unburnt alien vegetation using the 23 MODIS 16-day composites. The process was repeated for pixels representing (c) burnt and (d) unburnt fynbos vegetation. The time series NDVI values (of classes a-d) were analyzed in the TIMESAT software. (see appendix C for time series of NDVI values for a, b, c, and d). The time series NDVI values were converted to an ascii file for input to TIMESAT software for analysis.

In addition, the influence of soil types on the re-growth rate of fynbos and alien vegetation was considered. This was necessary to determine the effects of the soil types on the re-growth rate. The two dominant types of soils within the fire- affected areas are grey and glenrosa soils. Pixels were selected on each soil type and a time-series of NDVI values of burnt alien vegetation on grey and glenrosa soils were derived. The same process was applied for burnt fynbos on Namib and Glenrosa soils (see appendix C for time-series of NDVI values for e, f, g, and h).

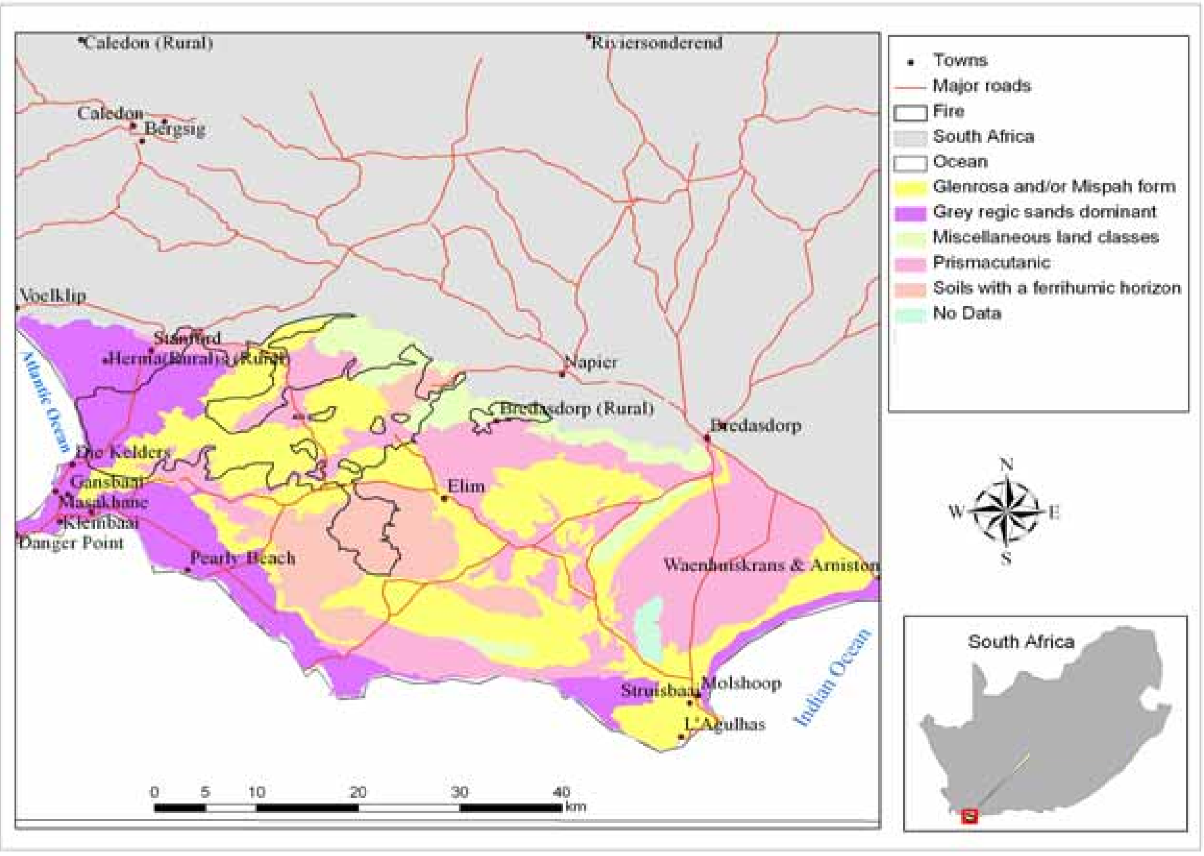


Figure 4.7 Soils of Agulhas Plain.

The grey soils are subdivided into two categories: grey regic sands dominant, grey regic sands and other soils, all of which are found along the coastal areas. The grey regic sands (Namib) dominant are mainly coastal sands with shell materials, dunes and blown sands of the Strandveld formation, Bredasdorp Group. The grey regic sands and other soils consist of aerolite (partly calcareous) of the Waenhuiskrans formation, Bredasdorp Group. These soils are covered by the sands of the Strandveld formation. They are also covered by colluvial sands on midslopes and alluvial in the lower areas. The alien vegetation dominant on this soil type is *Acacia cyclops* (Cowling & Richardson 1995).

On the other hand, Glenrosa soils (Glenrosa and/or Mispah forms) are mainly found inland. Lime may be generally present or rare and absent in the entire landscape depending on the location. They contain quartzitic sandstones of the Peninsula formation, Table Mountain group in the north and south-western side, mudstone, siltstone, shale and feldspathic sandstone of the Gydo formation. The alien vegetation dominating this soil type includes *Pinus pinata, Hakea gibbosa,* and the *Acacia* species *(A. saligna* and *A. cyclops).*

4.2 RESULTS

The results obtained from the analysis are presented according to the aim and objectives set for the study. The re-growth rates of indigenous and alien vegetation as determined from MODIS products were also tested statistically for significant difference. The values used for the analysis in the TIMESAT software is presented in Appendix D. The time-series of NDVI values fitted to all the functions is presented below.

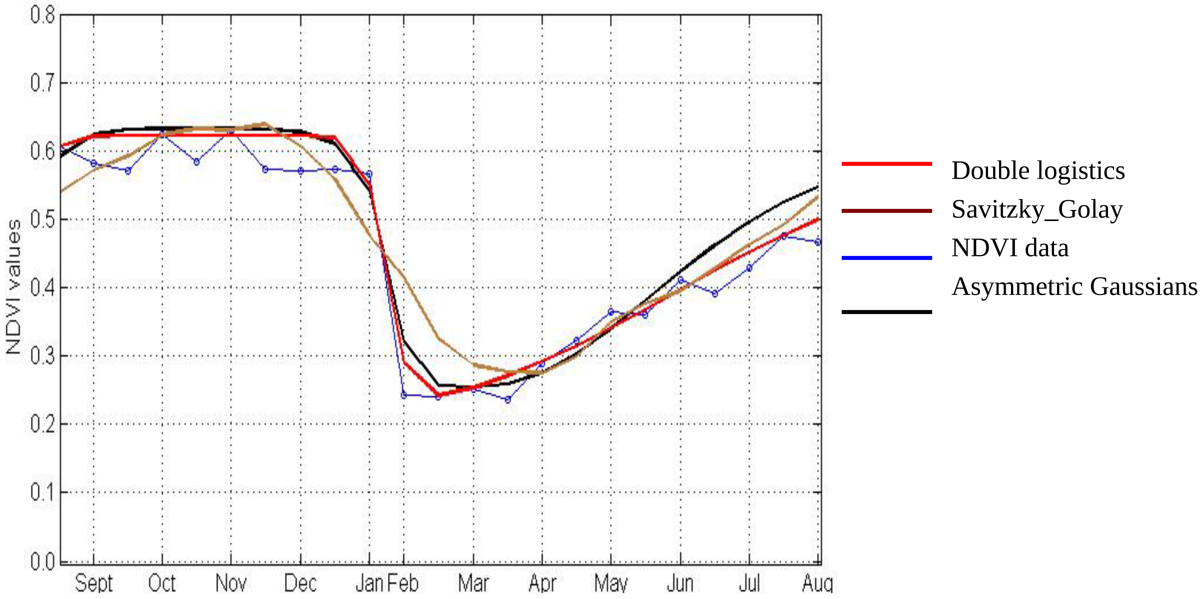


Figure 4.8 Time series of NDVI data fitted to all functions for the period of August 2006.

Brown represents Savitzky-Golay, black represents Asymmetric Gaussians, red represents double logistics and blue the NDVI data. Though the time- series of NDVI values were fitted to three functions, to derive the results, only the double logistics function will be used in other figures. This is because the double logistics represents the NDVI data more accurately. The Savitzky-Golay and Asymmetric Gaussians do not truly represent the sharp reduction in NDVI values in February. On the other hand, the double logistics function represent the variation in the NDVI values across the months more accurately.

The phenology was also derived from the analysis, to have an understanding of the seasonal variations in fynbos.

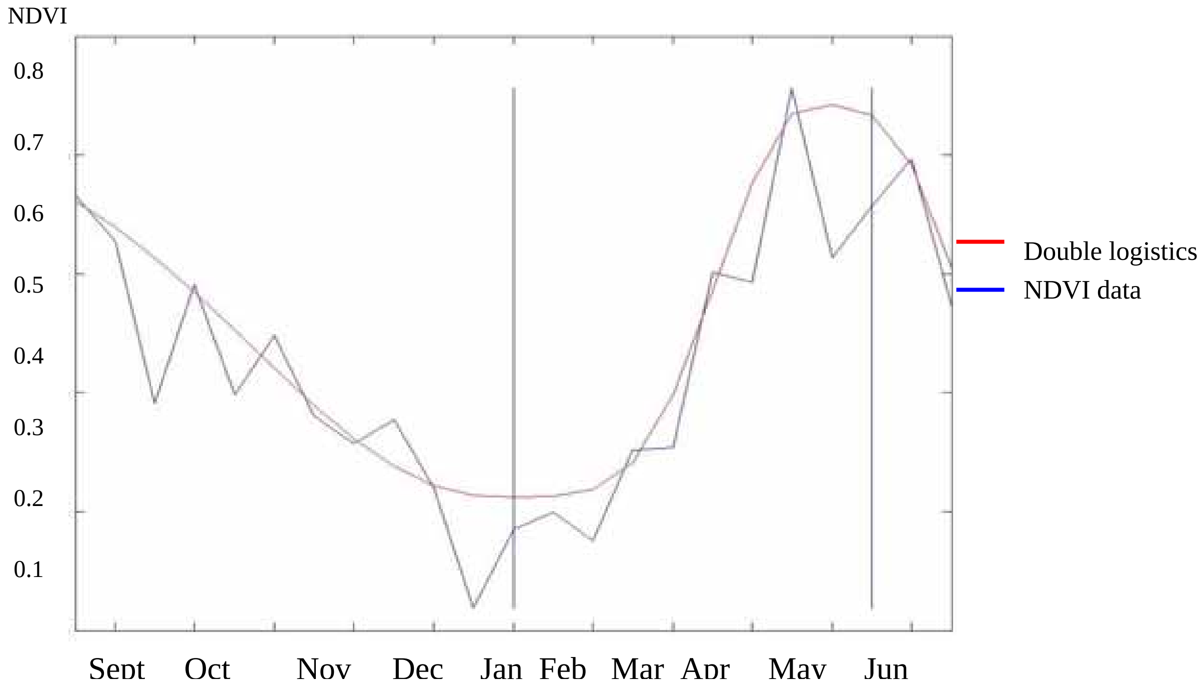


Figure 4.9 Phenology of fynbos

From above, the y-axis represents the values of vegetation vigor while the x-axis represents the acquired bi-monthly products. As mentioned earlier, the start of season is defined by the point at which the values have increased by a specified percentage (20% increase as specified in this analysis) This (20% increase) is also the normal specification in TIMESAT. Therefore, the start of season for fynbos is represented as the increase after the first vertical line in March in Figure 4.9, which is the beginning of South African autumn months (March – May). The peak of the season is represented by the second vertical line in July, which is the middle of winter (June – August). Fynbos reaches its peak during the winter, as a result of the associated heavy rainfalls.

