Determining the hydrological benefits of clearing invasive alien vegetation on the Agulhas Plain, South Africa.

by
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Declaration

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Thesis abstract

Invasive alien plants (IAPs) reduce streamflow and threaten the biodiversity of South Africa's Cape Floristic Region. Up-to-date information on invasive vegetation is required for land management agencies to formulate policies and make appropriate resource management decisions. Invasion maps are typically not updated often enough because of the time and expenses required to do so. As a result, invasion maps for South Africa are limited to coarse resolution data or isolated small scale studies. Invasive alien plants change the landscape by destabilizing catchments and thereby increasing soil erosion, altering fire regimes and hydrology, as well as changing the physical and chemical composition of the soil. Information on IAPs is needed at a landscape scale. Remote sensing is a powerful tool that can be used to characterise landscapes in a biologically meaningful manner. The Normalised Difference Vegetation Index (NDVI) was used to create an up-to-date invasion map of the Agulhas Plain, lying at the heart of the species rich Cape Floristic Region. This information was combined with actual evapotranspiration data from the Surface Energy Balance Algorithm for Land (SEBAL) study done by Water Watch and the Council for Scientific and Industrial Research. The results showed that invasive vegetation uses more water than natural fynbos vegetation and that the greatest amount of water would be made available by clearing the invaded deep sands on the Agulhas Plain. These deep sand areas conflict with the priority areas of the Working for Water programme. This IAP eradication programme targets sparsely invaded upland areas for long-term sustainability. The recommendation of this study is to clear invaded wetland and riparian areas as these zones yield the greatest hydrological benefit per hectare and meet the priorities of Working for Water. Overall, 36 million cubic meters of water would be made available by clearing the Agulhas Plain. It can be concluded that there is a significant hydrological benefit to clearing invasive alien vegetation on the Agulhas Plain.

Opsomming

Indringerplante (IP) verminder stroomvloei en bedreig die biodiversiteit van Suid-Afrika se Kaapse Floristiese Streek. Die nuutste inligting oor uitheemse plantegroei is nodig vir grondbestuuragentskappe om beleide te formuleer vir die neem van toepaslike hulpbronbestuur besluite. As gevolg van die tyd en uitgawes wat nodig is om indringingskaarte op te dateer, word dit gewoonlik nie dikwels genoeg gedoen nie. Dus is indringingskaarte vir Suid-Afrika beperk tot growwe resolusie data of geïsoleerde kleinskaal studies. Indringerplante verander die landskap deur opvangsgebiede te destabiliseer en sodoende te lei tot gronderosie, verandering van vuurregimes en hidrologie, sowel as die verandering in die fisiese en chemiese samestelling van die grond. Inligting oor IP is nodig op 'n landskapskaal. Afstandswaarneming is 'n kragtige tegniek wat gebruik kan word om landskappe op 'n biologies betekenisvolle manier te karakteriseer. Die *Normalised Difference* plantegroei-indeks (NDVI) is gebruik om 'n opgedateerde indringingskaart van die Agulhas-vlakte, wat in die hart van die spesiesryke Kaapse Floristiese Streek lê, te skep. Hierdie inligting is gekombineer met die werklike evapotranspirasie data vanaf die *Surface Energy Balance Algorithm for Land* (SEBAL) studie gedoen deur *Water Watch* en die Raad vir Wetenskaplike en Nywerheidnavorsing. Die resultate het getoon dat uitheemse plantegroei meer water gebruik as natuurlike fynbosplantegroei en dat die grootste hoeveelheid van hierdie water beskikbaar gestel sal word deur IP op diepsand op die Agulhas-vlakte skoonte maak. Hierdie diepsand areas is in konflik met die prioriteitsgebiede van die Werk vir Water-program. Hierdie IP uitroeiingsprogram fokus op yl ingedringde berggebiede vir langtermyn volhoubaarheid. Die aanbeveling van hierdie studie is om duidelik ingedringde vleilande en oewergebiede skoon te maak, siende dat hierdie sones die hoogste opbrengs en die grootste hidrologiese voordeel per hektaar bied, en voldoen aan die prioriteite van Werk vir Water. In totaal sou 36 miljoen kubieke meter water beskikbaar gestel word deur die skoonmaak van die Agulhas-vlakte. Dus kan dit afgelei word dat die verwydering van hidrologiese indringerplante op die Agulhas-vlakte 'n beduidende voordeel sal inhou.

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To my mother, I dedicate this thesis. Her steadfast dedication to the cause and the effort she has put into reading over every draft is worthy of a medal.

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Nowell, M.S., Le Maitre, D.C., Esler, K.J. (2011) Streamflow reduction by invasive alien plants on the Agulhas Plain.

Introduction

Thesis statement

Invasive Alien Plants (IAPs) threaten the biodiversity and ecosystem processes of South Africa's Cape Floristic Region due to their ability to outcompete native vegetation for resources such as water, nutrients, light and space. The Working for Water programme aims to increase water security, but little scientific evidence is available to validate the clearing of IAPs from a hydrological viewpoint. Quantifying the benefits of clearing IAPs is needed for prioritization. There is insufficient capacity to control the IAP problem and as such, prioritization is essential to maximise the benefits with limited funding. Valuation of water resources as an ecosystem service is required so that rational choices can be made regarding competing forms of land use. Payment for ecosystem services has been suggested as the only way of ensuring intervention and providing an incentive for conservation. This thesis aims to quantify the amount of water made available by clearing invasive vegetation on the Agulhas Plain so that eradication strategies can optimize the hydrological benefits with the limited resources available.

Motivation

Ecosystem services are increasingly recognized as vital to society and of significant economic value (Lant et al. 2005). Ecosystem services are the "conditions and processes through which natural ecosystems, and the species that make them up, sustain and fulfil human life" (Daily 1997). They include nutrient cycling, hydrological processes, soil formation, pollination, and energy fixation, among others, and are regarded as natural capital. According to the Millennium Assessment (2005), natural capital is limited and rapidly diminishing. Restoration of natural capital (RNC) has been suggested as the most direct and effective remedy for addressing the depletion of ecosystem goods and services (Aronson et al. 2007). RNC is defined as "any activity that integrates investment in a replenishment of natural capital stocks to improve the flows of ecosystem goods and services while enhancing all aspects of human well-being" (Aronson et al. 2007). One such example of RNC is the eradication of invasive alien plants (IAPs). Invasive alien plants are a major threat to global biodiversity (Reid et al. 2009; Solarz 2007; Wal et al. 2008). IAPs have the ability to outcompete native vegetation for essential resources, change the natural landscape by destabilizing catchments and thereby increase soil erosion, alter fire regimes and hydrological processes, as well as change the physical and chemical composition of the soil (Joshi et al. 2004; Le Maitre et al. 1996; Tabacchi et al. 2000). IAP eradication programmes such as Working for Water (WfW) have been launched in South Africa with the aim of restoring natural capital by controlling invading species and enhancing water security (WFWP 2000). One justification for the establishment of this programme was that clearing IAPs would make more water available (Dye & Jarmain 2004). There is limited quantifiable evidence to support this justification (Dye & Versfeld 2007). As such, it is difficult to develop a market for the payment of ecosystem services (PES) and advocate for future funding for RNC (Aronson et al. 2010).

The limited knowledge regarding the quantity of water made available by eradicating IAPs has management implications as well. The first concerns regarding the amount of water used by alien vegetation referred specifically to exotic plantation trees (Dye & Versfeld 2007). The long-term catchment studies that were set up in Jonkershoek in the Western Cape province of South Africa monitored runoff in areas under plantations (Dye & Versfeld 2007). The studies found that afforestation with exotic species reduced streamflow (Prinsloo & Scott 1999). As a result of these findings, forestry practices are now strictly controlled as to reduce the impact on water resources by withdrawing from riparian areas (Dye & Versfeld 2007; Enright 2000). Invasive alien vegetation, on the other hand, is strongly associated with riparian areas (Dye et al. 2001). Improved knowledge is needed to determine the impacts of invasive alien vegetation and native vegetation on hydrology, particularly for riparian and dryland conditions (Clulow et al. 2009; Dye et al. 2008). This has implications for prioritization. Due to the extent of the problem, there is insufficient capacity to control invasive vegetation (van Wilgen 2010). Prioritization is necessary to maximise benefits with limited funding (Dye et al. 2001). The criteria used for prioritization by WfW are: presence of priority IAP species, impact on hydrology, impact on biodiversity, impact on grazing, impact on harvested products, and the impact on fire hazards (van Wilgen 2010). Although invasion is a complex problem and clearing strategies should be context specific (van Wilgen 2010), certain guidelines exist for prioritizing clearing. According to CapeNature's 'A landowner's guide to planning alien control,' priority areas for IAP clearing are areas with young, less dense invasive vegetation, which has a lower potential of spreading as a result of a lower seed bank (CapeNature Unknown). Less densely invaded areas also require fewer resources to clear. The size and location of clearing activities is dictated by the resources available for follow-up exercises. Follow-ups are essential to prevent further growth and spread of IAPs after the initial clearing. Other considerations include the potential land use of the area post-clearing, the threat to crops and pastures, and rehabilitation and restoration potential. The impact alien plant eradication and restoration has on streamflow remains largely unknown (Dye et al. 2001). There is very little scientific evidence to validate the clearing of IAPs from a hydrological viewpoint (Dye et al. 2001).

Goals and objectives

The objective of this study was to quantify the hydrological benefits of restoring natural capital by clearing invasive alien plants. Water resources as an ecosystem service require valuation so that rational choices can be made regarding competing forms of land use (van Wilgen et al. 1998). This is true for invasive alien vegetation which is the most significant threat to South Africa's species diverse fynbos vegetation (Binns et al. 2001; Lombard et al. 1997; Rebelo 1992; Rouget et al. 2003; van Wilgen 2010). The hydrological benefits of restoring natural capital by clearing IAPs need to be quantified. This information is necessary for management of the IAP problem, such as prioritization of eradication strategies, as well as for developing markets for water resources as an ecosystem service. Payment for ecosystem service (PES) has been suggested as the only way of ensuring intervention and providing an incentive for conservation (Aylward & Barbier 1992; Palmer & Filoso 2009).

This study forms part of a greater study on the impacts of restoration of natural capital (RNC) conducted by ASSET Research for the Water Research Commission. The data from this hydrological study will feed into a partnered cost-benefit analysis from an economical perspective conducted by Helanya Vlok as well as a PhD project on the benefits of restoration. The overarching objective of the ASSET Research project is:

*RNC improves **water flow** and **water quality**, **land productivity**, in some cases sequesters more carbon and, in general, increases both the **socio-economic value** of the land in situ, and in the surroundings of the restoration site, as well as the **agricultural potential** of the land.*

This study explores the water flow objective of the ASSET Research project. In order to quantify the amount of water made available by clearing invasive alien vegetation, three goals had to be met:

1. Firstly, an up-to-date invasion map was needed. The extent of invasion on the Agulhas Plain was last mapped in 2000 (Cole et al. 2000). As the spatial distribution of invasive vegetation can change rapidly over time, an inexpensive and quick technique of mapping IAPs was explored in Chapter 2. Three remote sensing techniques were evaluated for their accuracy of mapping vegetation.
2. The second goal was to explore the influence of disturbance (clearing and fire) on the spatial distribution of IAPs over a 9 year period (Chapter 3).
3. The final goal was to use the up-to-date invasion map and combine it with data from the Surface Energy Balance Algorithm for Land (SEBAL) model to quantify how much water is made available by restoring natural capital (Chapter 4). Hydrological priority areas for clearing operations were also identified.

Study site selection

The Agulhas Plain (AP) was chosen for the study as it has a reliable clearing history, an up-to-date detailed fire history, a pre-existing accurate invasion map and evapotranspiration data was available for the area from the SEBAL study by Water Watch and the Council for Scientific and Industrial Research. In addition, the Agulhas Biodiversity Initiative (ABI) was launched in 2004 with the aim of addressing the threats to the biodiversity of the area and promoting sustainability. Information on the hydrological benefits of clearing invasive alien plants (one of the most significant threats to the area) is needed to effective prioritization of clearing strategies.

The Agulhas Plain (see Figure 1.1) is located between 19°30’ and 20°15’ south, and 34°30’ and 34°50’ east, covering the southern-most tip of Africa. This is an area of exceptional species richness, lying at the heart of the Cape Floristic Region (CFR), a biodiversity hotspot. Over 1750 species of vascular plant have been found on the AP and it is renowned for its exceptional diversity of lowland fynbos, renosterveld and strandveld vegetation (Mucina & Rutherford 2006). The average rainfall of the area is 478mm a year, most of which falls in the winter months between May and August. Of this rainfall, around 37mm are converted to runoff. This 7% precipitation: runoff ratio is below the national average of 8.6% (DEAT 1999). The summer is long and dry, typical of a Mediterranean climate and is when most fires occur. The last fire in the area occurred in February 2006, burning a large portion of the AP. Fynbos is a fire-adapted vegetation type with fires generally occurring every 6 to 40 years (van Wilgen & Richardson 1985). The AP is also the windiest area year-round of the South African coast (Kraaij et al. 2009). The main river systems are the Klein River, Potsberg River and the Nuwejaars River. The underlying geology of the Agulhas Plain is Table Mountain sandstone in the mountainous catchments and limestone on the flats (Kraaij et al. 2009). This limestone retains water and is the reason for several wetlands in the area. The area is unique in that it has a wide range of wetland types within a relatively small area. Freshwater springs, rivers, floodplains, estuaries, lakes, vleis and endorheic pans can all be found on the AP (Jones et al. 2000). The De Mond estuary and De Hoop vlei are both classified as Ramsar sites (Kraaij et al. 2009). Eutrophic and non-calcarious soils constitute the main soil types on the AP (Cowling & Holmes 1992).