This phenology of fynbos as derived from the TIMESAT analysis of NDVI values, confirms the literature on fynbos Mediterranean climate of winter rainfall and summer droughts (Cowling 1992; Cowling & Richardson 1995). At the start of season in autumn, fynbos begins to sprout, and reaches it peak during the heavy winter rainfalls. At spring (September – November), there is a slight reduction as flowers are beginning to bud and a pronounced reduction with the onset of summer drought months (December – February).

In extracting vegetation parameters (e.g. growth rate) from the analysis, Figure 4.10 (A) shows the normal model of time-series to be expected. However, the time-series analyzed in this study began from the peak NDVI (winter 2005) and ends at peak NDVI (winter 2006), the model in Figure 4.2.1(B) was derived, as explained above.

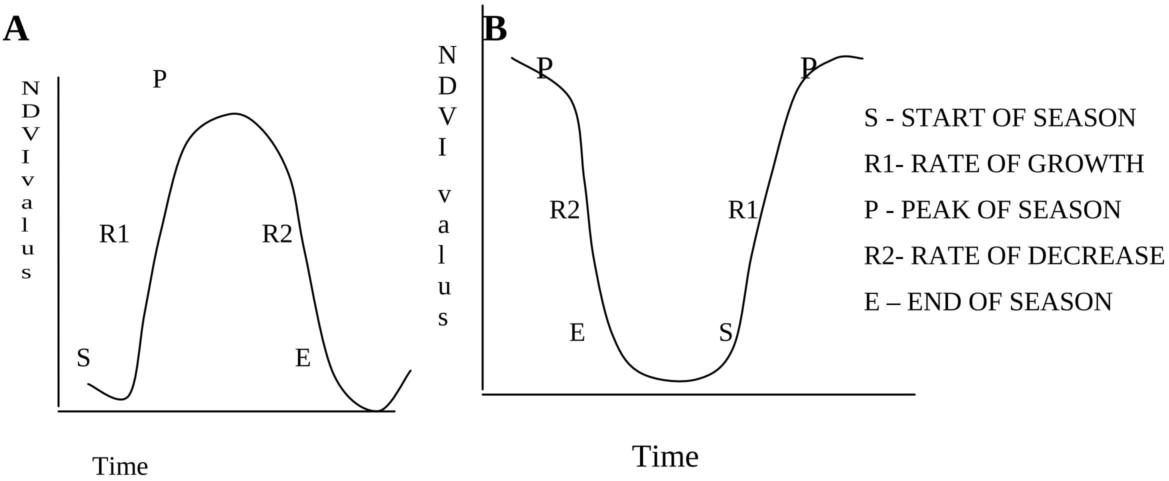


Figure 4.10 Model of time-series NDVI values.

4.2.1 Distribution of alien vegetation before fire

The distribution of alien vegetation before the fire was obtained from the vegetation map of the ARC (see Figure 4.11). Though alien vegetation has been recorded in each of the polygons represented in the map, it may not cover the whole polygon as shown on the map. Alien vegetation can either densely or sparsely occupy the area, but the presence of alien vegetation is recorded in each case. The total area covered by alien vegetation on the Agulhas Plain is estimated to be 1437km^2. It is about 66.5% of the total land surface of the study area. During the fire, an estimated land area of 528km^2 occupied by alien vegetation was affected by the fire. A summary is given below.

Table 4.1 Extent of alien vegetation before and during the fire.

		ESTIMATED TOTAL	
		BEFORE FIRE	AFFECTED BY FIRE
1	Alien vegetation	1437km^2 (66.52%)	528km^2 (24.44%)

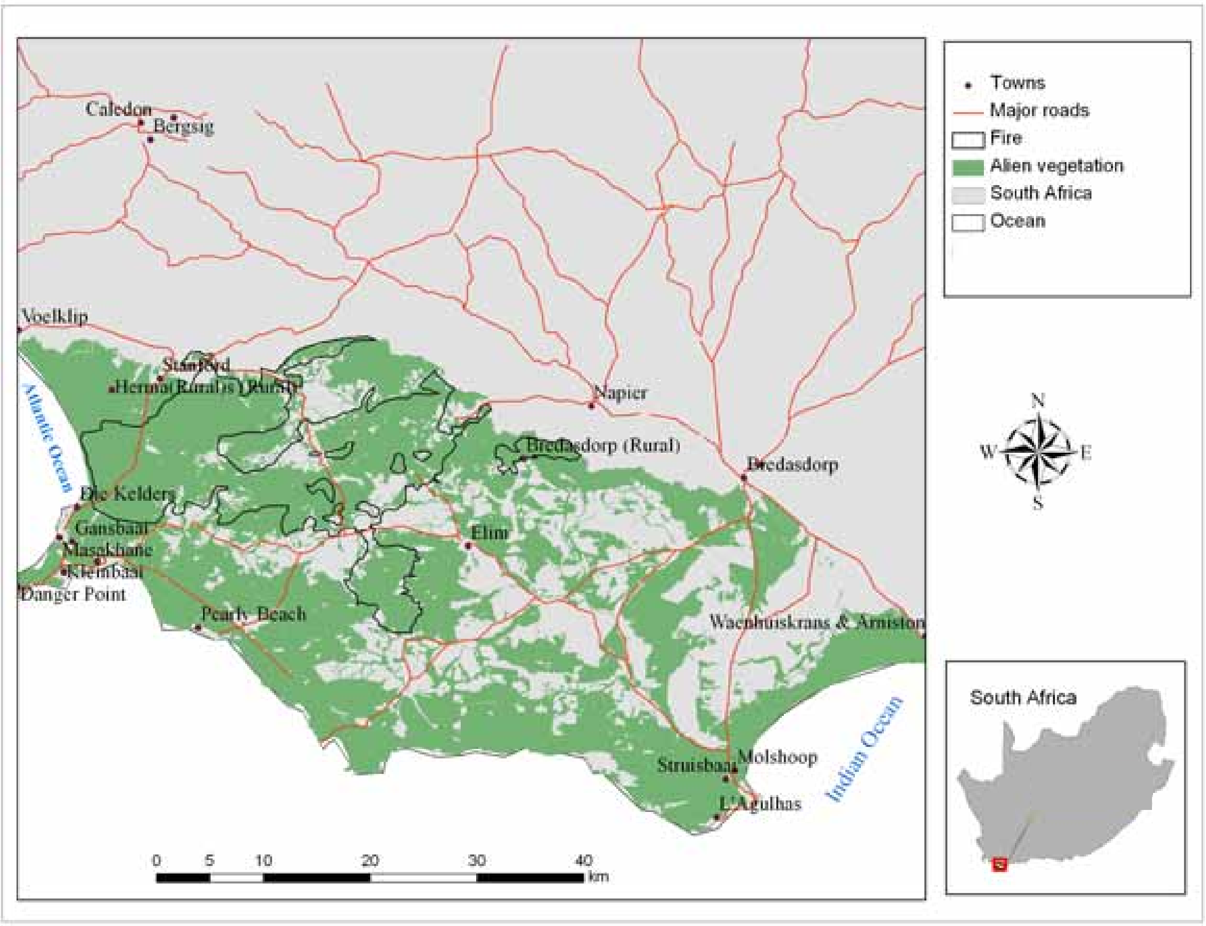


Figure 4.11 Distribution of alien vegetation before the fire in February 2006

4.2.2 Re-growth rate of alien vegetation

The re-growth rate of alien vegetation after fire was determined using time series of NDVI values from pixels representing alien vegetation. According to Jonsson & Eklundh (2004) the rate of growth (or biomass increase) can be determined by calculating the ratio of amplitude over time difference between the start and peak of season. In practical terms, this is the same as calculating the slope of the growth curve between the highest and lowest values. The time difference is estimated to be from the start of the season (March in this data provide exact dates of the composites) to the peak of the season (early August), i.e. five months.

Slope of the growth curve= $^{Amplitude}\!\big/_{Time}$

Where Amplitude is the difference between highest and lowest NDVI values, and Time is the difference from start to peak of season.

Also, to be able to determine the growth rate over the months after fire, it was necessary to substract the NDVI values at the start of the season (and consequent months) from the minimal value. The result was then divided by the maxima of the previous season. It was necessary to include the previous maxima so as to compare with the level of growth of the previous year (2005). The computation is shown below as:

$$\text{Growth rate} = {}^{Increase}\!/_{Maxima} \quad \text{X } 100$$

Where Increase is the change over time from the base value, and Maxima is the peak of NDVI values previous year). Therefore, the slope of the re-growth curve was determined and the re-growth rate over the months after fire was also considered.

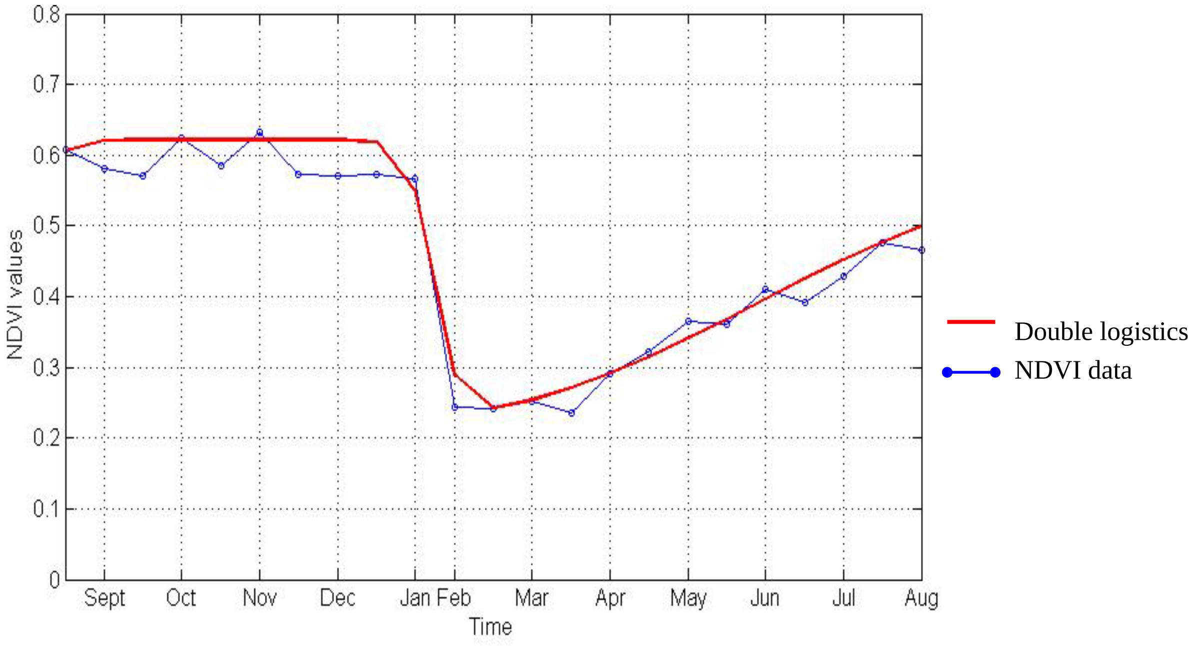


Figure 4.12a Re-growth of burnt alien vegetation

From December there was a reduction in the NDVI values due to the end of fynbos growth season in the summer drought months. A gradual reduction was expected from December to February as shown in the previous section. A sharp reduction in values was however seen in February, which denotes the fire occurence on the Agulhas Plain. As expected, with the loss of green vegetation (the collapse of chlorophyll pigments in leaves), the NDVI values reduce drastically. By April, the re-growth rate of alien vegetation was eight percent (8%) (see Table 4.2). Four months after the fire in June, the alien vegetation has started to grow by 25.6% of the previous vegetation (peak before the fire). There was also a noticeable increase in the growth rate during the winter months. The maxima and minima NDVI values are 0.625 and 0.24 respectively from the Double logistic model (red line).