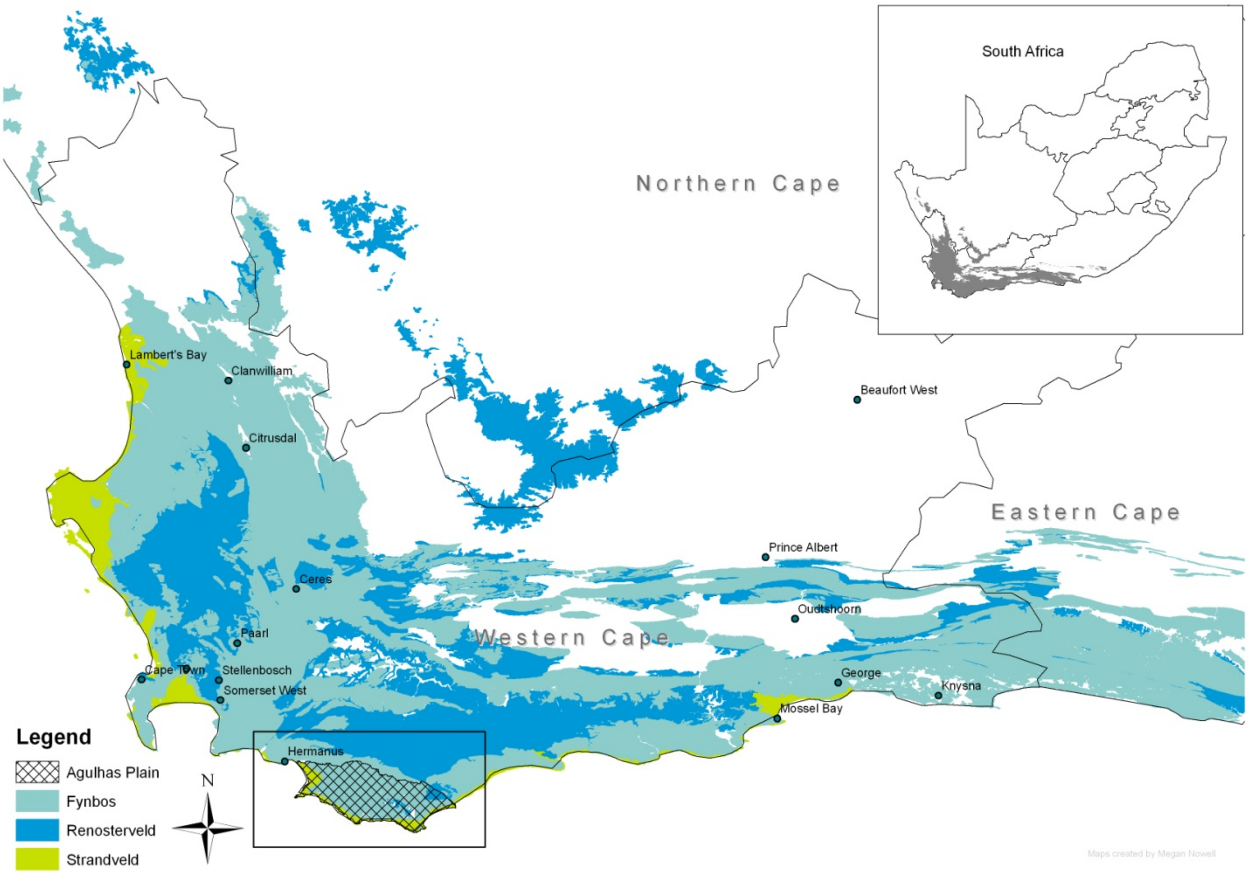

Figure 1.1: The Agulhas Plain is located at the southern tip of South Africa at the heart of the Cape Floristic Region.

The exceptional biodiversity of the AP is highly threatened by invasive alien plants. The dominant species are *Eucalyptus*, *Pinus*, and *Acacia* species. These three families account for 93% of the invasive species found on the AP (Cole et al. 2000). Much of the eucalyptus and pines have been planted as wind-breaks and as plantations, as well as around homesteads. The seeds are predominantly spread across the landscape in the direction of the wind. The mountainous areas are scattered with young pines in low densities. Eucalypts drop their seed below parent trees forming clustered stands. The leaves contain volatile oils which make them very flammable. After fire, eucalypts resprout (Bellingham & Sparrow 2000). *Acacia* species colonize the deep sandy coastal areas where they form closed stands with large seed banks (Holmes et al. 2000; van Wilgen et al. 1998). After fire, these seed banks germinate and may establish closed stands after only one or two fire cycles (Holmes et al. 2000). The riparian areas on the Agulhas Plain are densely invaded and in some cases the river has run dry above ground. This has significant impacts on the wetland areas and estuaries that are fed by these rivers.

Thesis outline

Interdisciplinarity is essential for the study of complex systems (Newell 2001). This is of particular relevance for this study which explores the impact on a complex ecosystem. An interdisciplinary approach was taken to determine the hydrological impacts of clearing invasive alien vegetation. This thesis encompasses a combination of different disciplines, namely geoinformatics, invasion ecology, and ecohydrology. Each chapter is a blend of technology, a touch of ecology, plenty invasion biology and of course, implications for management. The three data chapters are laid out as publishable papers so do expect a modest amount of repetition.

Chapter 1 is a review of the literature pertaining to invasion ecology, remote sensing and hydrological modelling. This chapter provides the background information on the topics covered in the thesis. I have Jesse Kalwij to thank for his invaluable technical input into Chapter 2. **Chapter 2** is a methodological chapter exploring the use of remote sensing for mapping invasive vegetation in fynbos areas. Three commonly used remote sensing techniques were evaluated for their accuracy of mapping vegetation. NDVI was found to be the most accurate technique and was used to create an up-to-date invasion map of the Agulhas Plain. When this map was compared to the reference invasion map, a low level of agreement was found for the spatial distribution of invasive vegetation. The influence of fire and clearing events as drivers for the change in spatial distribution of IAPs over time was assessed in **Chapter 3**. Karen Esler was a major role player in this chapter. Although limited conclusions could be drawn regarding fire as a promoter or inhibitor of invasion, an explanation for the change in spatial distribution since 2000 was found. **Chapter 4** was the final data chapter. The quantity of water made available by clearing invasive vegetation was calculated. These values were used to determine priority areas for clearing from a hydrological perspective. I thank David Le Maitre for guiding me through Chapter 4 and for his indispensible input into the previous two chapters. Finally, the long term benefits of clearing invasive vegetation under different scenarios were assessed in **Chapter 5**. The major conclusions and recommendations from the thesis were summarised in this chapter.

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Chapter 1

A review of the literature on invasive alien plants, remote sensing and hydrological modelling

1.1. Invasive alien plants

1.1.1. Definition

A simplified definition of an invasive alien plant is a non-indigenous plant species that has been introduced to an area, has become naturalized and is able to disperse and establish over large areas. Richardson et al. (2000) define “introduction” as the transportation of the plant or propagule across a major geographical border by humans. A plant is “naturalized” when it is able to overcome the abiotic and biotic barriers that limit reproduction and sustain populations over generations. Finally, a plant is considered “invasive” when naturalized species are able to produce seeds and propagules in very large numbers and are able to spread over a considerably large area (McGeoch et al. 2006).

These various stages of invasion can be broken down into five phases. Not all species introduced to an area will achieve these phases of invasion, however this information is important for assessing the progress of reducing this threat to biodiversity (McGeoch et al. 2006).

According to Richardson (2000) five phases of invasion exist:

1. **Introduction:** Propagules are introduced to an area outside their previous geographical range and establish adult populations.
2. **Colonization:** The adult population is able to reproduce, establishing a colony.
3. **Naturalization:** The colony establishes new populations and continues to disperse.
4. **Invasive:** The species reproduces in large numbers and spreads over a considerable area.
5. **Transformer:** The species begins to change the character, condition, form or nature of the ecosystem.

1.1.2. Threat to global biodiversity

A species may not necessarily be invasive or damaging in its native habitat, but when introduced to a new set of climatic and environmental conditions, the character traits and survival strategies of the plant species may result in it having a competitive advantage over native biota. Ignorance and lack of regulations and/or enforcement exacerbate the problem (McGeoch et al. 2006). An uncontrolled increase of IAPs has the potential to threaten biodiversity by altering ecosystem processes and displacing native species. The dominance of IAPs can eventually lead to environmental and economic losses (Pimentel et al. 2005; Sakai et al. 2001)(See Appendix A).

Studies have shown that IAPs demonstrate characteristics of pioneer species (germinate quickly with fast initial growth), have shorter generation times, high fecundity and high growth rates (Radford & Cousens 2000; Sakai et al. 2001). When plants with these traits are introduced into new areas where their native predators are absent, they have a competitive advantage with respect to water, nutrients, sunlight and space (Higgins et al. 1996; Richardson et al. 1996). IAPs also change the natural landscape by destabilizing catchments and thereby increasing soil erosion, altering fire regimes and hydrology, as well as changing the physical and chemical composition of the soil (Joshi et al. 2004; Le Maitre et al. 1996; Tabacchi et al. 2000). For these reasons, invasive alien vegetation is considered to be a major threat to biodiversity globally (Reid et al. 2009; Solarz 2007; Wal et al. 2008).

1.1.3. The IAP problem in South Africa

South Africa's IAPs have been introduced into the country for various reasons. Some were brought in as ornamentals, while others were used for forestry and agriculture (Cowling & Richardson 1995). The extent of invasion was estimated to cover a total of 10 million hectares or 8% of the country's land surface in 1997 and the area infested is still spreading (Henderson 2007; Le Maitre 2000). The Western Province has the highest level of infestation with a total of 28.82% of its area dominated by invasive vegetation (Binns et al. 2001; Le Maitre 2000). This invasive vegetation could double its impact every 15 years if it continues to invade at the current rate of 5% per year (Binns et al. 2001).

The end of the apartheid in South Africa gave an opportunity for many pressing issues to be addressed, such as the water supply crisis and the growing concern about the spread of invasive alien vegetation (Binns et al. 2001). Studies showed that this woody vegetation uses significant quantities of water, especially in mountain catchment areas (Dye & Jarmain 2004; Hope et al. 2009). In a country where rainfall is inadequate and unreliable and water resources are already under considerable demand from agriculture, urbanization and industry, IAPs exacerbate the water shortage problem (Binns et al. 2001). Most of South Africa is classified as semi-arid. Around 70% of the country receives less than 600mm of rainfall a year. Of this figure, 20% receives less than 200mm (Binns et al. 2001). According to the report, 'State of Freshwater Systems and Resources' (DEAT 1999), South Africa has one of the lowest Mean Annual Precipitation to Mean Annual Runoff ratios in the World with only 8.6% of precipitation being converted into excess runoff. The country's main catchment areas cover 10% of the country's land area, yet contribute over 50% of its water (Hosking & du Preez 1999). IAPs reduce the annual flow of South Africa's rivers by an estimated 4-7%, (Binns et al. 2001; Cullis et al. 2007). This quantity of water could meet the needs of 7.4% of South Africa's population of 49 million people (Gleick 1996).

1.1.4. History of IAP studies in South Africa

The potentially detrimental impact of invasive alien plants (IAPs) on natural fynbos vegetation in South Africa was recognized as far back as the early 1900s, although it was not until 1945 that the hydrological implications associated with invasion became a concern (van Wilgen et al. 1997). Professor C.L. Wicht, the father of forest hydrology in South Africa, was the first to recognise that invasive vegetation would increase 'loss of moisture' which was at that stage 'an unknown quantity' (van Wilgen et al. 1997). Wicht, working for the former South African Forestry Research Institute, set up experiments in Jonkershoek to determine the hydrological impacts of afforestation. In 1968 Malherbe documented the direct reduction in streamflow as a result of these plantations (Dye & Versfeld 2007). It was not until 1977 when Fred Kruger, a student of Wicht, published the first figures on water loss from invasive vegetation. Kruger concluded that 'extensive invasion of the Cape mountains is therefore very likely to have a serious impact on regional water supplies' (van Wilgen et al. 1997). From the 1970s onwards, tens of thousands of hectares of invasive plants were cleared and research on the problem intensified with these efforts. This research culminated in 1986 when a formal synthesis of the invasive species problem and the impact on water resources was published (van Wilgen et al. 1997). Shortly afterwards, political constraints saw the integrated control programmes lose momentum and funding and were eventually disbanded. Invasive plants began to re-invade the areas that had been cleared over the past decade. It was not until 1992 when Cowling published a book on the Fynbos biome in which it was reiterated that water resources decreased with increased invasion. This reduction in water would be devastating for water supplies to cities, industry and agriculture should the spread of invasive vegetation remain unchecked. These predictions resulted in the Department of Environmental Affairs funding a project that aimed at integrating the knowledge and lessons learnt in the past decade to determine the consequences of not managing invasive vegetation. The results were convincing and resulted in the Minister of Water Affairs, Kader Asmal, backed by a team of scientists, launching the Working for Water Programme (van Wilgen et al. 1997).

1.1.5. Working for Water

The Working for Water (WfW) programme was launched by the South African government in 1995 with the aim of sustainably controlling invading species across the country by employing underprivileged people as the task force. This programme was devised to address the social, economic and environmental issues, thereby improving the water supply for urban and rural areas alike (Binns et al. 2001; Dye et al. 2001; Dye & Versfeld 2007). The objectives of WfW are to "enhance water security, improve the ecological integrity of natural systems, restore the productive potential of the land, invest in the most marginalized sectors in South Africa and enhance their quality of life through job creation, and to develop economic benefits from wood, land, water and trained people" (WFWP 2000).

The 'Working for Water programme is (said to be) the most effective and efficient poverty relief instrument of the government' (WFWP 2000) and possibly 'one of the most successful integrated land management programmes in the world' (Hobbs 2004). Although the Working for Water programme is regarded as an effective social and economic development tool (Binns et al. 2001), there is very little scientific evidence to validate the clearing of IAPs from a hydrological viewpoint (Dye et al. 2001). One justification for the founding of the programme is that streamflow is enhanced by the clearing of IAPs (Dye et al. 2001; Dye & Versfeld 2007). According to Dye et al. (2001) limited data are available to support this assumption. The impact alien plant eradication has on streamflow remains largely unknown (Dye et al. 2001).

1.1.6. Mapping and monitoring IAPs

Management agencies operating at the landscape level require up-to-date information on land cover in order to formulate policies and make appropriate resource management decisions (Carrao & Goncalves 2006; Roura-Pascual et al. 2009; Rowlinson et al. 1999). This is particularly true for the management of invasive alien plant species, whose spatial distribution and cover can change rapidly, impacting management decisions (Higgins et al. 1996). Invasion maps are typically not updated often enough because of the time and expenses required to do so (WFWP 1999). As a result, invasion maps for South Africa are limited to coarse resolution data or isolated local scale studies (Poona & Shezi 2010; Van den Berg 2010). The most comprehensive IAP map available is the South African Plant Invader Atlas (SAPIA) mapped at a scale of quarter degree grid cells (27.78 km^2) (van Wilgen et al. 2001). This coarse scale is not sufficient to determine spatial estimates of invaded areas (van Wilgen et al. 2001).

An option for bridging the gap in data records is remote sensing. Many remote sensing techniques exist and can be used to characterize landscapes in a biologically meaningful manner (Gould 2000; Rogan & Chen 2004). Diversity patterns, changes and variation can be mapped at varying scales. Archived satellite images are a valuable retrospective monitoring tool that can provide the data necessary for modelling the spread and eradication of IAPs over time. Invasive alien plant species can be distinguished from native vegetation using techniques that exploit the differences in phenology, as well as the spectral and structural characteristics of plant species (Elmore et al. 2000; Jiang et al. 2006; Maselli 2004; Underwood et al. 2003; Weiss et al. 2004). In combination with Global Positioning System (GPS) and Geographic Information System (GIS) technologies, remotely sensed data can provide a platform on which to base sound decisions and management strategies (Gould 2000; Rogan & Chen 2004; Zavaleta et al. 2001).

1.2. Remote sensing

1.2.1. Definition

Remote sensing refers to the process of acquiring and recording information about an object without having direct contact with that object (Gibson & Power 2000). The result is a digital image containing information about the energy reflected by the object of interest. The main objective of remote sensing is to translate this raw digital image into an accurate and useful classified image (Verbyla 1995).

1.2.2. Advantages of remote sensing

Satellite images can be acquired for all habitats, over large spatial areas, and for frequent repeat cycles. Images can also be acquired relatively quickly, are cost effective and image processing can be automated thereby reducing labour costs (Kotzé & Fairall 2006; Underwood et al. 2003). Archived satellite images are a valuable retrospective monitoring tool. Multispectral imagery with a multi-temporal coverage allows for land cover changes to be detected and rates of change to be quantified (Joshi et al. 2004). In addition, remote sensing has been suggested and explored as a possible technique for creating invasion maps in South Africa (Cobbing 2006; Gibson & Low 2003; Poona & Shezi 2010; Van den Berg 2010).

1.2.3. Disadvantages of remote sensing

Although field work is reduced, image processing may be time consuming as a result of the spatial extent of these images (Underwood et al. 2003). Images also need to be orthorectified prior to analysis, which can take time (Underwood et al. 2003; Ustin et al. 2002). Another disadvantage of using remote sensing is that satellite images are sensitive to weather conditions such as cloud cover and care must be taken when choosing appropriate time periods (Kakembo et al. 2006). It may prove difficult to obtain cloud free images of areas such as mountain tops and tropical forests that are prone to cloud cover. Shadows and bare soil may also influence the results of remote sensing techniques. Exposed areas of ground have been found to influence vegetation index (VI) values (Elmore et al. 2000; Weiss et al. 2004) and light reflecting off these areas may modify VI values by up to 20% (Kakembo et al. 2006).

1.2.4. Background to remote sensing

Remotely sensed information can be acquired in one of two ways. The first and oldest form of remote sensing is aerial photography. In most cases a camera is fixed to an aircraft providing the user with photographs that are sensitive from the high ultraviolet to the infrared part of the electromagnetic spectrum (Gibson & Power 2000). Essentially a scene is captured of all visible wavelengths. Aerial photographs are available since the 1930s (Kalwij et al. 2005), however they are only available for limited areas and at irregular intervals. This is because aerial photography was primarily a military activity with little need to repeat surveys. It was only after the 1950s that aerial photography was used for non-military surveys. Aerial photography is a time consuming and expensive exercise resulting in more photographs being available for populated areas or areas with a specific interest, such those with forestry, mining or conservation efforts.

Another type of remote sensing is satellite imagery. A satellite image differs from a photograph in that information is obtained through sensors rather than capturing a scene through a lens. These sensors are sensitive to more wavelengths such as the thermal infrared and microwave part of the electromagnetic spectrum. This means more data about any given area can be acquired. Satellite images consist of either one or several bands or layers of information about the energy emitted from the Earth. Each layer contains information regarding the wavelengths reflected by the landscape below. If multiple layers are recorded, this is referred to as multispectral imagery. Most modern satellite images are multispectral. To make this information meaningful, false colouring is often used. Different colour combinations are used to give two similar surfaces more differentiation (Gibson & Power 2000). Under false-colouring, vegetation often has a characteristic red colour. This is a result of the high infrared reflectance by vegetation.

Remote sensing using satellite imagery can be further classified into two approaches: passive and active. Passive remote sensing is the most commonly used approach and relies on the energy of the sun. The system measures the amount of electromagnetic radiation reflected or emitted from a surface (Gibson & Power 2000). When a scene is captured, a component of the reflectance measured is due to scattering as the sun's radiation passes through the atmosphere. Shorter wavelength radiation is affected more than long wavelengths. Two common examples of passive remote sensing platforms are SPOT and Landsat imagery. Both types of imagery rely on the sun's energy as the primary source of electromagnetic radiation. The fundamental difference between the two types of imagery (besides resolution differences) is the scanner. Landsat uses a transverse scanner which has a rotating mirror that directs the reflectance onto a row of detectors. These detectors measure the strength of the signal in wavelengths.

Information is obtained from different detectors that are best suited to capture a specific wavelength or range of wavelengths. For example, Landsat uses three different types of detectors because silicon detectors are more sensitive to the visible and near-infrared spectral region, while indium-antimonide detectors are best suited to the mid-infrared spectral region and the thermal red spectral region is best captured by mercury-cadmium-telluride detectors (Verbyla 1995). Detectors pick up different wavelengths as the satellite travels over different land cover types below. Water absorbs more light and therefore will produce a weaker signal. Open ground has a high spectral reflectance.

SPOT on the other hand, uses a push-broom scanner, which consists of thousands of charge-coupled devices. Each detector measures a "ground-resolution cell", a small area within its range. Irrespective of the type of scanner, the wavelengths are converted into a scene in digital format. This information is stored in a pixel format. Each image is divided into a grid, each grid cell being referred to as a pixel. The size of this pixel depends on the spatial resolution of the imagery (the fineness of detail) and can range from centimetres as used by the military to a kilometre as with NOAA's AVHRR images. The spectral reflectance of each pixel cell is stored in a digital format that can be used to classify the image.

The second approach to remote sensing is active remote sensing. In this technique, a specific wavelength is generated by the system and the energy that is scattered back by the surface is recorded. The most well known form of active remote sensing is radar, where the time delay between the transmission of the wavelength and its return as well as the strength of the returned signal are used to produce a signature for the object below (Gibson & Power 2000). Radar has the advantage of being able to penetrate cloud cover and is especially useful for tropical regions (Gibson & Power 2000).

1.2.5. Types of satellite imagery

The first satellites designed for Earth observation were launched in the 1960s. Landsat was launched in 1972 and continues to orbit the Earth, capturing images at regular time intervals, providing users with an invaluable retrospective monitoring tool. Since then, tens of satellites have joined Landsat in orbit, each designed to meet the demand to monitor different priorities, such as the ocean, the polar ice caps, the atmosphere, Earth’s surface, etc. (Tatem et al. 2008). Spatial (the fineness of detail) and temporal (return period) resolution differs between images. SPOT 5 launched in 2002 provides images with a spatial resolution of up to 2.5m with a frequent return period, while Landsat 7 has a return period of 16 days and a spatial resolution of 30m for bands 1 to 7 and 15m for the panchromatic band (band 8). AVHHR on the other hand, has a daily return period, but the spatial resolution is a coarse 1.1km. Different spatial and temporal resolutions are best suited for different studies and need to be carefully considered when selecting imagery. Many other types of imagery are also available, but for the purpose of this study, only SPOT 5, SPOT 4, Landsat 7, MODIS, MERIS and ASTER imagery will be considered as there are accessible and can be acquired free of charge. It must be noted that Landsat 7 images are not available after 2003 due to an error with the scanner causing sweep-lines. The specifications, advantages and disadvantages of each are presented in the Table 1.1.

Spatial resolution is often the main consideration when selecting satellite imagery, however spectral resolution must also be taken into account. Spectral resolution refers to the ability of the remote sensing instrument to detect the electromagnetic spectrum. The greater the spectral resolution, the more spectral differences will be discerned and in turn, more vegetation types and land covers can be delineated (Conway & MSGC 1997; Verbyla 1995).

Table 1.2: The advantages, disadvantages and attributes of the multi-spectral satellite imagery that were considered for this study.

Imagery	Spatial resolution	Number of bands	Return period	Cost	Advantages	Disadvantages
AVHRR	+1km	6	12 hours	Free	▪ Excellent temporal resolution ▪ Reduced cloud cover ▪ Fast processing	▪ Very coarse resolution
QuickBird	0.6-2.44m	4	1-4 days	+$\$16/km^2$	▪ High resolution	▪ Expensive for large areas
MODIS	250-1000m	36	1-2 days	Free	▪ Images can be acquired already processed for NDVI, EVI and LAI ▪ Widely used ▪ Free of charge	▪ Cloud cover ▪ Coarse resolution
MERIS	260x300m	15	3 days	Free	▪ Good spectral resolution ▪ Free of charge	▪ Excessive cloud cover ▪ Coarse resolution
ASTER	15-90m	14	16 days	No access	▪ Good spatial resolution ▪ Good for vegetation mapping	▪ No access to non-NASA employees
Landsat 7 ETM+	15-60m	8	16 days	Free	▪ Good spatial resolution ▪ Commonly used for land cover mapping ▪ Free of charge	▪ Scan lines with missing data
SPOT 4	10-20m	4	<26 days	Free	▪ Good spatial resolution ▪ Free of charge	▪ Not compatible with tasseled cap transformation ▪ Geo-referencing required
SPOT 5	5-20m	5	<26 days	€1900	▪ Excellent spatial resolution ▪ Good for vegetation mapping	▪ Expensive

1.2.6. Pre-processing techniques

Pre-processing techniques are used to correct and enhance information from imagery. Image restoration techniques are used to correct data errors, noise and geometric distortions occurring during image capturing. These techniques include radiometric and geometric corrections as well as haze and noise reductions. Line dropouts and offsets can also be restored. Image enhancement is a pre-processing technique that is used to alter the visual impact of the image. Enhancements include contrast, saturation, stretching, filtering as well as creating mosaics (Sabins 1996).

1.2.7. Remote sensing techniques

Many remote sensing techniques exist and can be used to characterize landscapes in a biologically meaningful manner (Gould 2000; Rogan & Chen 2004). Diversity patterns, changes and variation can be mapped at varying scales. Three remote sensing techniques were selected for this study and are reviewed below. These techniques were selected because they have been used for monitoring land cover changes on the Agulhas Plain or in Mediterranean type ecosystems such as the Cape Floristic Region. NDVI was used in the most commonly used vegetation index and was used in the studies of Fatoki 2007, Hope et al. 2009, Díaz-Delgado et al. 1998 and Fernández et al. 2010. The Table Mountain Group Pilot Study 2004 and Engelbrecht et al. 2005 used the Tasseled cap transformation in the Agulhas Plain area. Supervised classification has been used by Rouget et al. 2003 to map invasive alien vegetation in the Cape Floristic Region, and by Berberogu & Akin 2009 to detect changes in land cover in a Mediterranean ecosystem.

The Normalised Difference Vegetation Index (NDVI) is the most commonly used measure of vegetation cover in remote sensing (Jiang et al. 2006; Kakembo et al. 2006). Almost 90% of spectral information relevant to vegetation is contained in the red and near-infrared portion of the electromagnetic spectrum (Fatoki 2007). NDVI uses the red (R) and near-infrared (NIR) bands and is calculated using Equation 1.1.

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}$$

Equation 1.1: Equation for calculating the Normalised Difference Vegetation Index.

The resulting NDVI pixel value is a value between -1 and +1. Positive values indicate green, vegetated areas (Weiss et al. 2004). A value closer to +1 indicates vegetation with higher water content and a higher rate of photosynthesis. Negative NDVI values are characteristic of un-vegetated areas such as water or bare soil (Weiss et al. 2004). NDVI is most suited to vegetation mapping and decreases in accuracy with lower densities of vegetation (Broge & Leblanc 2001).

Tasseled cap transformationis another type of spectral enhancement. Tasseled cap works differently to NDVI (which uses an equation to combine red and infrared into a single value). Tasseled cap is a type of transformation that compresses the volume of data to three essential bands: red, green and blue (Crist & Kauth 1986; Huang et al. 2002). The red band gives an indication of brightness which is used to identify low vegetation and strong reflectors such as bare soil. The green band is used to map and monitor vegetation based on the ‘greenness’ of the pixel. The final band, the blue band, indicates wetness and is used to identify water or moisture. Each pixel consists of a combination of these three bands which can be used to classify an area.

The third technique explored in the study was supervised classification. This form of classification does not necessarily use enhancements or transformations, although the technique can be performed on enhanced or transformed imagery. The objective of this automated classification is to cluster pixels into classes based on similarities in the spectral signatures. Supervised classification requires an analyst to select training classes (representative spectral signatures) for each land cover type which are then automatically extrapolated to the entire image. This technique may result in under- or over-representation of classes based on similarities in spectral signatures.

1.2.8. Application for vegetation mapping

Remote sensing has long been used to monitor vegetation cover, going back to the 1980s (Tueller 1989). Almost 90% of spectral information relevant to vegetation is contained in the red and near-infrared portion of the electromagnetic spectrum. This is because shorter wavelengths, such as infrared are more readily absorbed by water in the leaf. The spectral response depends on the chlorophyll of the plant (Underwood et al. 2003). As chlorophyll is an indicator of the health or vigor of the plant, classification can be based on how much light is absorbed (Fatoki 2007). Chlorophyll a and b absorb red and blue light in order to photosynthesize. Green light is reflected which is why plants appear green to human eyes. Photosynthesis is the process in which light and carbon dioxide are converted into chemical energy and oxygen. As a plant grows older and begins to senesce, the chlorophyll breaks down and the red wavelengths are reflected, giving a plant an orange or brown appearance. This spectral response from satellite imagery can be used to distinguish age classes, health and other parameters of the vegetation (Fatoki 2007; Rouget et al. 2003).

Invasive alien plant species can be distinguished from native vegetation using techniques that exploit the differences in phenology as well as the spectral and structural characteristics of plant species (Elmore et al. 2000; Jiang et al. 2006; Maselli 2004; Underwood et al. 2003; Weiss et al. 2004). Studies have shown NDVI values to be dependent on canopy coverage, productivity, leaf area, foliage chlorophyll absorption and the phenology of plants (Elmore et al. 2000; Jiang et al. 2006; Maselli 2004; Weiss et al. 2004). These properties can be exploited to distinguish invasive alien plants from the natural fynbos vegetation (Underwood et al. 2003). Medium and tall alien trees have a broader leaf area than fynbos as well as a higher level of productivity and water use (Stock et al. 1995). These characteristics enable medium and tall alien trees to be detected using NDVI.

1.2.9. Remote sensing for mapping IAPs in South Africa

Remote sensing (RS) has been used to map invasive vegetation and land cover across the globe as well as in South Africa (Joshi et al.; Souci & Doyle; Underwood et al. 2003). Some examples of remote sensing of invasive alien plants (IAPs) in the Cape Floristic Region (CFR) are the studies by Rouget et al. (2003), Cobbing (2006) and Fatoki (2007). Poona and Shezi (2010) and van den Berg (2010) have explored the use of remote sensing to map invasive vegetation in other parts of the country. Rouget et al. (2003) mapped IAPs in the CFR using Landsat 7 ETM+ imagery and supervised classification. Supervised and un-supervised classification are two examples of RS techniques that are used to classify satellite images based on similarities in spectral signatures. These techniques were also used by Cobbing (2006) who found them to be the most cost and time effective RS techniques for mapping IAPs. He also found that Landsat 7 imagery can be used to map *Acacia* species with a 75% level of accuracy. Fatoki's (2007) study was able to determine the IAP re-growth rate after fire on the Agulhas Plain using MODIS imagery and Normalised Difference Vegetation Index (NDVI). NDVI is a spectral enhancement technique used to classify vegetation based on the water content and foliage chlorophyll absorption of plants. Poona and Shezi (2010) found SPOT 5 derived NDVI to be the best RS technique for mapping IAPs in a heterogeneous landscape. NDVI was also used by van den Berg (2010) to map the distribution of *Prosopis* species in the arid Northern Cape with 72% accuracy.