Table 4.2 Re-growth rates of burnt alien vegetation

	MONTHS	VALUE FROM MINIMA	DIFFERENCE FROM MINIMA (0.24)	RATE: DIFF/MAXIMA (0.625)	% GROWTH RATE (CUMULUTIVE)
1	March	0.25	0.01	0.016	1.6
2	April	0.29	0.05	0.08	8
3	May	0.34	0.1	0.16	16
4	June	0.4	0.16	0.256	25.6
5	July	0.45	0.21	0.336	33.6
6	August	0.5	0.26	0.416	41.6

In order to determine if alien plants grow faster and spread more after a fire occurrence than in its absence, a comparison was made with the growth rate of alien vegetations that were not affected by the fire. The results from the TIMESAT analysis is shown below:

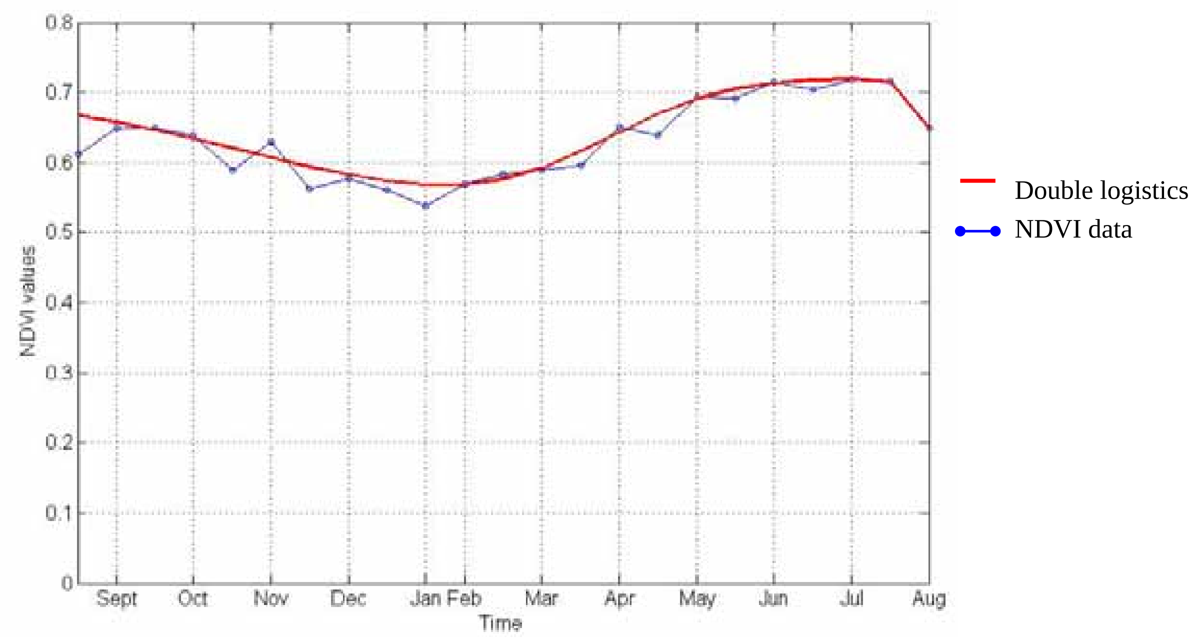


Figure 4.12b Growth of unburnt alien vegetation.

A slight reduction was seen in the NDVI values for the unburnt alien vegetation from September to December, (as observed in the burnt alien vegetation, above). However, the values remain low throughout the summer months. There was no sharp reduction in the absence of fire (as experienced by burnt alien vegetation). The maxima and minima NDVI values were considered as 0.67 and 0.57 respectively. The growth rate for the months are computed as shown below in comparison to the re-growth rate of burnt alien vegetation derived earlier.

Table 4.3 Comparison between the growth rates of unburnt and burnt alien vegetation.

N	MONTHS (TIME)	VALUE FROM MINIMA	DIFFERENCE FROM MINIMA (0.57)	RATE: DIFF/MAXIMA (0.67)	UNBURNT RATE	BURNT RATE
1	March	0.59	0.02	0.030	2.99	1.6
2	April	0.64	0.07	0.104	10.45	8
3	May	0.69	0.12	0.179	17.91	16
4	June	0.71	0.14	0.209	20.90	25.6
5	July	0.72	0.15	0.224	22.39	33.6
6	August	0.65	0.08	0.119	11.94	41.6

Although the re-growth rate of burnt alien vegetation was very low (8-16) within three months after the fire, there was a remarkable increase towards the end of winter (25.6 - 41.6) which could be attributed to the heavy rainfalls and open space to spread (less competition from other plant types). On the other hand, the growth rate of the unburnt alien vegetation was low throughout the months. The reduction seen in August may be due to clearing of alien vegetation at some sites. The germination of new plants after the fire contributed to the increase in the high re-growth rate of the alien vegetation, as opposed to the growth of vegetation that was not affected by the fire.

The slope of the re-growth curve was also determined for both burnt and unburnt alien vegetation. This was determined by the ratio of the amplitude to the time difference as shown in Table 4.4. The slope of the burnt vegetation was steeper than that of the unburnt alien vegetation confirming that the burnt alien vegetation grows faster than the unburnt alien vegetation.

Table 4.4 Comparison between the slopes of growth curves of unburnt and burnt alien vegetation.

	Start of season	Mid of season	Amplitude	Time difference (months)	Slope
Burnt	0.25	0.475	0.225	5	0.045
Unburnt	0.594	0.716	0.122	5	0.0244

From the comparisons above, it was not enough to determine the re-growth rates from the two methods. The aim of this study was to test the capability of the improved 250m spatial resolution of MODIS data to distinguish between indigenous and alien vegetation, and to be used for monitoring the re-growth rate after fire. Therefore, it was necessary to statistically test if the there was a significant difference between the re-growth rate as determined from the 250m spatial resolution of MODIS data or not.

Using the NDVI values of the burnt and unburnt alien vegetation, a T-test was computed (see Appendix F for results of T-test computation). The T-test assesses whether the means of two groups are statistically different from each other (Trochim 2006). From the result, the probability that the re-growth rate determined was by chance is 0.0002, showing that there was a significant difference between the NDVI values of burnt alien vegetation and the unburnt alien vegetation, as selected from the MODIS data. The calculated t-value was 9.3365 while the 95% (P<0<0.05) confidence interval for the mean was -0.3762 to -0.2138. Another T-test was also computed to compare the fynbos and the alien vegetation at a later stage.

Furthermore, a comparison was made between the growth rates of unburnt and burnt fynbos. The graphs are shown below and the comparison summarised in Table 4.5. The process of computing the growth rate is the same as specified earlier. A comprehensive calculation of each growth rate is shown in appendix E.

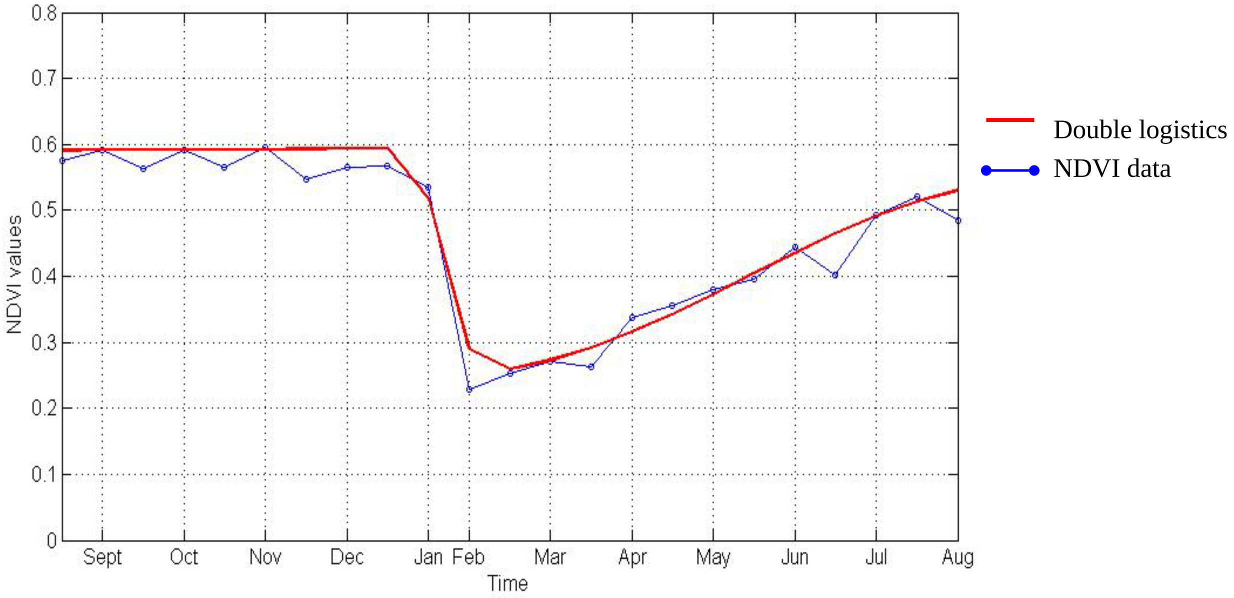


Figure 4.12c Re-growth of burnt fynbos

Table 4.5 Comparison between the growth rates of unburnt and burnt fynbos

	MONTHS	% INCREASE (CUMULATIVE)	
		Unburnt fynbos	Burnt fynbos
1	March	0.00	2.54
2	April	3.48	10.17
3	May	17.39	19.49
4	June	26.78	30.51
5	July	28.52	38.98
6	August	27.65	45.76

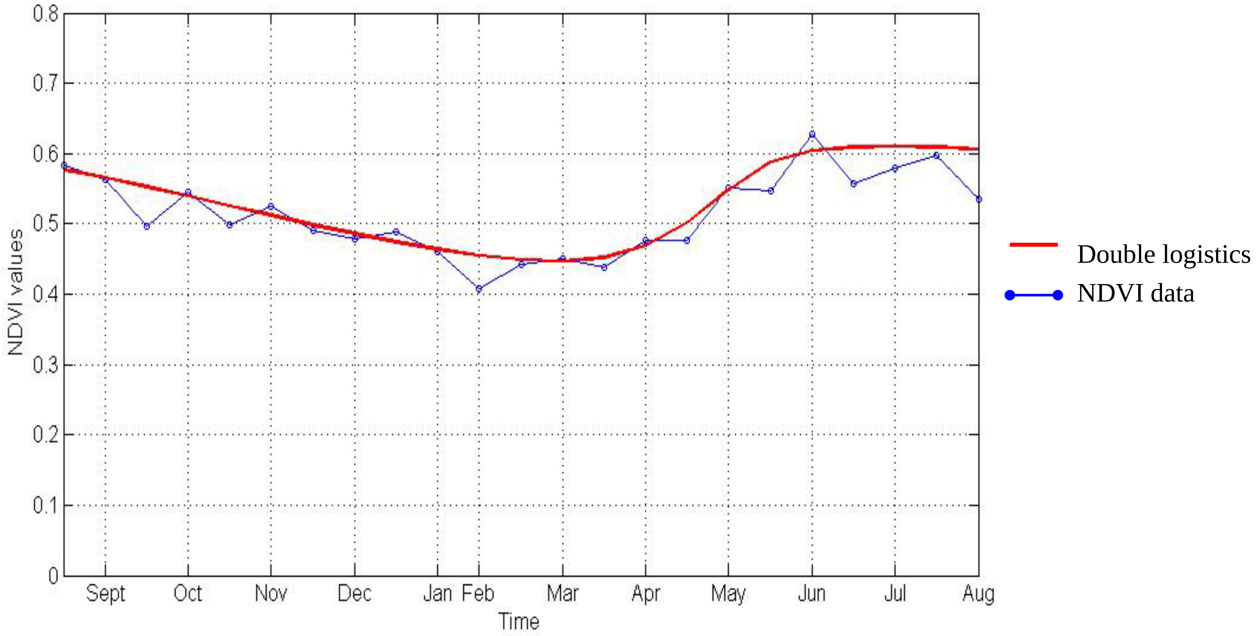


Figure 4.12d Growth of unburnt fynbos

Like the burnt alien vegetation, burnt fynbos is growing faster than unburnt fynbos. This may be attributed to the fact that plants germinate and grow faster at the initial stage. The slopes of the re-growth curve of the NDVI values of both burnt and unburnt fynbos were also obtained for comparison. The slope of the burned fynbos was steeper than that of the unburnt fynbos.

Table 4.6 Comparison between the slopes of growth curves of unburnt and burnt fynbos

	Start of season	Mid of season	Amplitude	Time diffirence (months)	Slope
Burned Fynbos	0.274	0.534	0.26	5	0.052
Unburnt Fynbos	0.45	0.61	0.16	5	0.032

Furthermore, a T-test was also calculated to determine if there was any significant difference in the NDVI values of burnt and unburnt fynbos as slected from the MODIS product. The probability value is also 0.000. This showed that there was a significant difference between the NDVI values selected for both burnt and unburnt fynbos from the MODIS data product. The calculated t-value was 9.4723 while the 95% confidence interval for mean was from -0.18371 to -0.10529. From the above tests (i.e. T-test for burnt and unburnt alien vegetation, and burnt and unburnt fynbos vegetation) it can be observed that there were significant differences between the two results.

It was also necessary to test the re-growth rates obtained from both burnt fynbos and alien vegetation for significant differences. The tables above refer to the re-growth rates obtained from the burnt fynbos and alien vegetation. The probability value was 0.0038, which also showed that there was a significant difference in the re-growth rates obtained for both vegetation types. The calculated t-value was 5.085 while the 95% confidence interval was from -0.2819 to -1.7348. Thus, MODIS can be used to distinguish between plant communities.

4.2.3 Distribution of alien vegetation after fire

The distribution of alien vegetation after the fire was determined from the results from the re-growth rate. Most alien plants which are densely distributed over the landscape could still grow to dominate such areas if left uncontrolled for a long time. As alien vegetation tends to grow at a much faster rate after a fire than in the absence of it (as seen in the previous section), it is expected that it will cover the area as before the fire over a period of time. The lack of control measures (such as manual clearing, introduction of chemicals) permits the rapid spread of alien vegetations. Also, the open spaces created by the fire are breeding grounds for germination of seeds dispersed by wind or other agents.

However, for areas where both fynbos and alien vegetation co-exist, there is much competition in the distribution after the fire. Though this study has shown that fynbos tends to initially grow faster than the alien vegetation (at least within the first 6 months) after fire, such areas are expected to be showing more re-growth of fynbos with few alien plants scattered within it. This may not be the case in consequent months as there is the possibility that the alien vegetation, if not properly controlled, can subdue the growing fynbos and dominate the area eventually. The picture below shows an area dominated by burnt fynbos and much re-growth of fynbos, with less (very rare) alien vegetation growing in the area.

Figure 4.13 Distribution of fynbos after fire

The conceptual model of Higgins & Richardson (1996) of alien plant spread that suggested the use of the *demographic processes* to determine the output component (i.e. *alien abundance*) could be applied to determine the distribution. Alien abundance, according to them, is determined by the interaction between *autecological attributes* (life history or eco-physiological attributes) and *environmental resource fluctuations*. Both the biotic and abiotic properties of a target area (habitat) are as important as the autecological attributes of the invading species (vegetation in this case). Environmental resource fluctuation can be in two forms: resource availability and disturbance. The successful plant-environment interaction leads to alien abundance. The fynbos biome possesses the resources (such as nutrients, moisture and space) and disturbance (fire) that match the life history or ecophysiological attributes of the alien vegetation. The successful invasion (alien abundance) of alien vegetation within the fynbos biome can be attributed to the successful plant-environment interaction.

Holmes et al. (2000) considered the recovery of fynbos after invasion by dense stands of alien trees and clearing through fire burning in the Western Cape, South Africa. A comparison was made in the fynbos plant density, cover, functional and biological guilds and species richness, after fire at both invaded and controlled sites. Sample data were collected at a 18 months post-fire invaded site, and a 13 years post fire controlled site. The data were analysed using one way ANOVA (Analysis of Variance). Their results showed that species' richness and fynbos plant density were lower for invaded sites compared to those sites that were controlled.

A change in the distribution pattern of the vegetation after fire could not be concluded to be true as it could not be determined in this study due to time constraints. Field surveys of the area in consequent months would be necessary to accurately describe the post fire distribution

4.2.4 Influence of soils on re-growth rate of vegetation

Working on a per pixel basis as used in this study makes the method applicable to other areas of interest. NDVI values of both indigenous and alien vegetation can be selected on a per pixel basis for various criteria, such as soils and geology. The re-growth rates of burnt alien vegetation on both grey sands and Glenrosa soils were compared to determine if the soils contribute to their re-growth after fire as shown in Figure4.14a and Table 4.7. The graphs derived from the analysis and comparison of the results are shown below.

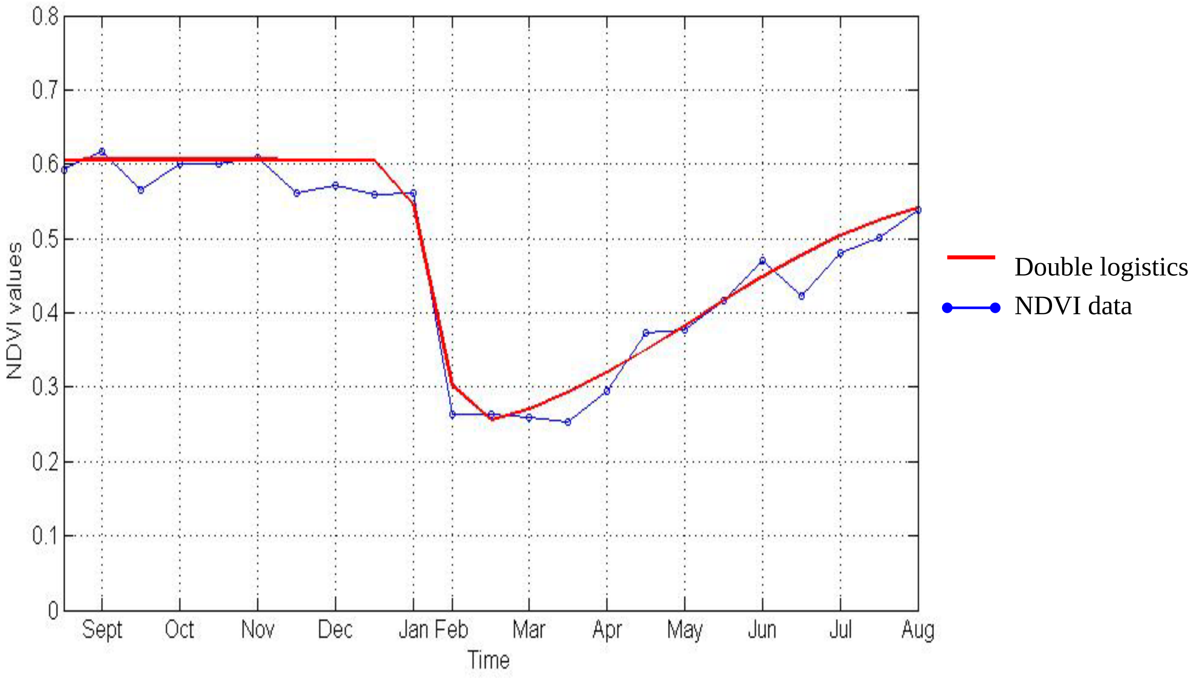


Figure 4.14a Re-growth of burnt alien vegetation on grey sandy soils.

Table 4.7 Comparison between the re-growth rates of burnt alien vegetation on grey and glenrosa soils.