1.3. Hydrological modelling

1.3.1. Definition

The aim of a hydrological model is to represent the natural hydrological system of a catchment area, a river system, groundwater flow path or other systems associated with water (Kite & Pietroniro 1996; Trimble 2007). This representation can either be physical or numerical. Physical models provide a scaled representation of the process, while numerical models use mathematical equations and are computer based. Numerical models allow more flexibility to test different conditions and are often used to forecast predictions under proposed circumstances (Trimble 2007). Because there are so many aspects of the hydrological system that need to be considered such as runoff, infiltration, groundwater flow and interception, a model is often the only way of measuring, monitoring and making predictions about it, especially if new factors change or interfere with the natural system (Xianghu et al. 2008).

1.3.2. Hydrological system

The hydrological cycle is driven by solar energy which causes water to evaporate from the ocean and water bodies and condense as clouds before falling back to the ground as precipitation. During a precipitation event, rain will fall to the Earth's surface and either be absorbed into the soil or it will flow over the land's surface. Runoff is excess water on the land's surface that occurs when soil is saturated (Le Maitre et al. 1999). Runoff flows downhill and feeds into rivers and other water bodies. The water that is absorbed into the soil will either be intercepted by vegetation where it will be stored for growth or returned to the atmosphere through evapotranspiration. Alternatively, it will infiltrate the soil and become soil moisture or groundwater until it too eventually makes its way to a water body or is brought to the surface via a borehole, well, fountain or plants roots (Fatoki 2007). Many woody invasive alien plants are able to access this groundwater due to their competitive life history traits (Le Maitre 2000). This ability to remove water from the water balance of a catchment causes a shift in the equilibrium of the water balance equation. For a given catchment, the inputs (rainfall, condensation, etc.) into the hydrological system equal the outputs (runoff, evaporation, etc.). Invasive vegetation increases the outputs through evapotranspiration and thereby changing the storage of the system. Because this process is often over a relatively large temporal scale, it is impossible to predict future impacts without modelling (Xianghu et al. 2008).

1.3.3. Hydrological modelling of water resources

In recent years, water shortages have been a major challenge for the sustainable development of many countries (Liu & Zheng 2004). Hydrologists and water resource managers require information about the changes in the hydrological cycle for adaptive management strategies in water resource use (Liu & Zheng 2004)., Changes in hydrology as a result of invasion by alien vegetation or their removal are an essential consideration for managing South Africa’s limited water resources. Modelling changes in the components of the water cycle, such as streamflow or evapotranspiration, provides information on the water balance of a catchment. Modelling the changes in the water balance equation for a given catchment requires environmental inputs and well as knowledge of the hydrological system. Hydrological models vary in complexity, but the commonality is that the spatial distribution of inputs (such as topography, vegetation types, rainfall etc.) are incorporated to produce spatially accurate outputs predicting the impacts on various components of the water cycle, such as soil moisture dynamics, ground water fluxes and the level of the water table (Troch et al. 2003).

1.3.4. Application of remote sensing for hydro modelling

Hydrological modelling is a powerful and essential tool for water resource management, however hydrological systems are highly complex and modelling them can be time consuming and labour intensive (Liu & Zheng 2004). Remote sensing is a logical and effective means of acquiring accurate hydrological data at large scales over frequent repeat cycles (Engman 1996). This technique offers a considerably more time and cost effective means of providing the necessary inputs for hydrological models and has been suggested as the only viable option for providing data for hydrological models (Engman 1996; Xianghu et al. 2008). The SEBAL model is one such example of a hydrological process-based model.

1.3.5. The SEBAL model

The complexities of the hydrological cycle as well as natural heterogeneity mean that calculating evapotranspiration (ET) is not straightforward (Bastiaanssen et al. 2005). The Surface Energy Balance Algorithm for Land (SEBAL) is an energy balance model used to calculate actual ET. SEBAL is based on latent heat flux (the flux of heat from the Earth’s surface to the atmosphere when water evaporates) which provides a direct measurement of ET. This model uses inputs from satellite imagery as well as environmental data obtained from weather stations. Evapotranspiration is useful as an indicator of evaporative depletion and to provide a better understanding of relationships between different land uses and their effect on hydrology (Bastiaanssen et al. 2005). For example, ET can be used to indicate the impacts invasive alien plants have on the hydrology of an area.

Remote sensing is the only direct means of obtaining ET data from the SEBAL model without knowledge of the physical conditions of the area such as crop, soil and management conditions (Bastiaanssen et al. 1998a; Bastiaanssen et al. 2005). This model provides spatio-temporal data, which are essential for making accurate estimations of ET in order to manage water systems at different scales. SEBAL has sufficient spatial detail to allow analysis at a field, project and catchment scale. It also has the advantage of covering large areas so as to include entire river basins as well as taking non-optimal growing conditions into account (Bastiaanssen et al. 2005). Minimal collateral data are needed and the SEBAL model can be applied to various climates as it is a physical concept. Considerations when using SEBAL are that images used for input must be cloud-free, drylands and wetlands must both be present in the image for calibration purposes and this model is best suited to flat terrain (Bastiaanssen et al. 1998a).

Although SEBAL can be used at various scales, the resolution of the model ultimately depends on that of the input. As satellite imagery is the primary input source, the spatial resolution is an important consideration. A study performed by the Council for Scientific and Industrial Research (CSIR) and Water Watch was aimed at modelling the provinces of Kwa-Zulu Natal and the Western Cape using the SEBAL model and MODIS imagery (Meijninger & Jarmain In prep.). MODIS imagery has a medium to coarse spatial resolution which is advantageous in that it reduces processing time, but at the same time reduces the scale of the model. Although ET could be measured for pixels 250x250m in diameter, fine-scale conclusions such as changes in water use by specific vegetation could not be evaluated.

SEBAL has the potential to be a useful tool for modelling water use and streamflow reduction (Bastiaanssen et al. 2005). Versfeld (1998) identified the need for a more advanced system for modelling evapotranspiration at a wide range of scales. SEBAL fulfils this need and has the added advantage of temporal repeatability. In addition, this model measures actual evapotranspiration which can be used to quantify how much water is made available by clearing invasive alien vegetation.

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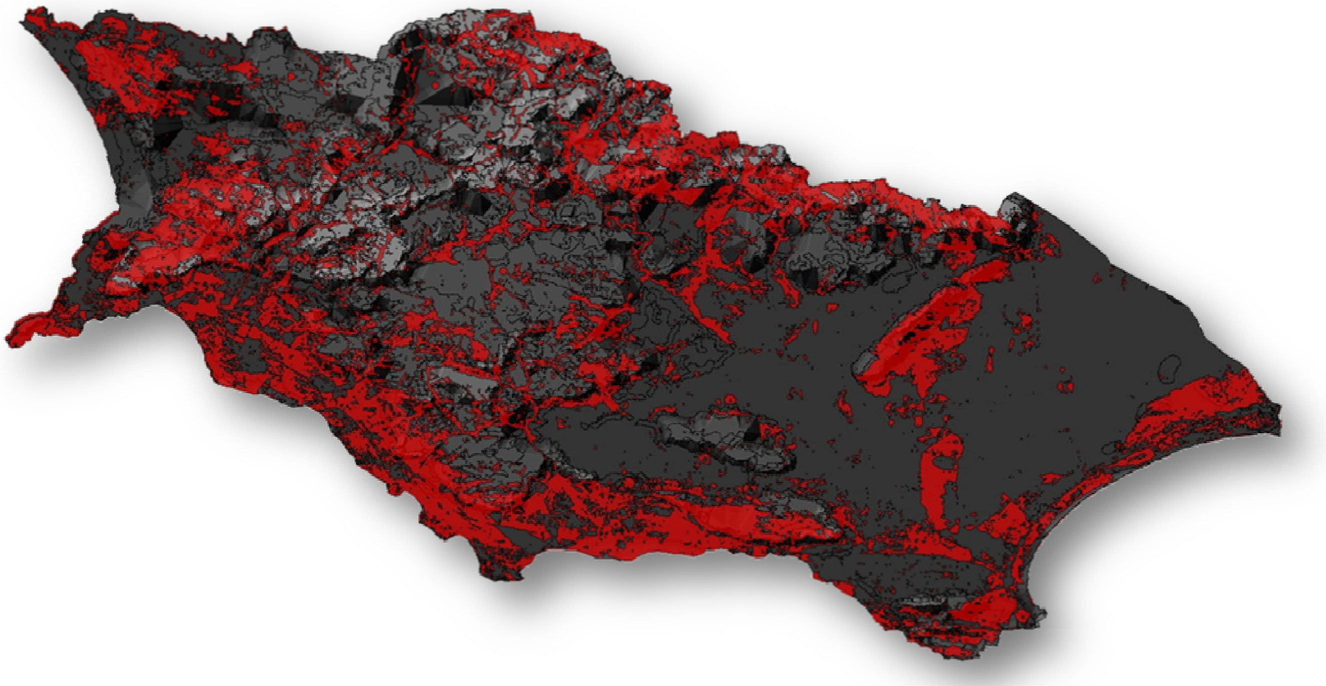
Chapter 2

Using remote sensing to map invasive alien plants on the Agulhas Plain



Preamble from a personal point of view:

Thomas Fuller once said, "All things are difficult before they are easy." This bittersweet chapter was that necessarily difficult thing that ensured smooth sailing for the chapters that follow. My previous experience with remote sensing was dismal, but I had two tiny details in my favour. First and foremost, I knew where to get satellite imagery. I had a starting point for my journey. The second point in my favour was that I could spend hours absorbed in the aesthetics of an image of Earth as seen from space. In retrospect, this somewhat strange obsession was what probably saved me from the depths of insanity. The hours that I spent staring at satellite images to realise this thesis are like the stars, many, some bright and hopeful, some faint and fading. Granted, there was the odd supernova and the occasional nebula, but mostly, I spent my time rerouting the flight plan around and out of black holes. My notebooks are littered with the problems encountered followed by page after page of failed solutions, until finally, "problem solved," that glorious victory, etched in blood and tears... figuratively of course. "Victory is sweetest when you've known defeat."

2.1. Abstract

Remote sensing is a powerful and valuable tool for retrospectively mapping and monitoring the spread of invasive alien vegetation over time. Remote sensing techniques can provide up-to-date information at a landscape scale that can be used by land management agencies such as Working for Water, to make sound management decisions and prioritize clearing strategies. Three remote sensing techniques were explored in this study. SPOT 4 derived NDVI was found to be the most accurate technique for mapping vegetation, although invasive alien vegetation below a 50% invasion density could not be detected. Despite this, the technique is able to provide land management agencies with information on invasion and changes in land use at a landscape scale.

2.2. Introduction

Land cover is transformed over time by urbanization, conversion to agricultural practices, and invasion by alien plants (IAPs) (Carrao & Goncalves 2006; Lombard et al. 1997; Rebelo 1992; Rouget et al. 2003). Management agencies operating at the landscape level require up-to-date information on land cover in order to formulate policies and make appropriate resource management decisions (Carrao & Goncalves 2006; Roura-Pascual et al. 2009; Rowlinson et al. 1999). This is particularly true for the management of invasive alien plant species, whose spatial distribution and cover can change rapidly, impacting management decisions (Higgins et al. 1996). Invasion maps are typically not updated often enough because of the time and expenses required to do so (WFWP 1999). As a result, invasion maps for South Africa are limited to coarse resolution data or isolated local scale studies (Poona & Shezi 2010; Van den Berg 2010). The most comprehensive IAP map available is the South African Plant Invader Atlas (SAPIA) mapped at a scale of quarter degree grid cells (27.78 km2) (van Wilgen et al. 2001). This coarse scale is not sufficient to determine spatial estimates of invaded areas (van Wilgen et al. 2001).

Studies have shown that IAPs demonstrate characteristics of pioneer species. They germinate quickly with fast initial growth, have shorter generation times, high fecundity and high growth rates (Radford & Cousens 2000; Sakai et al. 2001). When plants with these traits are introduced into new areas where their native predators are absent, they have a competitive advantage with respect to water, nutrients, sunlight and space (Higgins et al. 1996; Richardson et al. 1996). IAPs also change the natural landscape by destabilizing catchments and thereby increasing soil erosion, altering fire regimes and hydrology, as well as changing the physical and chemical composition of the soil (Joshi et al. 2004; Le Maitre et al. 1996; Tabacchi et al. 2000). For these reasons, invasive alien vegetation is considered to be a major cause of global biodiversity loss (Joshi et al. 2004; Mooney & Hobbs 2000; Reid et al. 2009; Solarz 2007; Wal et al. 2008).

Concern over the reduction of water resources and loss of biodiversity as a result of extensive invasion, in particular woody tree species, led to the launch of the Working for Water (WfW) programme by the South African government in 1995 (van Wilgen et al. 1997). The programme aims at sustainably controlling invading species across the country by employing underprivileged people as the task force. Working for Water was devised to address social, economic and environmental issues, thereby improving the water supply for urban and rural areas alike (Binns et al. 2001; Dye et al. 2001; Dye & Versfeld 2007). Although WfW is regarded as an effective social and economic development tool (Binns et al. 2001), many of the environmental aspects of the programme have not been assessed as a result of inadequate maps of the extent of invasion and progress of eradication (Gibson & Low 2003; Poona & Shezi 2010; Van den Berg 2010). In addition to insufficient mapping of the extent of invasion in South Africa, WfW has kept poor data records in the past regarding clearing operations and the density of stands (Marais et al. 2004). The current electronic database was implemented in 2000, allowing for reliable data to be recorded. The accuracy of the data prior to the initiation of this database varies between areas and project managers. The most complete records are only available since the 2002/2003 financial year (Marais et al. 2004).

An option for bridging the gap in data records is remote sensing. Many remote sensing techniques exist and can be used to characterize landscapes in a biologically meaningful manner (Gould 2000; Rogan & Chen 2004). Diversity patterns, changes and variation can be mapped at varying scales. Archived satellite images are a valuable retrospective monitoring tool that can provide the data necessary for modelling the spread and eradication of IAPs over time. Invasive alien plant species can be distinguished from native vegetation using techniques that exploit the differences in phenology, spectral signatures and structural characteristics of plant species (Elmore et al. 2000; Jiang et al. 2006; Maselli 2004; Underwood et al. 2003; Weiss et al. 2004). In combination with Global Positioning System (GPS) and Geographic Information System (GIS) technologies, remotely sensed data can provide a platform on which to base sound decisions and management strategies (Gould 2000; Rogan & Chen 2004; Zavaleta et al. 2001).

The aim of this study was to determine whether remote sensing could be used to accurately map invasive vegetation on the Agulhas Plain. This was done in two parts, namely: to first establish which of three remote sensing techniques (NDVI, tasseled cap and supervised classification) was the most accurate at classifying vegetation for the study area; and secondly, to determine the extent of invasion on the Agulhas Plain using the most appropriate remote sensing method.