	MONTHS	% INCREASE (CUMULATIVE)	
		Namib soils	Glenrosa soils
1	March	2.46	1.67
2	April	9.84	7.83
3	May	20.33	16.67
4	June	31.15	25.00
5	July	39.34	35.00
6	August	45.90	43.33

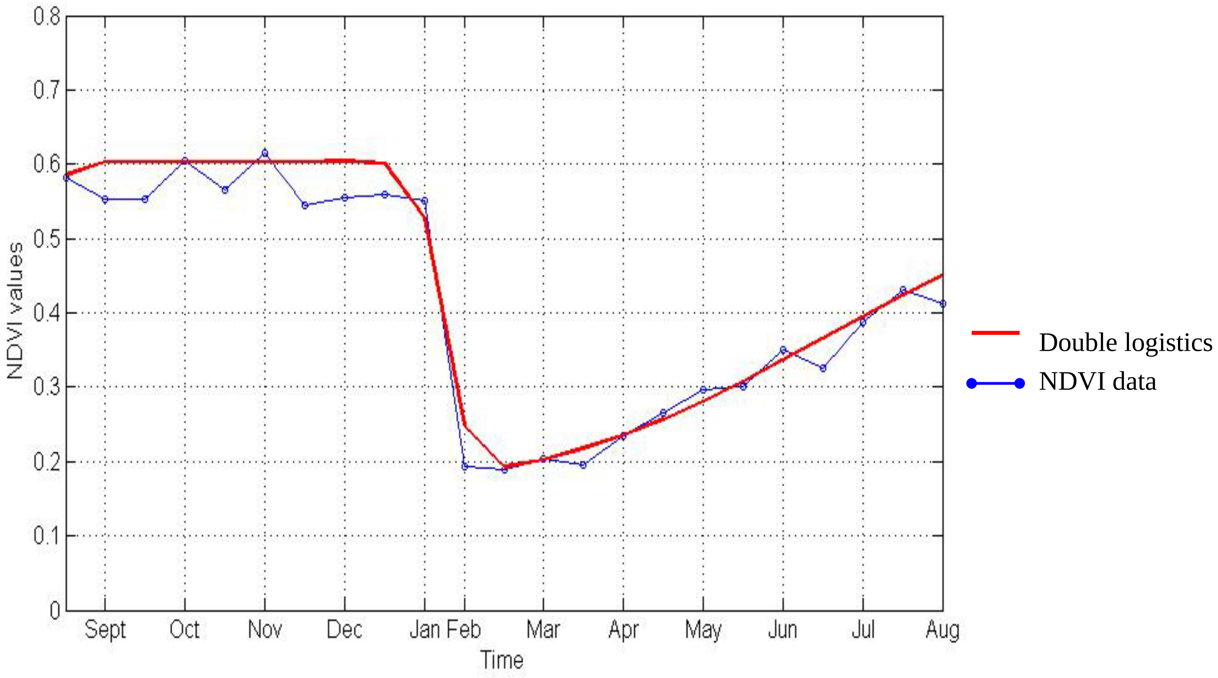


Figure 4.14b Re-growth of burnt alien vegetation on glenrosa soils.

The re-growth rate of alien vegetation on the Namib soils was higher than that on the Glenrosa soils. This may be due to the distribution of the soils. Namib soils are found closer to the ocean and are mainly dunes, which are disturbed by wind action. The Glenrosa soils are further from the coast and have a lower re-growth rate. The process of computing the growth rate is the same as specified earlier. The slopes of the re-growth curves of burnt alien vegetation on both soils were computed for comparison. The burnt alien vegetation on Grey soils grow faster (steeper slope) than that on the Glenrosa soils as shown in Table 4.8.

Table 4.8 Comparison between the slopes of burnt alien vegetation on grey and glenrosa soils.

	Start of season	Mid of season	Amplitude	Time difference	Slope
Grey soils	0.27	0.54	0.27	5	0.054
Glenrosa soils	0.2	0.45	0.25	5	0.05

Furthermore, a comparison was made between the re-growth rates of burnt fynbos vegetation on both soils. The graphs are shown below and comparison made in Table 4.9.

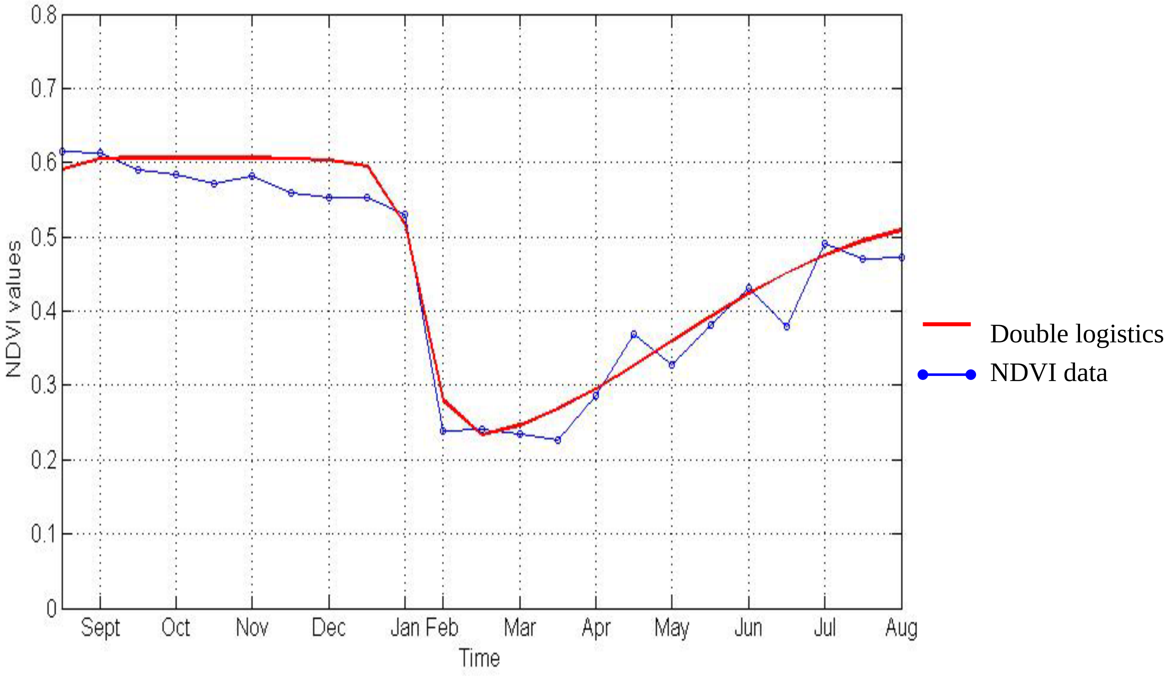


Figure 4.14c Re-growth of burnt fynbos on grey soils.

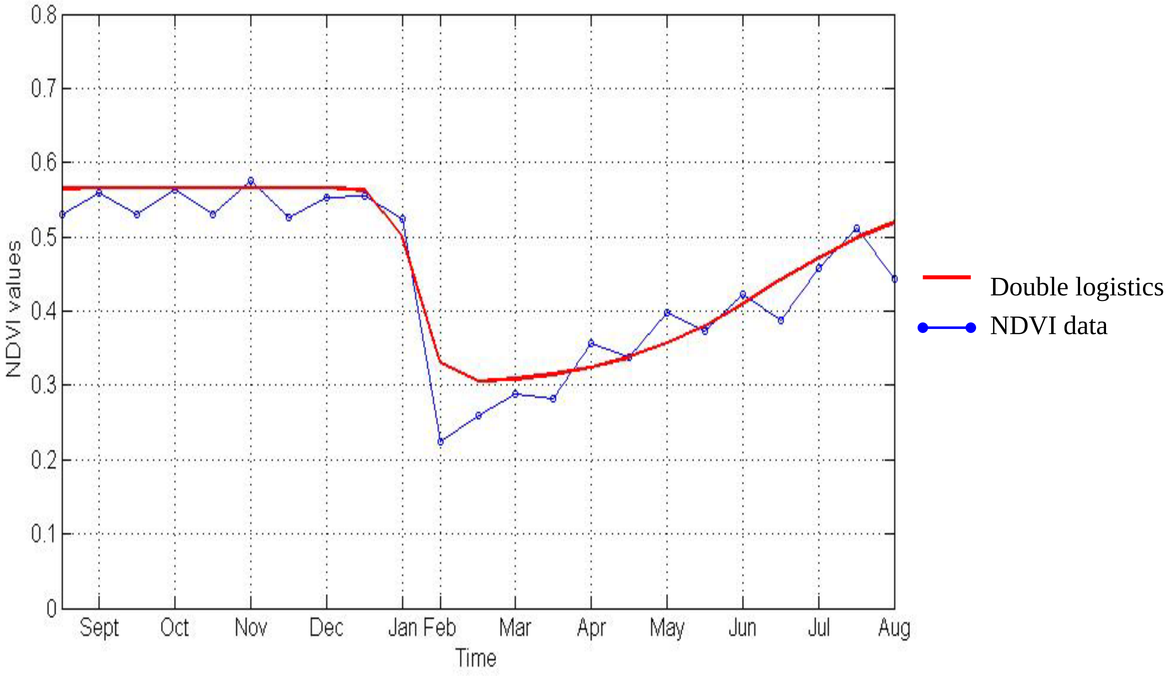


Figure 4.14d Re-growth of burnt fynbos on glenrosa soils.

Table 4.9 Comparison between the re-growth rates of burnt fynbos on grey and glenrosa soils.

N	MONTHS	% INCREASE (CUMULATIVE)	
		Grey soils	Glenrosa soils
1	March	2.62	0.88
2	April	10.82	2.64
3	May	21.31	8.80
4	June	31.31	18.84
5	July	39.51	28.17

6	August	45.90	37.68

Like the re-growth rate of alien vegetation on different soil types, the fynbos grows faster on the Namib soils than on the Glenrosa soils. Also, the slopes of the re-growth curves were determined for comparison. The slope of the re-growth of fynbos on Namib soils was steeper than the re-growth on Glenrosa soils, indicating a higher re-growth rate.

Table 4.10 Comparison between the slopes of burnt fynbos on grey and glenrosa soils.

	Start of season	Mid of season	Amplitude	Time difference (Months)	Slope
Namib soils	0.25	0.51	0.26	5	0.052
Glenrosa soils	0.31	0.52	0.21	5	0.042

The nutrients and location of the Namib soils could have contributed to the higher re-growth rate of fynbos on this soil type. Richards, Stock & Stock (1997) have considered soil nutrient dynamics in relation to fynbos near Cape Agulhas, South Africa. Soil characteristics relating to total nutrient content (such as pitrogen, potassium and phosphorus) were assessed along boundaries between different plant communities. There was a wide range in the degree of change in soil nutrient content across the community boundaries. They proposed that the spatial variation of soil nutrient availability rather than total soil nutrient may be important in explaining the species distribution and community composition in the nutrient poor Mediterranean areas.

CHAPTER 5: CONCLUSION

5.1 DISCUSSION

Though a lot of effort has been made to control the invasion of the natural vegetation by alien plants in South Africa, much more still needs to be done to effectively monitor the spread of alien vegetation. A lot of financial support has been given to curb the effect of the invasion in Western Cape. And although there have been notable results from the various programmes put in place to combat alien vegetation (Versfeld, Le Maitre, and Chapman 1998), this study has introduced a relatively low cost method that can be employed to assist in the monitoring of alien vegetation in South Africa.

Fire regimes are vital in maintaining diversity in species-rich communities like fynbos (Cowling & Richardson 1995). Fire has been used by resource managers to conserve fynbos species and also to combat alien vegetation. The monitoring of the re-growth rate of vegetation after fire can play an important role in the management of alien vegetation. For effective management of alien vegetation, three phases have been identified to be crucial by the Council for Scientific and Industrial Research (CSIR 2000). These are listed below:

- Initial control: drastic reduction of existing population
- Follow-up control: control of seedlings, root suckers and coppice growth
- Maintenance control: sustaining low alien plant numbers with annual control

Monitoring the re-growth rate of alien vegetation falls within the follow-up phase. Without it, the first phase may be a wasted effort and the third phase may not be attainable. This follow-up (monitoring) has been carried out through statistical models (Higgins et al. 1999) and several field surveys to physically monitor the growth rate (Van Wilgen & Le Maitre 1981). Due to the spatial extent of the distribution of alien vegetation, its labour-intensive nature, budget and time constraints of field surveys, the monitoring has not been very effective.

However, remote sensing can be used to achieve this goal. Though colour infrared digital cameras have been used in certain areas of South Africa (e.g. Stow et al. 2000; Kakembo, Palmer, & Rowntree 2006), there is the need to test satellite remote sensing as an alternative data source for monitoring vegetation dynamics. Medium spatial resolution imagery with one- to two day temporal resolutions have been used in other countries with remarkable results (Zhang et al. 2003; Beck et al. 2006). This study tested the capabilities of medium resolution

MODIS products to monitor the re-growth of alien vegetation after fire in South Africa, using the Agulhas Plain as a case study. It has determined the re-growth rate of alien vegetation after the February 2006 fire over the first six months.

As shown in the results, alien vegetation does not grow as fast as the fynbos within six months after a fire, therefore these months are crucial to the restoration and conservation of indigenous vegetation (fynbos). Various methods to achieve these goals can be employed. For example, the re-growth of alien vegetation at this stage should be cleared. Also, the seeds of fynbos plant species could be introduced to fire affected areas to allow the growth and spread of indigenous vegetation. This is in accordance to one of the guidelines suggested by the Council for Scientific and Industrial Research (CSIR) 2000. This states that the control of invasion is not just about clearing the invaded sites, but it includes the introduction of indigenous species to the cleared sites for conservation purposes.

Without the aid of remotely sensed data, Thompson & Leishman (2005) have determined the post fire vegetation dynamics in both nutrient-rich and nutrient-poor woodlands of Syndey. They used field data of soils (nutrient-rich and nutrient-poor) and vegetation to determine the re-growth rate of alien and indigenous vegetation on both types of soils after fire. The data was analyzed using statistical measures such as ANOVA (Analysis of Variance) and SPSS (Statistical Package for the Social Sciences). Their results showed that the re-growth rate of alien vegetation on nutrient-poor soils was lower than the re-growth rate of alien vegetation on nutrient-rich soils. Therefore they suggested that though fire could be used as a tool for alien vegetation removal on nutrient-rich soils, it does not promote the diversity of indigenous vegetation.

Thompson & Leishman's (2005) study is similar to this study, however they were only able to analyze a small area surface due to their method of data collection, which was field surveys. This study has shown that the re-growth rates of both fynbos and alien vegetation after fire can be determined at a regional scale by the use of satellite data (e.g. medium resolution imagery). Furthermore, it has determined the re-growth rate on the dominant soil types within the fire-affected area to determine if the soil types (grey regic sands, and glenrosa soils) have an influence on the re-growth of both fynbos and alien vegetation. It has been established that both plant types grow faster on the grey regic soils, which are common along the coast line, than on the glenrosa soils that are found inland. The fact that the method employed in this study works on a per pixel basis makes it easier to compare the re-growth rate on different factors. Apart from comparison with soil types, other climatic factors such as temperature, rainfall, wind and geology can be introduced.

In another post fire study, Moser & Wohlgemuth (2006) considered which plant species dominate early after fire. According to them, the establishment of dominant species during early post-fire succession may be an essential factor that affect the rate of natural re-forestation in the Central Alpine region of Valais, Switzerland. They monitored the burnt vegetation at various altitudes (from 800m to 2100m above sea level) using systematic sampling of the sites. Their results showed that early vegetation development is faster above 1400m and tree regeneration is also more abundant at higher altitudes.

Also, to confirm that satellite data can be used effectively to determine post fire vegetation dynamics, Clemente et al. (2006) used Landsat Enhanced Thematic Mapper plus (ETM+) and Thematic mapper (TM) images to map vegetation dynamics, vegetation recovery and diversity changes in Mediterranean forest. They combined satellite data and field data, and used statistical and quantitative analysis. The changes in NDVI values since 2000 to 2005 were observed and their results showed that the regeneration of the dominant tree species has remained poor due to the history of disturbances (such as fire) and subsequent repopulation of vegetation.

Additionally, the capability of using the 250m spatial resolution of MODIS product in monitoring the re-growth rate of indigenous and alien vegetation on Agulhas Plain was tested. Based on the assumption that each vegetation type can be represented more accurately on each pixel of 250m, (in contrast to 1000m of other high temporal resolution imagery), pixels representing each vegetation types were selected. The selection was made from a comprehensive map of the area collated by the ARC and validated through field survey. The values obtained from the MODIS data product showed significant difference, that is to say, the MODIS data product was able to distinguish between the indigenous and alien vegetation. Various change detection methodologies were investigated and a change detection method was chosen for monitoring vegetation dynamics on the Agulhas Plain, South Africa. From the results, it is believed that the objectives of the research have been fully realized.

5.2 RECOMMENDATIONS

The fact that annual fires or frequent fires are common in the Western Cape makes the use of medium resolution imagery attractive for monitoring the re-growth rate at a regional scale after fire. Also, due to budget constraints, the MODIS products that are made available to the public, prove to be better alternative, economically. Considering the extent of land surface to be monitored, one can suggest that the use of satellite remote sensing is appropriate. In the event of a remarkable change in the MODIS product, an aerial survey can be planned to have a more detailed observation of the changes in vegetation types. This is necessary to effectively study the landscape at multiple scales.

The re-growth rate of alien vegetation after fire on the Agulhas Plain has been determined within the first six months due to time constraints. There is thus a need to incorporate this method to determine the re-growth of alien vegetation within an at least 12 month period after fire. This will help in fully understanding the phenology of alien vegetation after fire. It will also aid resource managers to understand when it is best to apply other control methods (biological, mechanical or chemical) to combat the growth of alien vegetation.

It is highly recommended that the selection of pixels representing the plant types should be done as accurately as possible to achieve the best results. The method works well with densely distributed plant types. To aid in the accurate selection of pixels, a comprehensive vegetation map should be used. This calls for a compilation of accurate database for geographical analysis. Moreover, it is important that this database be updated regurlarly as the vegetation changes naturally or due to fire or invasion by an alien vegetation. A database of fynbos types, height and age should be developed and maintained before fire is introduced as a management tool for conservation of fynbos diversity.

Finally, it is hoped that the methods used and tested in this study will be implemented by the ARC in the conservation of fynbos diversity on the Agulhas Plain, South Africa.

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APPENDICES

Appendix A: TERRA SATELLITES

MODIS Bands

Primary Use	**Band**	**Bandwidth**
Land/Cloud	1	620 - 670
Boundaries	2	841 – 876
Land/Cloud/Aerosol	3	459 – 479
Properties	4	545 – 565
	5	1230 – 1250
	6	1628 – 1652
	7	2105 – 2155
Ocean Colour/	8	405- 402
Phytoplankton/	9	438 – 448
Biogeochemistry/	10	483 – 493
	11	526 – 536
	12	546 – 556
	13	662 – 672
	14	673 – 683
	15	743 – 753
	16	862 – 877
Atmospheric	17	890 – 920
Water Vapor	18	931 – 941
	19	915 – 965
Cirrus Clouds	26	1.360 – 1.390
Surface/Cloud	20	3.660 – 1.390
Temperature	21	3.929 – 3.989
	22	3.929 – 3. 989
	23	4.020 – 4.080
Atmospheric	24	4.433 – 4.498
Temperature	25	4.482 – 4.549
Water Vapor	27	6.535 – 6.895
	28	7.175 – 7.475
	29	8.400 – 8.700
	30	9.580 – 9.880
	31	10.780 – 11.280
	32	11.770 – 12.270
Cloud Top	33	13.185 – 13.485
Altitude	34	13.485 – 13.785
	35	13.785 – 14.085
	36	14.085 – 14.385

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MODIS data ordering and details http://edcimswww.cr.usgs.gov/pub/imswelcome/

APPENDIX B: MODIS CONVERSION AND RE-PROJECTION INFORMATION

MODIS Reprojecting Tool (MRT) ordering and details: http://lpdaac.usgs.gov/landdaac/tools/modis/index.asp

Raw or downloaded MODIS imagery (MODIS/TERRA vegetation indices 16-day l3 global 250m sin grid v004) information.

Input Projection Type: ISIN (Integerized Sinusoidal)

Projection Parameters: (6371007.181 0 0 0 0 0 0 0 0 0 0 0 0 0 0)

Total Number of Bands: 11

Data Type: (INT16, INT16, UINT16, UINT16, INT16, INT16, INT16, INT16, INT16, INT16, INT16)

Pixel size: (231.7, 231.7, 231.7, 231.7, 231.7, 231.7, 231.7, 231.7, 231.7, 231.7, 231.7)

Number of lines: (4800, 4800, 4800, 4800, 4800, 4800, 4800, 4800, 4800, 4800, 4800)

Number of samples: (4800, 4800, 4800, 4800, 4800, 4800, 4800, 4800, 4800, 4800, 4800)

Lat/Long of Upper-Left Corner: (-29.999999997 11.547005382)

Lat/Long of Upper-Right Corner: (-29.999999997 23.094010765)

Lat/Long of Lower-Left Corner: (-39.999999996 13.054072891)

Lat/Long of Lower-Right Corner: (-39.999999996 26.108145783)

Datum: NODATUM

MODIS conversion information

Spectral_subset = (1 1 1 1 1 1 1 1 1 1 1)

Spatial_subset_type = input_lat_long

Spatial_subset_upper-left_corner = (-34.38 19.27)

Spatial_subset_lower-right_corner = (-34.84 20.24)

Output_filename =

Resampling_type = cubic_convolution

Output_projection_type = transverse mercator

Output_projection_parameters = (0.0 0.0 1.0 0.0 19.75 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0)

Datum = wgs84

Output_pixel_size = 250

APPENDIX C: TIME-SERIES OF NDVI VALUES

A Unburnt alien vegetation

ALIEN NOT IN FIRE-AFFECTED AREA						
MONTHS	**Pixel 1**	**Pixel 2**	**Pixel 3**	**Pixel 4**	**Pixel 5**	**Average**
Early September	0.7016	0.5778	0.4866	0.6906	0.6028	**0.61188**
End September	0.6983	0.6295	0.5578	0.731	0.6314	**0.6496**
Early October	0.764	0.6403	0.5916	0.6927	0.5551	**0.64874**
End October	0.6765	0.5543	0.591	0.726	0.648	**0.63916**
Early November	0.7006	0.519	0.4676	0.6876	0.5698	**0.58892**
End November	0.7261	0.5922	0.5145	0.6874	0.6277	**0.62958**
Early December	0.6347	0.5853	0.4325	0.6224	0.5355	**0.56208**
End December	0.6801	0.5216	0.5076	0.5949	0.5788	**0.5766**
Early January	0.6137	0.483	0.4784	0.6278	0.6002	**0.56062**
End January	0.6253	0.4508	0.4625	0.6141	0.5383	**0.5382**
February	0.5854	0.5718	0.4945	0.5966	0.5964	**0.56894**
Early March	0.673	0.5517	0.4639	0.593	0.6351	**0.58334**
End March	0.713	0.4389	0.5186	0.6266	0.6507	**0.58956**
Early April	0.6733	0.5366	0.4962	0.6395	0.6383	**0.59678**
End April	0.6773	0.5959	0.6095	0.6888	0.6812	**0.65054**
Early May	0.7273	0.5745	0.5963	0.7045	0.5915	**0.63882**
End May	0.7299	0.595	0.6718	0.7335	0.7374	**0.69352**
Early June	0.7726	0.514	0.684	0.7682	0.7167	**0.6911**
End June	0.7484	0.5599	0.7209	0.7755	0.7631	**0.71356**
Early July	0.7533	0.5825	0.6899	0.8131	0.6836	**0.70448**
End July	0.7469	0.5707	0.7578	0.7687	0.749	**0.71862**
Early August	0.7282	0.645	0.7334	0.7473	0.7285	**0.71648**
End August	0.6604	0.5661	0.7214	0.6877	0.6129	**0.6497**