2.3. Method

2.3.1. Study area

The Agulhas Plain (AP) was selected for this study as it has been the focus of much conservation planning over the years due to its high levels of endemism and the high concentration of rare plant species (Cowling & Heijnis 2001; Kotzé & Fairall 2006). The Agulhas Biodiversity Initiative (ABI) was launched in 2004 with the aim of addressing the threats to the biodiversity of the area and promoting sustainability. One of the most significant threats is invasion by alien plants (Binns et al. 2001; Lombard et al. 1997; Rebelo 1992; Rouget et al. 2003). The extent of invasion on the AP was last mapped in 2000 (Cole et al. 2000) and found to be 72% infested to some degree. An up-to-date invasion map is needed to formulate policies and make appropriate management decisions with regard to eradicating IAPs (Carrao & Goncalves 2006; Roura-Pascual et al. 2009; Rowlinson et al. 1999).

The Agulhas Plain is located between 19°30’ and 20°15’ south, and 34°30’ and 34°50’ east, covering 215 170 hectares at the southern-most tip of Africa (see Figure 2.1). The area consists of six different types of fynbos, easily identifiable by the presence of hard-leaved shrubs (mainly of the Proteaceae family), and narrow- and small-leaved ericoid shrubs and restioids (Midgley et al. 2003). In addition, small patches of afromontane forest, southern coastal milkwood forest and renosterveld are present. The AP consists of a gently rolling lowland landscape (Cowling & Holmes 1992), which makes it an ideal study site for testing remote sensing. Remote sensing techniques can be influenced by slope, aspect and shadow (Kakembo et al. 2006). Reducing the influence from these variables increases the accuracy of the remote sensing techniques (Ustin et al. 2002).

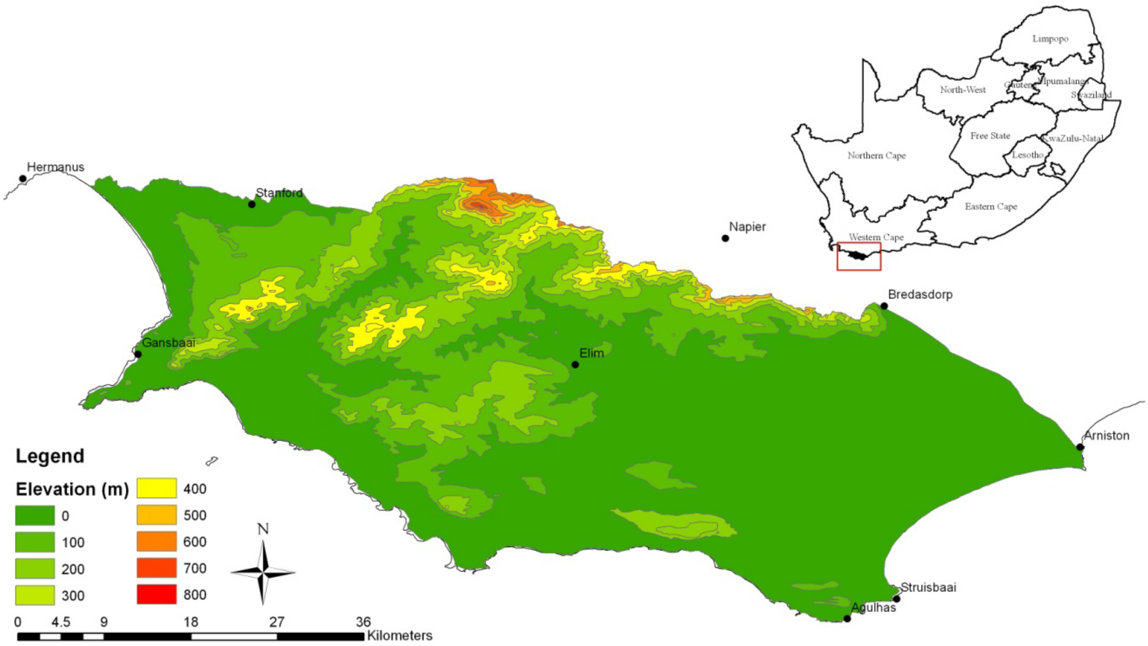


Figure 2.1: The Agulhas Plain is located at the southern-most tip of South Africa. The map shows the gently rolling lowland landscape of the study site.

2.3.2. Study design

Three potential techniques for mapping invasive vegetation were explored in an attempt to identify a cost and time effective means of updating invasion maps. These techniques (Normalised Difference Vegetation Index (NDVI), tasseled cap and supervised classification) were selected because they have been used for monitoring land cover changes on the Agulhas Plain or in Mediterranean type ecosystems such as the Cape Floristic Region. NDVI is the most commonly used vegetation index and was used in the studies of Fatoki 2007, Hope et al. 2009, Díaz-Delgado et al. 1998 and Fernández et al. 2010. The Table Mountain Group Pilot Study 2004 and Engelbrecht et al. 2005 used the Tasseled cap transformation in the Agulhas Plain area. Supervised classification has been used by Rouget et al. 2003 to map invasive alien vegetation in the Cape Floristic Region, and by Berberogu & Akin 2009 to detect changes in land cover in a Mediterranean ecosystem.

Remote sensing was chosen because satellite images can be acquired for all habitats, over large spatial areas, and for frequent repeat cycles. Images can also be acquired relatively quickly, are cost effective and image processing can be automated thereby reducing labour costs (Kotzé & Fairall 2006; Underwood et al. 2003). In addition, remote sensing has been suggested and explored as a possible technique for creating invasion maps in South Africa (Cobbing 2006; Gibson & Low 2003; Poona & Shezi 2010; Van den Berg 2010). SPOT 4 imagery was used for the NDVI and supervised classification. Tasseled cap was developed for Landsat imagery and as such, a Landsat 7 ETM+ image (30m spatial resolution) was acquired for the same time period as the SPOT 4 image and for a similar spatial resolution (20m). The three techniques were evaluated based on their accuracy for mapping vegetation in section 2.3.6 (shrubland and thicket as defined by the NLC 2000). The most accurate technique for vegetation mapping was then analysed further to map mixed invasive alien tall and medium trees on the Agulhas Plain (Section 2.3.7).

2.3.3. Imagery selection

Several types of imagery were considered for this study including MODIS, MERIS, ASTER, Landsat 7 ETM+ and SPOT 4 and 5. The advantages and disadvantages are given in Table 2.1. SPOT 4 and Landsat 7 imagery were chosen based on four criteria, namely: 1) accessibility, 2) cost, 3) spatial resolution, and 4) availability of cloud-free images.

Table 2.1: Six types of satellite imagery considered for this study. Landsat 7 ETM+ and SPOT 4 were chosen.

Image	Spatial resolution	Number of bands	Return period	Cost	Advantages	Disadvantages
MODIS	250m	36	1-2 days	Free	▪ Images can be acquired already processed for NDVI, EVI and LAI ▪ Widely used ▪ Free of charge	▪ Cloud cover ▪ Coarse resolution
MERIS	260x300m	15	3 days	Free	▪ Good spectral resolution ▪ Free of charge	▪ Excessive cloud cover ▪ Coarse resolution
ASTER	15m	14	16 days	No access	▪ Good spatial resolution ▪ Good for vegetation mapping	▪ No access to non-NASA employees
Landsat 7 ETM+	30m	8	16 days	Free	▪ Good spatial resolution ▪ Commonly used for land cover mapping ▪ Free of charge	▪ Scan lines
SPOT 4	20m	4	<26 days	Free	▪ Good spatial resolution ▪ Free of charge	▪ Not compatible with tasseled cap transformation ▪ Geo-referencing required
SPOT 5	10m	5	<26 days	€1900	▪ Excellent spatial resolution ▪ Good for vegetation mapping	▪ Expensive (€1900 per scene)

Seven SPOT 4 images were acquired for February 2009 with 0% cloud cover from the European Space Agency's Earth Observation Portal (see Table 2.2). February was selected as the most appropriate month because it is at the end of the dry season and as such, has the lowest rainfall. This is an important consideration for NDVI studies as rainfall events can influence the pixel values. Additionally, using dry season data allows wetlands, drylands and seasonally moist areas to be distinguished. A mosaic was created to form a single image of the area. A Landsat 7 ETM+ image was also acquired, as tasseled cap can only be performed on Landsat imagery. The spatial resolution of SPOT 4 and Landsat 7 is similar (20m and 30m respectively) and the images were matched in terms of date to avoid variation. All images used the WGS 84 datum with Transverse Mercator as the spatial reference.

Table 2.2: List of images acquired for the study with information on the position of the satellite when each image was taken (orbit/track/frame/path/row).

Image ID	Mission	Sensor	Acquisition date	Orbit	Track	Frame
1	SPOT-4	HRVIR	2009/02/23	169	121	420
2	SPOT-4	HRVIR	2009/02/23	169	121	419
3	SPOT-4	HRVIR	2009/02/23	169	122	419
4	SPOT-4	HRVIR	2009/02/22	155	119	419
5	SPOT-4	HRVIR	2009/02/17	84	120	420
6	SPOT-4	HRVIR	2009/02/17	84	120	419
7	SPOT-4	HRVIR	2009/02/17	84	120	418
Image ID	Mission	Sensor	Acquisition date	Orbit	Path	Row
8	Landsat-7	ETM+	2009/02/23	/	174	84

2.3.4. Pre-processing techniques

The SPOT 4 imagery was acquired at a processing level 1B. This processing level includes radiometric corrections, geometric correction of systematic effects (panoramic effect, Earth curvature, rotation), and internal distortion correction. Although geometric correction had been performed, additional geo-referencing was done in ERDAS Imagine 9.1 software (Leica) to correct for distortion arising from the projection of the imagery. Images were also normalized to minimize albedo variations and topographic effects. An ocean mask was used to limit the classification to terrestrial areas.

2.3.5. Classification

The Normalised Difference Vegetation Index (NDVI) is the most commonly used measure of vegetation cover in remote sensing (Jiang et al. 2006; Kakembo et al. 2006). Almost 90% of spectral information relevant to vegetation is contained in the red and near-infrared portion of the electromagnetic spectrum (Fatoki 2007). NDVI uses the red (R) and near-infrared (NIR) bands and is calculated using Equation 2.1.

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{R}}{\mathrm{NIR} + \mathrm{R}}$$

Equation 2.2: Equation for calculating the Normalised Difference Vegetation Index.

The resulting NDVI pixel value is a value between -1 and +1. Positive values indicate green, vegetated areas as indicated in Figure 2.2 (Weiss et al. 2004). A value closer to +1 indicates vegetation with higher water content and a higher rate of photosynthesis. Negative NDVI values are characteristic of un-vegetated areas such as water or bare soil (Weiss et al. 2004)(see Figure 2.2). NDVI is most suited to vegetation mapping and decreases in accuracy with lower densities of vegetation (Broge & Leblanc 2001). The yellow areas in Figure 2.2 illustrate the low NDVI values, which have lower vegetation cover (for example, cultivated land). The blue and green areas indicate areas with denser vegetation and a higher NDVI value.

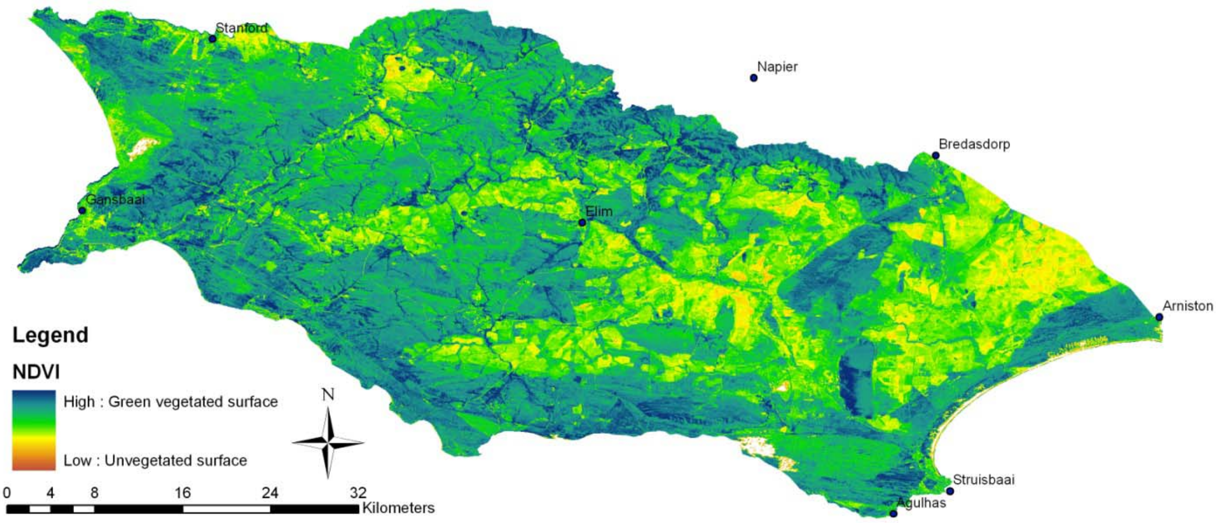


Figure 2.2: The NDVI derived SPOT 4 image of the Agulhas Plain is shown in this figure. NDVI assigns a value to each pixel between -1 and 1 as indicated in the scale. The closer the value is to 1, the higher the foliage water content of the vegetation. The lowest values in this image are areas of exposed ground with no or very low vegetation cover. The yellow areas are cultivated land.

Tasseled cap is another type of spectral transformation (Figure 2.3). Tasseled cap works differently to NDVI (which uses an equation to combine red and infrared into a single value). Tasseled cap is a type of transformation that compresses the volume of data into three essential bands: red, green and blue (Crist & Kauth 1986; Huang et al. 2002). The red band gives an indication of brightness which is used to identify low vegetation and strong reflectors such as bare soil. The green band is used to map and monitor vegetation based on the 'greenness' of the pixel. The final band, the blue band, indicates wetness and is used to identify water or moisture. Each pixel consists of a combination of these three bands (Figure 2.3) which can be used to classify an area.