B Unburnt Fynbos

MONTHS	**Pixel 1**	**Pixel 2**	**Pixel 3**	**Pixel 4**	**Pixel 5**	**Pixel 6**	**Avreage**
Early September	0.6164	0.6499	0.7051	0.4679	0.4777	0.5825	**0.583**
End September	0.6119	0.6503	0.4386	0.5058	0.6033	0.5734	**0.564**
Early October	0.5637	0.603	0.3377	0.4327	0.5046	0.5314	**0.496**
End October	0.5987	0.6373	0.4565	0.4758	0.5626	0.5422	**0.546**
Early November	0.5097	0.6115	0.3565	0.4266	0.5679	0.522	**0.499**
End November	0.6011	0.6554	0.3972	0.4799	0.4777	0.5328	**0.524**
Early December	0.5334	0.5678	0.3055	0.435	0.5943	0.5062	**0.490**
End December	0.5372	0.5701	0.3104	0.4118	0.5526	0.4894	**0.479**
Early January	0.5367	0.5701	0.3322	0.4838	0.5313	0.4765	**0.488**
End January	0.486	0.5271	0.2934	0.4417	0.4943	0.5195	**0.460**
February	0.4832	0.2623	0.2375	0.3955	0.5601	0.5178	**0.409**
Early March	0.4781	0.2714	0.2995	0.472	0.5869	0.546	**0.442**
End March	0.482	0.2594	0.2856	0.5067	0.6042	0.5608	**0.450**
Early April	0.4351	0.278	0.2928	0.4917	0.5771	0.5506	**0.438**
End April	0.5485	0.3002	0.2792	0.549	0.6118	0.566	**0.476**
Early May	0.5726	0.4119	0.2739	0.4575	0.5632	0.5825	**0.477**
End May	0.5617	0.4564	0.4007	0.5824	0.6777	0.6247	**0.551**
Early June	0.5645	0.47	0.4562	0.5814	0.5801	0.6268	**0.547**
End June	0.6659	0.5458	0.6375	0.5665	0.6457	0.7062	**0.628**
Early July	0.6259	0.5203	0.44	0.5547	0.5972	0.6031	**0.557**

End July	0.5369	0.5467	0.5109	0.594	0.631	0.6524	**0.579**
Early August	0.6335	0.5923	0.5361	0.5793	0.6338	0.6146	**0.598**
End August	0.5957	0.5607	0.4204	0.4989	0.568	0.5726	**0.536**

C Burnt alien vegetation

MONTHS	**Pixel 1**	**Pixel 2**	**Pixel 3**	**Pixel 4**	**Average**
Early September	0.4827	0.762	0.6862	0.5026	**0.608375**
End September	0.3613	0.806	0.6657	0.4916	**0.58115**
Early October	0.4307	0.7528	0.6245	0.4755	**0.570875**
End October	0.4954	0.7839	0.6827	0.5367	**0.624675**
Early November	0.4442	0.7751	0.6404	0.4784	**0.584525**
End November	0.4824	0.811	0.6823	0.5499	**0.6314**
Early December	0.4407	0.7378	0.6577	0.4531	**0.572325**
End December	0.4622	0.7518	0.6097	0.4551	**0.5697**
Early January	0.4642	0.7378	0.61	0.4781	**0.572525**
End January	0.4662	0.7277	0.6161	0.4586	**0.56715**
February	0.1699	0.2198	0.3948	0.1895	**0.2435**
Early March	0.1618	0.236	0.3971	0.171	**0.241475**
End March	0.1544	0.2624	0.3969	0.1938	**0.251875**
Early April	0.1348	0.2695	0.3575	0.1814	**0.2358**
End April	0.1387	0.3503	0.4562	0.2159	**0.290275**
Early May	0.1715	0.4033	0.4914	0.2218	**0.322**
End May	0.1858	0.4536	0.5701	0.2503	**0.36495**
Early June	0.184	0.4728	0.5419	0.2441	**0.3607**
End June	0.2359	0.534	0.5906	0.2796	**0.410025**
Early July	0.2203	0.5026	0.5862	0.2542	**0.390825**
End July	0.2887	0.55	0.5546	0.3226	**0.428975**
Early August	0.3179	0.6191	0.6153	0.3532	**0.476375**
End August	0.3509	0.6036	0.6249	0.2835	**0.465725**

D Burnt Fynbos

MONTHS	**Pixel 1**	**Pixel 2**	**Pixel 3**	**Pixel 4**	**Pixel 5**	**Average**
Early September	0.6435	0.6438	0.5294	0.5888	0.4715	0.5754
End September	0.6489	0.6315	0.5185	0.6353	0.525	0.59184
Early October	0.6109	0.6109	0.5033	0.5969	0.4894	0.56228
End October	0.6501	0.6184	0.5399	0.6265	0.5238	0.59174
Early November	0.6202	0.6177	0.5129	0.6234	0.4534	0.56552
End November	0.6241	0.6206	0.5514	0.6747	0.5019	0.59454
Early December	0.5637	0.5875	0.5032	0.5819	0.4943	0.54612
End December	0.5658	0.6001	0.5307	0.6238	0.5087	0.56582
Early January	0.5658	0.6054	0.5306	0.6249	0.5085	0.56704
End January	0.5301	0.5752	0.4954	0.5855	0.4886	0.53496
February	0.2441	0.2261	0.1932	0.1805	0.3024	0.22926
Early March	0.2429	0.2365	0.1914	0.1872	0.4024	0.25208
End March	0.2553	0.2345	0.2035	0.2123	0.4472	0.27056
Early April	0.2347	0.2332	0.1918	0.2155	0.4388	0.2628
End April	0.3324	0.2791	0.2884	0.32	0.4628	0.33654
Early May	0.3843	0.3774	0.2841	0.3552	0.3726	0.35472
End May	0.375	0.3325	0.3656	0.3931	0.4324	0.37972
Early June	0.4287	0.4323	0.3316	0.3987	0.393	0.39686
End June	0.4712	0.4831	0.3822	0.4319	0.4563	0.44494

Early July	0.4603	0.3883	0.3435	0.43	0.3875	0.40192
End July	0.5301	0.5636	0.4141	0.4752	0.4819	0.49298
Early August	0.5807	0.4817	0.4752	0.5092	0.5527	0.5199
End August	0.5547	0.5347	0.4083	0.4812	0.4432	0.48442

E Burnt alien vegetation on grey soils

MONTHS	Pixel 1	Pixel 2	Pixel 3	Average
Early September	0.5919	0.6438	0.5419	**0.593**
End September	0.5536	0.6315	0.6657	**0.617**
Early October	0.4622	0.6109	0.6245	**0.566**
End October	0.4999	0.6184	0.6827	**0.600**
Early November	0.5425	0.6177	0.6404	**0.600**
End November	0.5236	0.6206	0.6823	**0.609**
Early December	0.4411	0.5875	0.6577	**0.562**
End December	0.5017	0.6001	0.6097	**0.571**
Early January	0.4659	0.6054	0.61	**0.560**
End January	0.4954	0.5752	0.6161	**0.562**
February	0.1676	0.2261	0.3948	**0.263**
Early March	0.1555	0.2365	0.3971	**0.263**
End March	0.1452	0.2345	0.3969	**0.259**
Early April	0.1707	0.2332	0.3575	**0.254**
End April	0.1458	0.2791	0.4562	**0.294**
Early May	0.2517	0.3774	0.4914	**0.374**
End May	0.2318	0.3325	0.5701	**0.378**
Early June	0.2737	0.4323	0.5419	**0.416**
End June	0.3371	0.4831	0.5906	**0.470**
Early July	0.2928	0.3883	0.5862	**0.422**
End July	0.3248	0.5636	0.5546	**0.481**
Early August	0.4079	0.4817	0.6153	**0.502**
End August	0.4567	0.5347	0.6249	**0.539**

F Burnt alien vegetation on glenrosa soils

MONTHS	Pixel 1	Pixel 2	Pixel 3	Average
Early September	0.4827	0.5026	0.762	**0.582**
End September	0.3613	0.4916	0.806	**0.553**
Early October	0.4307	0.4755	0.7528	**0.553**
End October	0.4954	0.5367	0.7839	**0.605**
Early November	0.4442	0.4784	0.7751	**0.566**
End November	0.4824	0.5499	0.811	**0.614**
Early December	0.4407	0.4531	0.7378	**0.544**
End December	0.4622	0.4551	0.7518	**0.556**
Early January	0.4642	0.4781	0.7378	**0.560**
End January	0.4662	0.4586	0.7277	**0.551**
February	0.1699	0.1895	0.2198	**0.193**
Early March	0.1618	0.171	0.236	**0.190**
End March	0.1544	0.1938	0.2624	**0.204**
Early April	0.1348	0.1814	0.2695	**0.195**
End April	0.1387	0.2159	0.3503	**0.235**
Early May	0.1715	0.2218	0.4033	**0.266**
End May	0.1858	0.2503	0.4536	**0.297**

Early June	0.184	0.2441	0.4728	**0.300**
End June	0.2359	0.2796	0.534	**0.350**
Early July	0.2203	0.2542	0.5026	**0.326**
End July	0.2887	0.3226	0.55	**0.387**
Early August	0.3179	0.3532	0.6191	**0.430**
End August	0.3509	0.2835	0.6036	**0.413**

G Burnt Fynbos on grey soils

MONTHS	**Pixel 1**	**Pixel 2**	**Pixel 3**	**Average**
Early September	0.6435	0.6438	0.5557	**0.614**
End September	0.6489	0.6315	0.557	**0.612**
Early October	0.6109	0.6109	0.5497	**0.591**
End October	0.6501	0.6184	0.4864	**0.585**
Early November	0.6202	0.6177	0.4787	**0.572**
End November	0.6241	0.6206	0.5017	**0.582**
Early December	0.5637	0.5875	0.5246	**0.559**
End December	0.5658	0.6001	0.489	**0.552**
Early January	0.5658	0.6054	0.4914	**0.554**
End January	0.5301	0.5752	0.4837	**0.530**
February	0.2441	0.2261	0.244	**0.238**
Early March	0.2429	0.2365	0.2445	**0.241**
End March	0.2553	0.2345	0.2153	**0.235**
Early April	0.2347	0.2332	0.2098	**0.226**
End April	0.3324	0.2791	0.2498	**0.287**
Early May	0.3843	0.3774	0.3489	**0.370**
End May	0.375	0.3325	0.2752	**0.328**
Early June	0.4287	0.4323	0.2809	**0.381**
End June	0.4712	0.4831	0.3359	**0.430**
Early July	0.4603	0.3883	0.2888	**0.379**
End July	0.5301	0.5636	0.3749	**0.490**
Early August	0.5807	0.4817	0.352	**0.471**
End August	0.5547	0.5347	0.3284	**0.473**

H Burnt Fynbos on glenrosa soils.