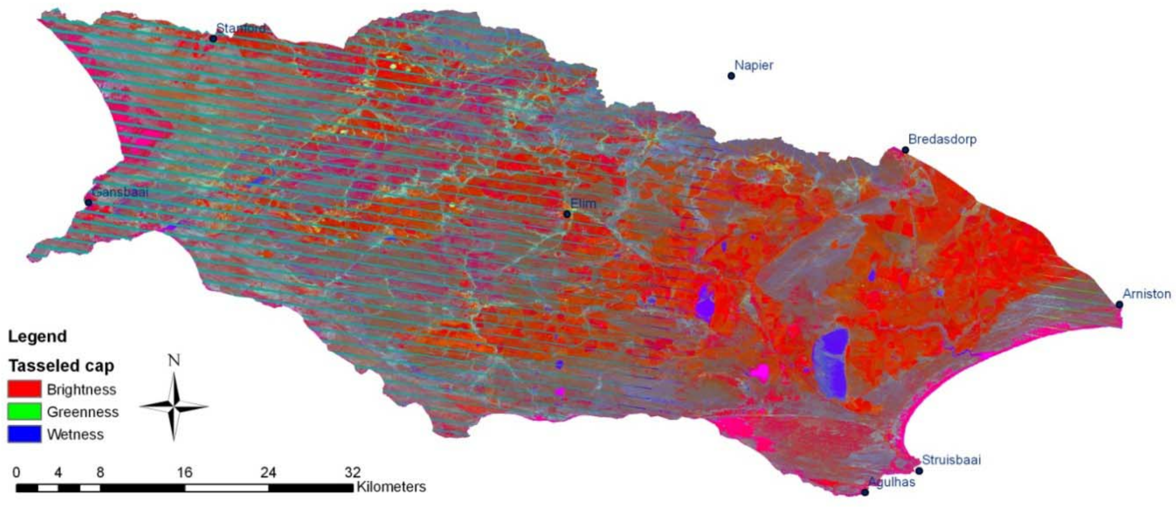


Figure 2.3: The combination of the brightness, greenness and wetness using tasseled cap transformation enable classification as seen in the Landsat 7 image. The red areas indicate cultivated land which has a higher level of reflectors.

The third technique explored in the study was supervised classification (Figure 2.4). This form of classification does not necessarily use enhancements or transformations, although the technique can be performed on enhanced or transformed imagery. The objective of this automated classification is to cluster pixels into classes based on similarities in the spectral signatures. Supervised classification requires an analyst to select training classes (representative spectral signatures) for each land use type which are then automatically extrapolated to the entire image. This technique may result in under- or over-representation of classes based on similarities in spectral signatures.

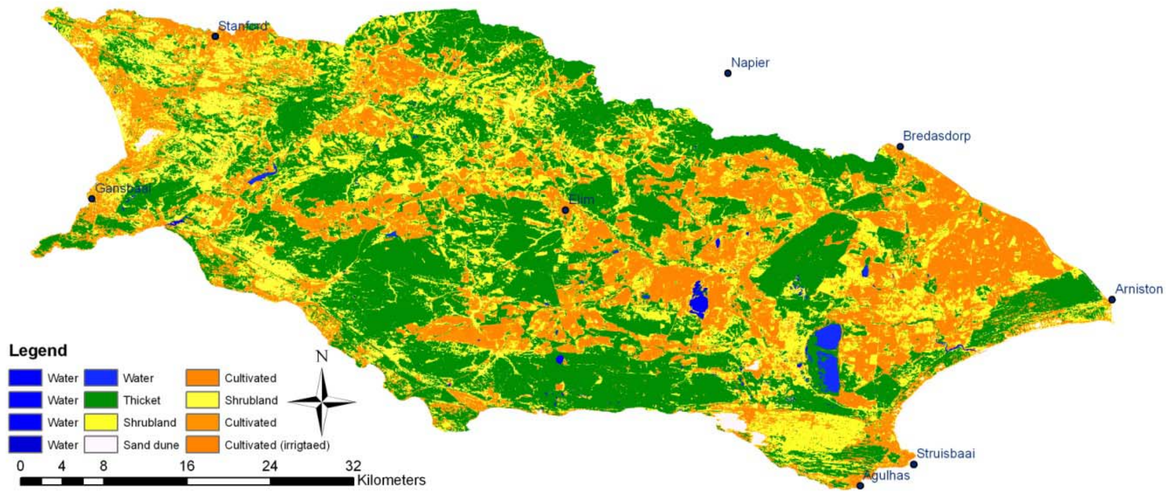


Figure 2.4: The supervised classification of the Spot 4 image. Thicket is over-estimated using this technique, while shrubland is under-represented. The orange areas represent cultivated land for which supervised classification is best suited.

2.3.6. Land cover analysis

ERDAS Imagine 9.1 software (Leica) was used to perform the land cover analysis as well as to prepare the satellite images. The purpose of doing a land cover analysis was to determine which of the three remote sensing techniques would be used to map invasive vegetation. NDVI was derived and the imagery transformed for tasseled cap. A pixel seeding function was used to select training classes for the supervised classification which was run through a maximum likelihood classifier. Once the remote sensing techniques had been performed in ERDAS, ESRI ArcMap 9.2 Spatial Analyst was used to reclassify the images using the Iso-cluster function and maximum likelihood classification. The Agulhas Plain was classified into five land cover classes for each of the three techniques. The classes were: bare soil, cultivated, shrubland, thicket and waterbodies (as defined by the NLC 2000). The National Land Cover 2000 (NLC 2000) was used as the reference data and was cross tabulated against the classified images. Ten thousand random points were generated using Hawth's Tools (Beyer 2004) and linked to the reference and class data at each point. The data were cross-tabulated using PASW Statistics v. 18.0.0 (SPSS_Inc. 2009) and used to calculate the user's accuracy for each class. This is an informative way of testing whether the classification of a class is the same as the reference data. The user's accuracy of the classification was calculated as the difference between the class assigned to the point using remote sensing analysis and the class according to the reference data. The technique with the highest user's accuracy for mapping vegetation was re-classified in detail to create an invasion map of the Agulhas Plain.

2.3.7. Invasive vegetation classification

Once a suitable technique of mapping vegetation had been chosen, Iso-cluster (ESRI ArcMap 9.2 Spatial Analyst) was used to classify the image into 30 preliminary classes. Dendrograms were used to determine how closely related individual classes were. The image was re-classified into 18 unique classes of which, three were found to be invasive vegetation. As a species level assessment was beyond the scope of this study, these three classes were grouped together to create an up-to-date invasion map of the Agulhas Plain. The extent of invasion was compared to the invasion map of the Agulhas Plain from 2000 using cross tabulation. A shortcoming of the spatial resolution of SPOT 4 imagery was that areas below a 50% level of invasion could not be detected in 2009.

2.3.8. Accuracy assessment

Ground-truthing was done in two in-field roadside visual assessments. The first ground-truthing field trip was to confirm land cover using a Global Positioning System (GPS). A land cover map was created based on the classification by NDVI and a route was chosen that would pass through all land cover classes on the Agulhas Plain. The route was driven and for each class, several random GPS coordinates were taken as training points. These training points were later used with high resolution aerial photographs (0.5m resolution) to cross-check land cover classes and invaded areas. The second ground-truthing field trip was to confirm the spatial distribution of invaded areas. A team of experts followed a route through the Agulhas Plain and assessed the extent and density of invasion. Again, GPS coordinates were taken as training points. The conservation manager of the Nuwejaars Special Management Area and a local vegetation and invasive species mapper also assessed the invasion map.

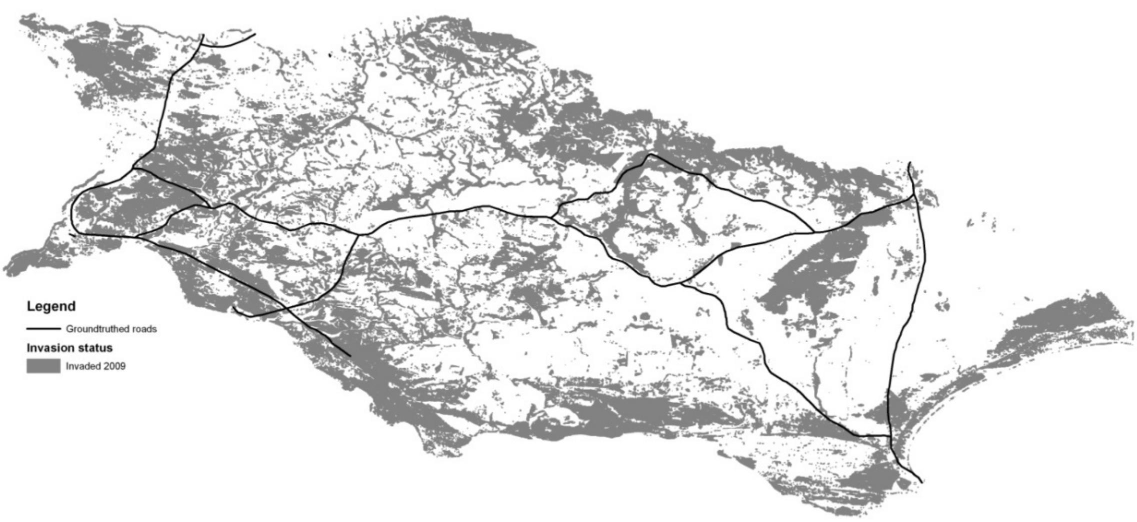


Figure 2.5: The route that was driven to ground-truth invaded areas on the Agulhas Plain is indicated by the black line. Invaded areas are given in grey.

Finally, the extent of invasion was cross tabulated against the Cole et al. (2000) invasion map to determine the correlation between the two invasion maps. The maps were overlaid and 32446 points representing overlapping polygons were cross tabulated using PASW. The user's accuracy and kappa value was calculated to determine the level of agreement between the two maps. Kappa values give an indication of the extent of agreement between the classification of invasive vegetation by NDVI and the invaded areas previously mapped in the reference data. The closer the kappa value is to one, the higher the agreement.

2.4. Results

2.4.1. Selecting a remote sensing technique

The first goal of this study was to determine the most suitable method of remote sensing for mapping vegetation. The three classification techniques were cross-tabulated with the NLC 2000 reference data and the user's accuracy was determined as given in Table 2.3.

Table 2.3: The user's accuracy of each of the remote sensing methods is given in the following table. NDVI is the most accurate method for classifying vegetation (given in bold), while tasseled cap and supervised classification are most suited to classifying exposed areas.

	User's accuracy		
Class	NDVI	Tasseled cap	Supervised classification
Bare soil	21%	86%	79%
Cultivated	65%	71%	81%
Shrubland	**49%**	**44%**	**41%**
Thicket	**59%**	**56%**	**57%**
Waterbodies	4%	19%	11%
Total	39%	55%	54%

Table 2.3 shows that tasseled cap was the most accurate technique for overall classification (55%), followed closely by supervised classification (54%). Despite this, NDVI had the highest accuracy for classifying vegetation types (shrubland: 49%, thicket: 59%). The bare soil and cultivated land classes had a high accuracy for tasseled cap and supervised classification, however these two techniques did not perform as well for vegetated areas. NDVI was therefore chosen to map the current extent of invasion.

2.4.2. Current extent of invasion

The second goal of the study was to map the current extent of invasion on the Agulhas Plain. This was done using NDVI and maximum likelihood classification. The updated land cover is given in Figure 2.5.

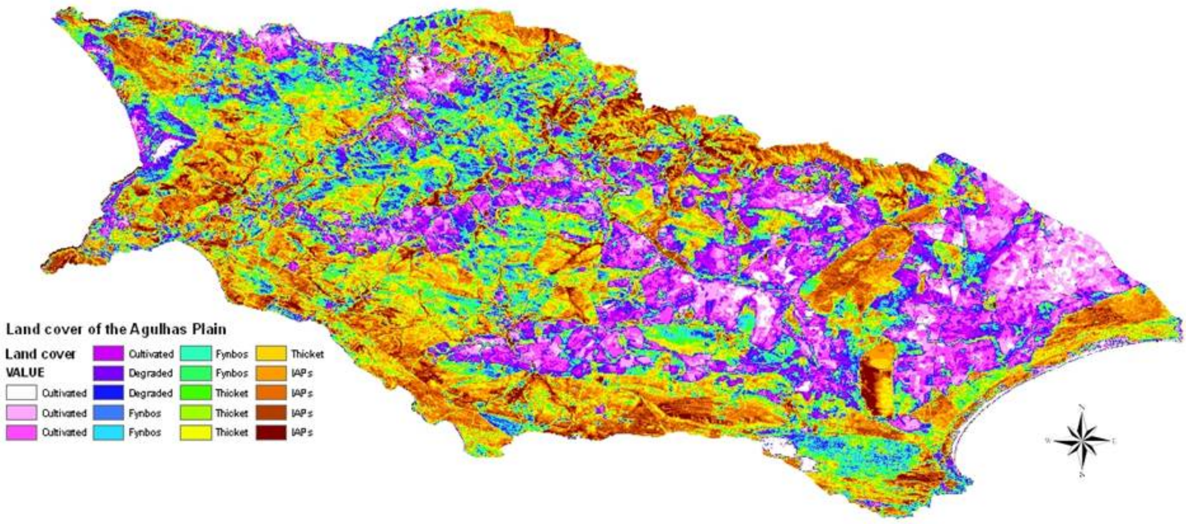


Figure 2.6: NDVI was derived from a SPOT 4 image of the Agulhas Plain. The NDVI was classified using maximum likelihood classification. Dark orange and red indicates invasive vegetation while purple is cultivated land.

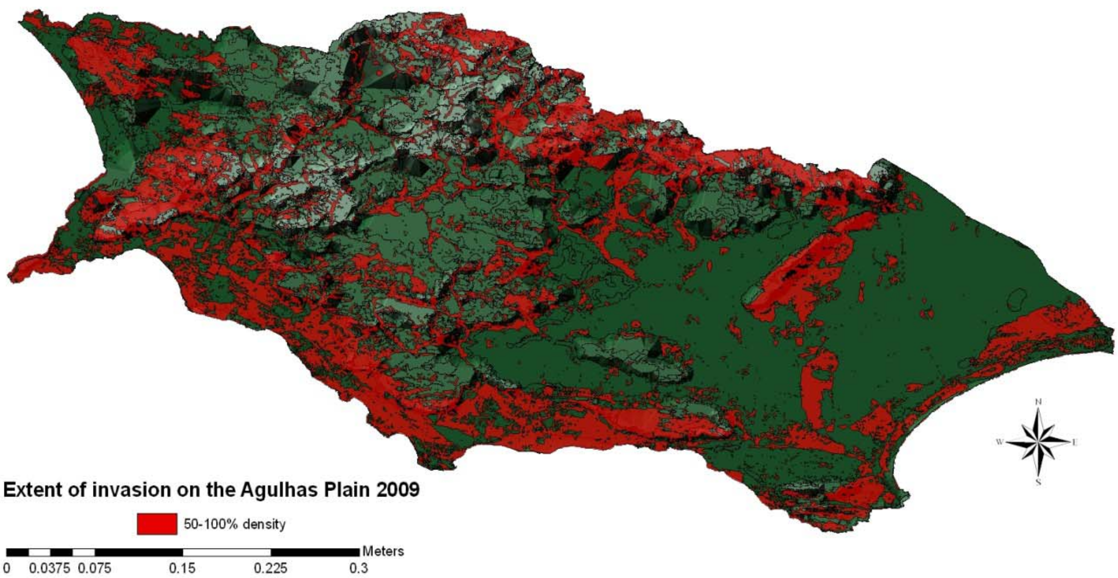


Figure 2.7: Four land cover classes were identified as invasive vegetation and combined into a single invasion layer. The red areas indicate invasive vegetation with an average density of 75%. The lighter areas in this 3D map represent a higher altitude. The highest point on the AP is 800m.

An invasion map was derived from the land cover map (Figure 2.6). The extent of invasion on the AP amounts to 31% of the area with a density of invasion above 50%. In comparison to previous estimates by similar studies, the current extent of invasion is greater than the 2000 estimate that 14% of the AP was invaded above a 50% density and 19% was invaded above a 25% density (Cole et al. 2000). Prior to this, Lombard et al. (1997) mapped the AP in 1997. They estimated that 11% of the AP was invaded. The most recent invasion map of the AP was by Rouget et al. (2003) who mapped the entire Cape Floristic Region (CFR) using remote sensing. The study found the CFR to be 3% invaded. Rouget et al. (2003) attribute this low extent of invasion to rugged topography, cloud cover and overlapping spectral signatures reducing the accuracy of the remote sensing techniques. The invasion map by Cole et al. (2000) is considered to be the most accurate and reliable invasion estimate as it was mapped at a finer scale (1:250 000) than Lombard et al. (1997) and Rouget et al. (2003) and is used for planning on the Agulhas Plain (Cole et al. 2000). The extent of invasion in 2009 (31%) is considerably higher than in 2000 (14%) for areas with an invasion density of 50% and above. If areas that were in the 25% to 50% class in 2000 are included, the current (2009) extent of invasion on the Agulhas Plain still exceeds the 19% estimate by Cole et al. (2000).

The 2000 and 2009 invasion maps were cross tabulated and the kappa value calculated (Table 2.4). The user's accuracy was moderate indicating that there is limited correlation (44% to 68%) between the areas invaded in 2000 and the areas invaded in 2009. This is further validated by the very low kappa value (0.012) which suggests a low level of agreement. Values closer to 1 indicate a high level of agreement.

Table 2.4: The 2000 and 2009 invasion maps were cross tabulated to determine the level of agreement between the spatial distribution of the two maps. A very low level of agreement was found, as indicated by the kappa value of 0.012.

User's accuracy	Invaded2009	
Invaded2000	NO	YES
NO	68%	32%
YES	54%	46%
Kappa	0.012	

2.5. Discussion

Remote sensing has proved to be a practical approach in the field of biological invasion in recent years with well-documented advantages in similar studies (Joshi et al. 2004). This is a potentially valuable tool for land management agencies such as Working for Water to map the distribution and monitor changes in invasive alien vegetation over time. Remote sensing was successfully used to map invasive alien vegetation on the AP in this study. The overall extent of invaded land on the AP has not changed significantly since 2000, but the results indicate that the spatial distribution of invasive vegetation has changed considerably. Multispectral imagery with a multi-temporal coverage allows for land cover changes to be detected and rates of change to be quantified (Joshi et al. 2004). SPOT 4 derived NDVI is able to detect tall and medium alien tree stands with a density of 50% and above. Although NDVI cannot differentiate between different species of invasive vegetation at this spatial resolution (20-30m), these data are certainly able to provide land managers with an idea of what happening at a landscape level. This information can be used to monitor and make decisions for the prioritization of clearing efforts.

Of the three remote sensing techniques tested, tasseled cap performed the best for overall classification of the five land cover classes. However, in terms of classifying vegetation, NDVI had the highest accuracy out of the three techniques. Tasseled cap and supervised classification utilise more bands of information from the image and are therefore better at classifying a range of land cover classes (Underwood et al. 2003).

NDVI only uses the red and near infrared bands of an image, but almost 90% of spectral information relevant to vegetation is contained in this portion of the electromagnetic spectrum (Fatoki 2007). This gives NDVI an advantage for classifying vegetation, but means that it is not the best technique for mapping other land cover classes. NDVI also has an advantage in that pixel values derived from an image reflect the physiological characteristics of vegetation (Underwood et al. 2003; Weiss et al. 2004). Studies have shown NDVI values to be dependent on canopy coverage, productivity, leaf area, foliage chlorophyll absorption and the phenology of plants (Elmore et al. 2000; Jiang et al. 2006; Maselli 2004; Weiss et al. 2004). These properties were exploited to distinguish invasive alien plants from the natural fynbos vegetation (Underwood et al. 2003). Medium and tall alien trees have a broader leaf area than fynbos as well as a higher level of productivity and water use (Stock et al. 1995). These characteristics enabled medium and tall alien trees to be detected using NDVI. Invasive plants similar in physiology or structure to fynbos vegetation cannot be detected using this technique as a result of similarities in the spectral signatures. This was also found by Rouget et al. (2003) who suggest that overlapping spectral signatures may account for a low level of accuracy when detecting invasive vegetation in fynbos areas. NDVI is also sensitive to vegetation density (Broge & Leblanc 2001). The accuracy of NDVI decreases with lower vegetation densities as reflectance from bare soil may influence NDVI values (Broge & Leblanc 2001). The study found that IAP stands below a 50% density could not be detected using SPOT 4 derived NDVI. This may be explained by the spatial resolution of the SPOT 4 imagery. Each pixel of the satellite imagery was 20m x 20m, which would mean that more than 50% of the pixel would need to be invasive vegetation in order to be classified as ‘invaded’. The NDVI values of pixels with lower density invasions would reflect the dominant natural vegetation and would be classified as ‘not invaded’ although invasive vegetation may be present. As NDVI is primarily a measure of the water content of vegetation, it is subject to variability depending on a range of factors such as recent precipitation events, slope, and aspect (Underwood et al. 2003). Rainfall data were obtained for the period of acquisition of the satellite imagery and found to have no influence as less than 2mm of rainfall was recorded for that week. Influence from slope and aspect is unlikely as the Agulhas Plain consists of a gently rolling lowland landscape (Cowling & Holmes 1992a). Waterbodies and bare ground had the lowest accuracy of classification by NDVI. Exposed areas of ground have been found to influence NDVI values (Elmore et al. 2000; Weiss et al. 2004) and light reflecting off these areas may modify NDVI values by up to 20% (Kakembo et al. 2006). Waterbodies have a similar NDVI value to other non-vegetation areas such as bare ground (Fatoki 2007; Weiss et al. 2004). The low accuracy of classification for these two classes is most likely a result of overlapping NDVI classes.

The low level of agreement between the spatial distribution of the 2000 and 2009 invasion maps can be explained by changing spatial distributions of IAPs on the Agulhas Plain and lower density stands in invasive vegetation that could not be detected using NDVI. Fire and IAP eradication were the most likely explanations for significant changes in the spatial distribution of invasive vegetation over time. The influence of these two factors on the spatial distribution of IAPs is explored in detail in Chapter 3.

Land management programmes, such as Working for Water, need up-to-date, accurate invasion maps at a landscape scale that can be acquired in a time and cost efficient manner. This information would facilitate the management of invasive alien vegetation and water resources (Rowlinson et al. 1999). It can be concluded that NDVI is a suitable technique for mapping invasive alien plants above 50% in density in the Cape Floristic Region for a gentle rolling lowland landscape such as the Agulhas Plain.

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Chapter 3

The spatial distribution of invasive alien vegetation over time

Image: www.esa.org. SMOS satellite

Preamble from a personal point of view:

Remote sensing is a pretty nifty technique. It is incredible that the spectral signature of invasive vegetation can be detected from space and used to create an invasion map. Really very impressive indeed. Unfortunately, something was amiss when the invasion map was compared to the reference dataset in chapter 2. The spatial distribution of invasive vegetation in 2009 had a surprisingly low level of correlation to that of 2000. Invasive alien plants are notorious for their ability to invade and conquer and changes in spatial distributions over time are not unexpected. This is all good and well as an explanation for areas that have become invaded since 2000, but a peculiar phenomenon also seemed to be taking place on the Agulhas Plain. Large tracts of land were becoming un-invaded over time. Given the reputation of invasive vegetation, this was highly unlikely without a little help. The two most obvious candidates were clearing operations and fire. Clearing operations should in all good faith, reduce the extent of invasion, but fire can be a double-edged sword. Fire can promote invasion or inhibit it depending on the frequency, intensity and seasonality of the fire. Now, I didn't have a lot of time to go into the fastidious details of burning because after all, this study was about water, not fire. In this chapter, I investigate disturbance as the driver of the un-invasion phenomenon and explore whether fire is inducing invasion or preventing it.

3.1. Abstract

Disturbance events can change the spatial distribution of invasive alien plants over time. Whether invasion is promoted or inhibited by disturbance is context specific. This study explored the role of fire and clearing on changes in the spatial distribution of invasive vegetation on the Agulhas Plain (AP) over a 9 year period. Fire and clearing were able to explain some of the changes between 2000 and 2009, but it could not be concluded whether disturbance was promoting or inhibiting invasion. Disturbance data is an essential component of monitoring changes in invasive vegetation over time.

3.2. Introduction

Fire is known to facilitate invasion in many cases (Keeley et al. 2005; Lockwood et al. 2006). This is an important consideration for the management of invasive alien plants (IAPs) in fynbos areas, where fire is an important ecosystem service required for the regeneration of indigenous species (van Wilgen & Richardson 1985). Although fynbos is fire-adapted, life history traits of IAPs may allow invasive vegetation to exploit the conditions following fire (Keeley et al. 2005). IAPs often have large, persistent seed banks which germinate after fire when competition with native vegetation is at its lowest (Keeley et al. 2005; Wood & Morris 2007). Once established, these seedlings grow faster and taller than fynbos, forming closed stands after only one or two fire cycles (Holmes et al. 2000). A closed canopy results in decreased light penetration and changes in nutrient cycling and litter accumulation (Holmes et al. 2000). Increased biomass also increases the fuel load, which can alter fire regimes by increasing the frequency, intensity and seasonality of fires. Altering fire regimes beyond the range of variation to which the fynbos vegetation is adapted can alter and weaken native communities resulting in a competitive advantage for IAPs (Brooks et al. 2004). Despite evidence of fire promoting invasion, the effects of disturbance are context specific (Higgins & Richardson 1998). In some cases, disturbance may reduce invasion. Increased fire intensity may kill established invasive vegetation, thereby reducing seed production and inhibiting invasion (Buckley et al. 2007).

When invasive alien plants are introduced to a new area, the natural predators and pathogens that control the species in their native habitat are absent. This may result in 'ecological release' where the invasive species may multiply rapidly and invade the indigenous fynbos vegetation. Biological control (or biocontrol) is the deliberate introduction of host-specific invertebrates or diseases aimed at reducing 'ecological release', thereby reducing aggressive invasion. Biocontrol agents have been introduced in many parts of South Africa to control the spread of IAPs (van Wilgen et al. 2004).

The two objectives of this study were to explore whether fire and clearing activities were driving the changes in the spatial distribution of invasive vegetation on the AP over time, and to investigate the influence of burning and eradication on invasion. This information is needed for effective management of invasive vegetation in fire-adapted ecosystems. This is especially true for IAP eradication programmes such as Working for Water. This programme has been active on the AP since the late 1990s and has cleared 16% of the area since 2000. Fires have become increasingly frequent in the area. More than 42 000 hectares of land have been burnt since 2000. This amounts to 20% of the AP. In 2006, a large fire burnt almost 39 000 hectares of land. The AP was chosen for the study as it has a reliable clearing history, an up-to-date detailed fire history, a pre-existing accurate invasion map and cloud free satellite imagery was available.

3.3. Method

3.3.1. Study site selection

The Agulhas Plain is located between 19°30' and 20°15' south, and 34°30' and 34°50' east, covering 215 170 hectares at the southern-most tip of Africa (see Figure 3.1). The AP has been the focus of much conservation planning over the years due to its high levels of endemism, vulnerability of ecological processes, and the high concentration of rare plant species (Cowling & Heijnis 2001; Kotzé & Fairall 2006). One of the most significant threats to the water resources and biodiversity of the area is invasion by alien plants (Binns et al. 2001; Lombard et al. 1997; Rebelo 1992; Rouget et al. 2003). *Acacia*, *Pinus* and *Eucalytus* species account for 93% of the invasive vegetation on the AP. *Acacia* species are the dominant IAP species, accounting for 71% of the invaded areas in the year 2000 with about 56% of this with a density of <25%.

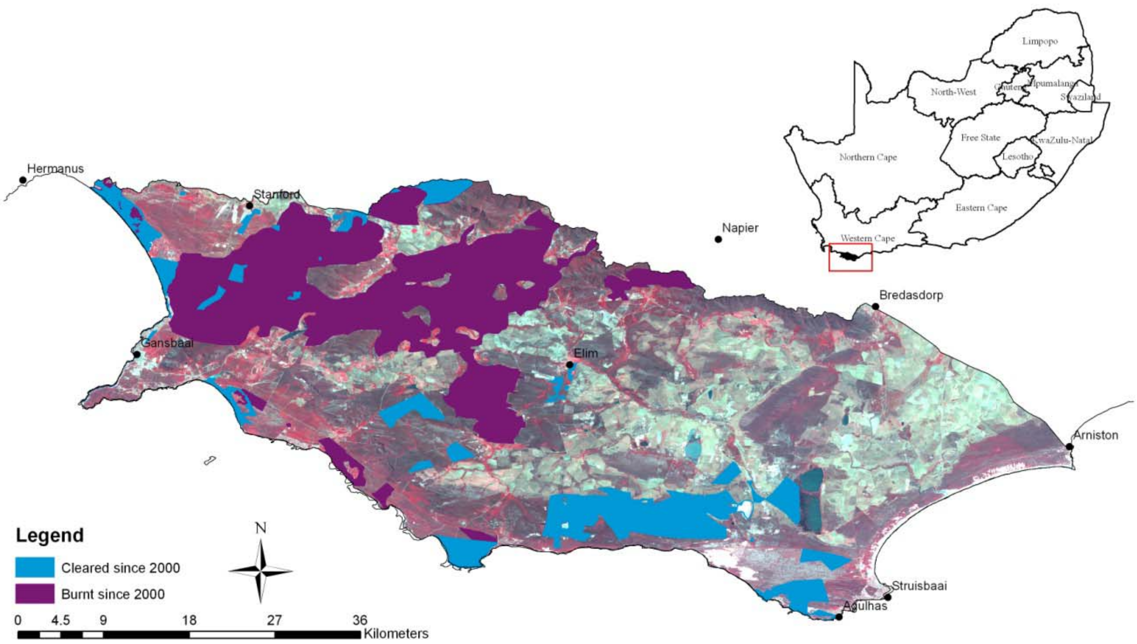

Figure 3.1: The Agulhas Plain is located at the southern-most tip of South Africa, at the heart of the Cape Floristic Region. The areas that have burnt since 2000 are illustrated in purple, while those that have been clearing of IAPs since 2000 are given in blue.

3.3.2. Study design

Remote sensing was used to determine the current (2009) extent of invasion on the AP in Chapter 2. Remote sensing has proved to be a practical approach in the field of biological invasion in recent years with well-documented advantages in similar studies (Joshi et al. 2004). Multispectral imagery with a multi-temporal coverage allows for land cover changes to be detected and rates of change to be quantified (Joshi et al. 2004). The Normalised Difference Vegetation Index (NDVI) was used to classify SPOT 4 satellite imagery as it was found to be the most accurate remote sensing technique for mapping vegetation on the AP (see Chapter 2). The Cole et al. (2000) invasion map was chosen as the reference dataset for this study. All spatial analyses took place using ESRI ArcMap 9.2.