MONTHS	**Pixel 1**	**Pixel 2**	**Pixel 3**	**Average**
Early September	0.5294	0.5888	0.4715	**0.530**
End September	0.5185	0.6353	0.525	**0.560**
Early October	0.5033	0.5969	0.4894	**0.530**
End October	0.5399	0.6265	0.5238	**0.563**
Early November	0.5129	0.6234	0.4534	**0.530**
End November	0.5514	0.6747	0.5019	**0.576**
Early December	0.5032	0.5819	0.4943	**0.526**
End December	0.5307	0.6238	0.5087	**0.554**
Early January	0.5306	0.6249	0.5085	**0.555**
End January	0.4954	0.5855	0.4886	**0.523**
February	0.1932	0.1805	0.3024	**0.225**
Early March	0.1914	0.1872	0.4024	**0.260**
End March	0.2035	0.2123	0.4472	**0.288**
Early April	0.1918	0.2155	0.4388	**0.282**
End April	0.2884	0.32	0.4628	**0.357**
Early May	0.2841	0.3552	0.3726	**0.337**

End May	0.3656	0.3931	0.4324	**0.397**
Early June	0.3316	0.3987	0.393	**0.374**
End June	0.3822	0.4319	0.4563	**0.423**
Early July	0.3435	0.43	0.3875	**0.387**
End July	0.4141	0.4752	0.4819	**0.457**
Early August	0.4752	0.5092	0.5527	**0.512**
End August	0.4083	0.4812	0.4432	**0.444**

APPENDIX D: TIMESAT ANALYSIS OF NDVI VALUES ON AGULHAS PLAIN

TIMESAT Ordering and details:
http://www.nateko.lu.se/personal/Lars.Eklundh/TIMESAT/timesat.html

Timesat single time-series (Matlab)

To perform the analysis, start Matlab and add the directory TIMESAT_MATLAB to the search path. Move to the directory RUN and complete the following dialog in the Matlab command window. *Note comments in italics.*
>timesatseries
    TIMESAT series version 2.2 for Matlab
    Per Jönsson and Lars Eklundh
    per.jonsson@lut.mah.se, lars.eklundh@nateko.lu.se
    January 2006

Give name of sensor data file
>Fynbos.txt *(For other analysis, text files are Alien_out.txt, Fynbos_out.txt, Alien.txt etc).*

Sensor data values in the range [min,max] are accepted. Data outside this range are assigned weight 0. Give min and max
>[1000 10000] *(Values range from -2000 to 10000 in MODIS NDVI 16-bit integer).*

Give name of mask data file: write NONE if mask data is unavailable
>NONE

Time-series with amplitudes less than A are not processed A = 0 forces all time-series to be processed. Give A
>0

Single spikes are detected by a comparison with median filtered values and with closest neighbors. If the distance is greater than S*ystd, where ystd is the standard deviation for data values, we have a spike. S = 2 is the normal value. Give S
>2

Give parameter that is used to determine the number of annual seasons. Parameter value should be in the range [0,1]. A value close to 0 will force the program to interpret a small depression in the main curve as a second annual season. A value close to 1 will force the
program to always use only one annual season. Give season parameter.
>1

Fitted curves adapts to the upper envelope of the sensor data values in an iterative procedure. Give the number of fitting steps: 1, 2 or 3.
>3

Give the strength of the adaptation. Value should be in the range [1,10] where 2 is the normal value.
>2

Specify the processing methods Savitzky-Golay (0/1), Asymmetric-Gauss (0/1), Double-Logistic (0/1)
>[1 1 1]

```
Savitzky-Golay window sizes for each of the fitting steps
>[4 5 6]

The time for the season start (end) is defined as the time for which the sensor data value,
measured from the base level, has increased (decreased) to X % of the seasonal amplitude. X =
20 is the normal value. Give X
>20

Plot and print to screen (0/1), Debug (0/1)
>[1 0]

Give an identification tag for the job (text string of max 20 chars)
>Fynbos1

pixel 1 1, has been processed ………………………………………..

Processing finished

Phenological parameters written to:
phenologySG_Fynbos1
phenologyAG_Fynbos1
phenologyDL_Fynbos1

Sensor data and fitted functions written to:
sensordata_Fynbos1
fitSG_Fynbos1
fitAG_Fynbos1
fitDL_Fynbos1

Input data written to:
input_Fynbos1.txt
```

APPENDIX E: CALCULATION OF THE GROWTH RATES

A. Growth rates of burned Fynbos

N	**MONTHS (TIME)**	**VALUE FROM MINIMA**	**DIFFERENCE FROM MINIMA (0.26)**	**RATE: DIFF/MAXIMA (0.59)**	**% GROWTH RATE (CUMULTIVE)**
1	**March**	0.275	0.015	0.025	**2.54**
2	**April**	0.32	0.06	0.102	**10.17**
3	**May**	0.375	0.115	0.195	**19.49**
4	**June**	0.44	0.18	0.305	**30.51**
5	**July**	0.49	0.23	0.390	**38.98**
6	**August**	0.53	0.27	0.458	**45.76**

B. Growth rates of unburnt Fynbos

N	**MONTHS (TIME)**	**VALUE FROM MINIMA**	**DIFFERENCE FROM MINIMA (0.45)**	**RATE: DIFF/MAXIMA (0.57)**	**% GROWTH RATE (CUMULTIVE)**
1	**March**	0.45	0	0.000	**0.00**
2	**April**	0.47	0.02	0.035	**3.48**
3	**May**	0.55	0.1	0.174	**17.39**
4	**June**	0.604	0.154	0.268	**26.78**
5	**July**	0.614	0.164	0.285	**28.52**
6	**August**	0.609	0.159	0.277	**27.65**

C. Re-growth rate of burned alien vegetation on grey soils

N	**MONTHS (TIME)**	**VALUE FROM MINIMA**	**DIFFERENCE FROM MINIMA (0260)**	**RATE: DIFF/MAXIMA (0.61)**	**% GROWTH RATE (CUMULTIVE)**
1	**March**	0.275	0.015	0.025	**2.46**
2	**April**	0.32	0.06	0.098	**9.84**
3	**May**	0.384	0.124	0.203	**20.33**
4	**June**	0.45	0.19	0.311	**31.15**
5	**July**	0.5	0.24	0.393	**39.34**
6	**August**	0.54	0.28	0.459	**45.90**

D. Re-growth rate of burned alien vegetation on glenrosa soils

N	**MONTHS (TIME)**	**VALUE FROM MINIMA**	**DIFFERENCE FROM MINIMA (0.19**	**RATE: DIFF/MAXIMA (0.6)**	**% GROWTH RATE (CUMULTIVE)**
1	**March**	0.2	0.01	0.017	**1.67**
2	**April**	0.237	0.047	0.078	**7.83**
3	**May**	0.29	0.1	0.167	**16.67**
4	**June**	0.34	0.15	0.250	**25.00**
5	**July**	0.4	0.21	0.350	**35.00**
6	**August**	0.45	0.26	0.433	**43.33**

E. Re-growth rate of burned Fynbos vegetation on grey soils

N	MONTHS (TIME)	VALUE FROM MINIMA	DIFFERENCE FROM MINIMA (0.23)	RATE: DIFF/MAXIMA (0.61)	% GROWTH RATE (CUMUL-TIVE)
1	**March**	0.25	0.016	0.026	**2.62**
2	**April**	0.3	0.066	0.108	**10.82**
3	**May**	0.364	0.13	0.213	**21.31**
4	**June**	0.425	0.191	0.313	**31.31**
5	**July**	0.475	0.241	0.395	**39.51**
6	**August**	0.514	0.28	0.459	**45.90**

F. Re-growth rate of burned Fynbos vegetation on glenrosa soils

N	MONTHS (TIME)	VALUE FROM MINIMA	DIFFERENCE FROM MINIMA (0.31)	RATE: DIFF/MAXIMA (0.568)	% GROWTH RATE (CUMUL-TIVE)
1	**March**	0.315	0.005	0.009	**0.88**
2	**April**	0.325	0.015	0.026	**2.64**
3	**May**	0.36	0.05	0.088	**8.80**
4	**June**	0.417	0.107	0.188	**18.84**
5	**July**	0.47	0.16	0.282	**28.17**
6	**August**	0.524	0.214	0.377	**37.68**

APPENDIX F: CALCULATION OF T-TEST

1. NDVI values of burned and unburnt alien vegetation.

Burned : 0.25, 0.29, 0.34, 0.4, 0.45, 0.5.
Unburnt: 0.59, 0.64, 0.69, 0.71, 0.72, 0.65

Paired t test results:

P value and statistical significance:

The two-tailed P value equals 0.0002
By conventional criteria, this difference is considered to be extremely statistically significant.

Confidence interval:

The mean of Group One minus Group Two equals -0.2950
95% confidence interval of this difference: From **-0.3762 to -0.2138**

Intermediate values used in calculations:

t = 9.3365
df = 5
standard error of difference = 0.032

Group	Group One	Group Two
Mean	0.3717	0.6667
SD	0.0958	0.0493
SEM	0.0391	0.0201
N	6	6

2. Raw values of burned and unburnt] Fynbos

Burned; 0.275, 0.32, 0.375, 0.44, 0.49, 0.53
Unburnt: 0.45, 0.47, 0.55, 0.604, 0.614, 0.609

P value and statistical significance:

The two-tailed P value equals 0.0002
By conventional criteria, this difference is considered to be extremely statistically significant.

Confidence interval:

The mean of Group One minus Group Two equals -0.14450
95% confidence interval of this difference: **From -0.18371 to -0.10529**

Intermediate values used in calculations:

t **= 9.4723**, df = 5, standard error of difference = 0.015

Group	Group One	Group Two
Mean	0.40500	0.54950
SD	0.09910	0.07334
SEM	0.04046	0.02994
N	6	6

3. Re-growth rates of burned alien and Fynbos vegetation.

Burned Alien: 1.60, 8.00, 16.00, 25.60, 33.60, 41.60
Burned Fynbos: 2.54, 10.17, 19.49, 30.51, 38.98

P value and statistical significance:

The two-tailed P value equals 0.0038

By conventional criteria, this difference is considered to be very statistically significant.

Confidence interval:

The mean of Group One minus Group Two equals -3.5083

95% confidence interval of this difference: From **-5.2819 to -1.7348**

Intermediate values used in calculations:

t = 5.0850, df = 5, standard error of difference = 0.690

Group	Group One	Group Two
Mean	21.0667	24.5750
SD	15.3272	16.7954
SEM	6.2573	6.8567
N	6	6