3.3.3. Data analysis

The updated invasion map was cross tabulated against the reference invasion map to assess the changes in spatial distribution of invasive vegetation since 2000. This was done by cross tabulating 32446 data points representing overlapping polygons of all density classes using PASW Statistics v. 18.0.0. These data points were obtained by overlaying the reference dataset and invasion map in ArcMap 9.2. The user's accuracy and kappa value were calculated to determine the level of agreement between the datasets. This is an informative way of testing whether the classification of a class is the same as the reference data. The user's accuracy was calculated as the difference between the invasion status in 2000 and the invasion status in 2009. Kappa values give an indication of the extent of agreement between two datasets. The closer the kappa value is to one, the higher the level of agreement.

To determine the role of disturbance events on the changing spatial distribution of IAPs, fire and clearing data were overlaid with the 2000 and 2009 invasion maps as illustrated in Figure 3.2. A detailed fire history and a clearing history were obtained from CapeNature in the form of Geographical information System (GIS) shapefiles. The clearing history of the Agulhas National Park and surrounding areas managed by South African National Parks Working for Water were acquired from the SANParks Invasive Species Control Unit GIS Hub. In Figure 3.2, the red indicates areas that have become invaded over time. Blue areas were invaded in 2000 and remain invaded. The green areas are areas that were invaded in 2000, but are currently mapped as 'not invaded.' The role of fire (black outline) and clearing events (shaded) as drivers of the change in spatial distribution over time were explored in this study. Only areas of natural vegetation were included. Habitat transformation and other anthropogenic disturbance events were excluded as far as possible.

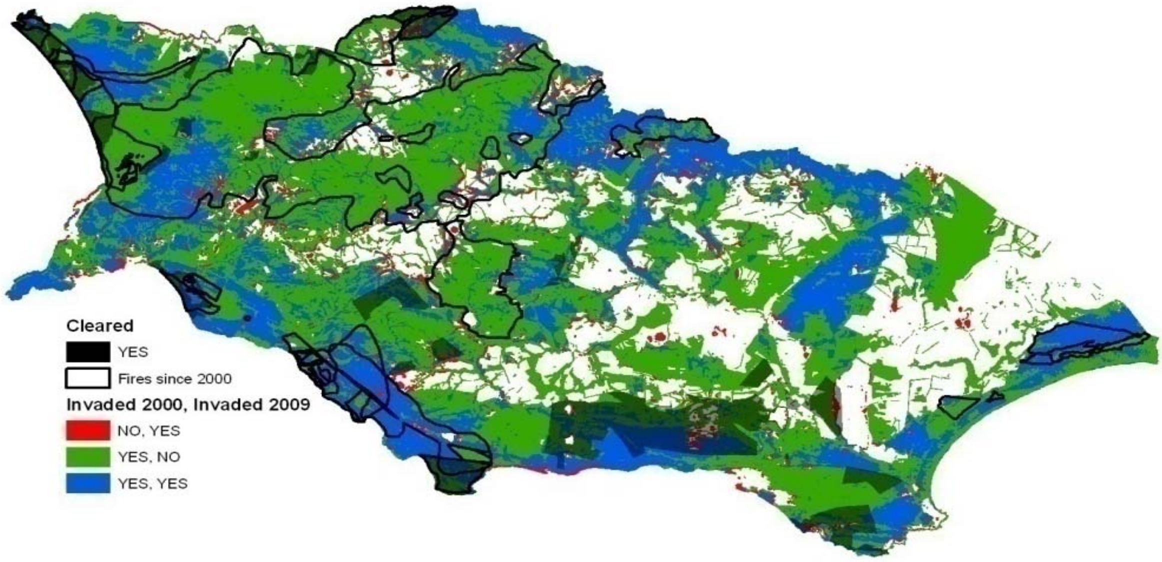

Figure 3.2: Fire and IAP clearing operations can explain why some previously invaded areas are no longer invaded (given in green). Red areas indicate areas that have become invaded since 2000.

It was not possible to detect invasive vegetation stands below a 50% density at the spatial resolution of the SPOT 4 derived NDVI and as a result only areas with an invasion density above 50% were used in the reference dataset. Hawth's Tools (Beyer 2004) was used to generate 10 000 random points across the Agulhas Plain. Of the 10 000 points, cultivated and urban areas were excluded leaving 6884 data points representing natural areas. For each point, the invasion status in 2000 and 2009 was derived as well as whether it was burnt or cleared. A cross tabulation was performed in PASW to determine if these disturbance events are responsible for the changes in spatial distribution using the user's accuracy.

3.4. Results

The 2000 and 2009 invasion maps were cross tabulated and the kappa value calculated (Table 3.1). The user's accuracy was moderate indicating that there is some correlation (46% to 68%) between the areas invaded in 2000 and the areas invaded in 2009. The kappa value (0.012) suggests a low level of agreement between the two datasets indicating a change in spatial distribution over time.

Table 3.1: User's accuracy for the classification of the 2009 invasion map based on the invasion map of Cole et al. (2000).

User's accuracy	Invaded in 2009	
Invaded in 2000	NO	YES
NO	68%	32%
YES	54%	46%
Kappa	0.012	

The cross tabulation showed that 54% of the natural areas on the Agulhas Plain were classified as invaded in 2000, are now classified as 'uninvaded' (i.e. IAP canopy cover <50%). The drivers behind this reduction in invaded areas were explored. Fire and eradication activities are the most likely explanations for this change in spatial distribution (Table 3.2).

Table 3.2: A breakdown of the area that has become 'uninvaded' over time.

Description	Ha	%
Total area 'uninvaded' over time	86924.7	\
'Uninvaded' area above 50% density	13898.1	16%
'Uninvaded' area above 50% density and burnt	4655	33%
'Uninvaded' area above 50% density and cleared	1453.2	10%
Total area 'uninvaded' above 50% density not explained by burning or clearing	7789.9	9%

Of the total area that has become 'uninvaded' over time, only 16% was above 50% in density in 2000. Areas below 50% density could not be detected using remote sensing and are thus excluded from the analysis. The results of Table 3.2 show that fires account for 33% of the 'uninvaded' areas above 50% density and clearing explains 10%. Although 57% of the 'uninvaded' areas above 50% density are still unaccounted for, this only amounts to 9% of the total area that has been 'uninvaded' over time. Table 3.3 explores disturbance as a promoter or inhibitor of invasion over a 9 year period.

Table 3.3: The effects of burning and clearing in two scenarios are compared in this table. The first scenario includes areas that were classified as invaded above 50% density in both 2000 and 2009. Areas that were not invaded in 2000, but were classified as invaded above 50% in 2009 are given in scenario 2.

Scenario 1: >50% in 2000, >50% in 2009		
	Cleared	Not cleared
Burnt	3%	38%
Not burnt	32%	57%

Scenario 2: <50% in 2000, >50% in 2009		
	Cleared	Not cleared
Burnt	46%	23%
Not burnt	45%	41%

Scenario 1 in Table 3.3 indicates that 57% of the areas that were invaded above a 50% density in 2000 were classified as unchanged in 2009 (i.e. - they are classified as invaded above 50% density in 2009). Burning and clearing change the spatial distribution of invasive vegetation with only 38% and 32% of the areas remaining invaded over time, respectively. Combined burning and clearing caused the most significant change in spatial distribution with only 3% of the previously invaded area detectable as invaded above 50% in 2009. In the second scenario, areas that were not invaded in 2000 (or below a 50% density) and have become invaded above a 50% were analysed. The data indicate that without disturbance, 41% of the areas became invaded. Only 23% of the areas previously below 50% density, increased to above 50% after fire, while clearing caused 45% of the areas to become invaded over time. Forty six percent of areas that were burnt and cleared were classified as having become invaded in 2009.

3.5. Discussion

Disturbance events can have unpredictable effects on invasion and as such, it is difficult to make broadly applicable generalizations about disturbance-induced invasion (Higgins & Richardson 1998; Keeley et al. 2005; Lockwood et al. 2006). The impact of disturbance on invasive vegetation is context specific and should be viewed in light of plant attributes, environment and disturbance levels (Higgins & Richardson 1998). The frequency, intensity and seasonality of fires also play an important role in determining whether invasion will be promoted or inhibited (Brooks et al. 2004). An understanding of the influence of disturbance on the spatial distribution of invasive vegetation is important for management decisions (Higgins et al. 1996).

The first objective of this study was to determine if disturbance events were driving the changes in spatial distribution of invasive vegetation over time. Spatial and spectral resolution constraints limited the ability to detect invasive alien vegetation. The spatial resolution of the SPOT 4 imagery used to create the invasion map was not adequate to detect invasive plants below a 50% density, as explored in Chapter 2. Figure 3.3 illustrates that the majority of areas that are mapped as ‘uninvaded’ are simply invasive vegetation below a 50% density.

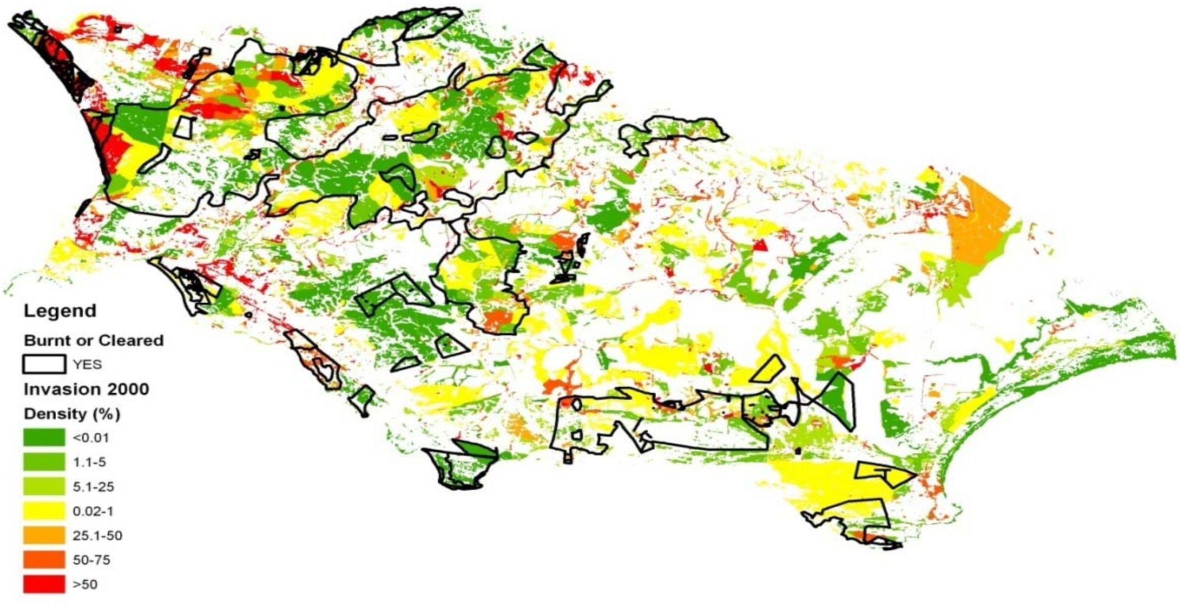

Figure 3.3: The areas in green, yellow and light orange are IAP stands below 50% in density that could not be detected in 2009. The dark orange and red areas are above 50% in density but were classified and not invaded in 2009 although they were invaded in 2000. Fire and clearing (black outline) account for 43% of this change in spatial distribution.

Fire and clearing events did not necessarily eradicate invasive vegetation, but may have reduced the size or density of the IAPs so that they could not be detected using remote sensing. The consequence is that areas may appear to become 'uninvaded' over time, although in reality, they could not be detected using this technique. The results show that 43% of the areas above 50% in density that had become 'uninvaded' over time were driven by fire and clearing. The remaining 57% of the area accounted for 9% of the total area that was classified as 'uninvaded.' The most likely explanations for the reduction in invasion in this small area are a reduction in canopy cover resulting from biocontrol or inaccuracies associated with the invasion map. Wood and Morris (2007) found that biocontrol agents reduced the tree density of *Acacia saligna* stands by between 87% and 98% over a 14 year period. Biocontrol was most effective in areas that had not been disturbed in some time. Morris (1997) also noted the negative effect of fire on the efficacy of biocontrol. *Acacia* species are predominantly found in the deep sands on the Agulhas Plain and biocontrol agents have been released for several species (*A. saligna, A. cyclops, A. longifolia, A. melanoxylon, and A. mearnsii*). It is not unfeasible that the canopy density may be reduced below the detectable threshold as a result of biocontrol. Alternatively, discrepancies in spatial reference of the maps may account for small inaccuracies. Slope, aspect and shadow can also influence NDVI values (Kakembo et al. 2006) and may account for an overestimation of the extent of invasion in mountainous areas. The images were normalized to minimize topographic effects, but further topographic corrections are recommended.

The second objective was to explore whether disturbance was promoting or inhibiting invasion on the Agulhas Plain. The results of this study could not be used to determine the impact of disturbance on invasion. The results indicate that fire appears to reduce invasion in the short term. This is merely a reflection on the reduction of invasive plant biomass following a fire. Fire has been found to stimulate the germination of the IAP seed bank (Wood & Morris 2007), which may form closed stands over time (Holmes et al. 2000). Seedlings are undetectable using remote sensing at the spatial resolution of SPOT 4 imagery (20x20m) because their small size results in confusion with the spectral signature of natural vegetation (Gibson & Low 2003). These areas of undetectable invasion were classified as 'not invaded'. Fire or clearing would reduce the detectable invasive vegetation in the short term, but it is inconclusive whether invasion is promoted or inhibited. The time frame (9 years) of this study did not allow for long-term impacts to be assessed. There was an overall trend that clearing was more effective at reducing the spatial distribution than fire. This is not unexpected. Clearing operations utilise techniques that optimise the long-term reduction of IAPs. A combination of clearing and burning was found to be the most effective combination of disturbance events, almost eliminating previously invaded IAP stands. This is a prescribed technique by Working for Water for the eradication of non-sprouting invasive alien plants which store their seeds in the canopy (Holmes et al. 2000).

Although fire and clearing events have an influence on the spatial distribution of IAPs, the results of Chapter 2 showed that the total extent of invasion has not changed significantly since 2000. This may indicate that the rate at which WfW is clearing IAPs is the same rate at which IAPs are invading new areas. The results suggest that eradication activities by WfW are not reducing the overall extent of invasion, but merely controlling it. This is analogous to the case of the Red Queen in Lewis Carroll's book, "Through the Looking Glass". Carroll's Red Queen observes that 'it takes all the running you can do, to keep in the same place.' In other words, relative progress (clearing of IAPs) is necessary for maintenance (of the extent of invasion on the Agulhas Plain).

In conclusion, it is essential to include disturbance data in analyses when mapping invasive vegetation using remote sensing. Fire and clearing events are known to play a role in the changes in the spatial distribution of invasive vegetation over time. The spatial resolution and time frame of this study were not adequate to draw conclusions on the influence of disturbance on invasion in lowland fynbos areas.

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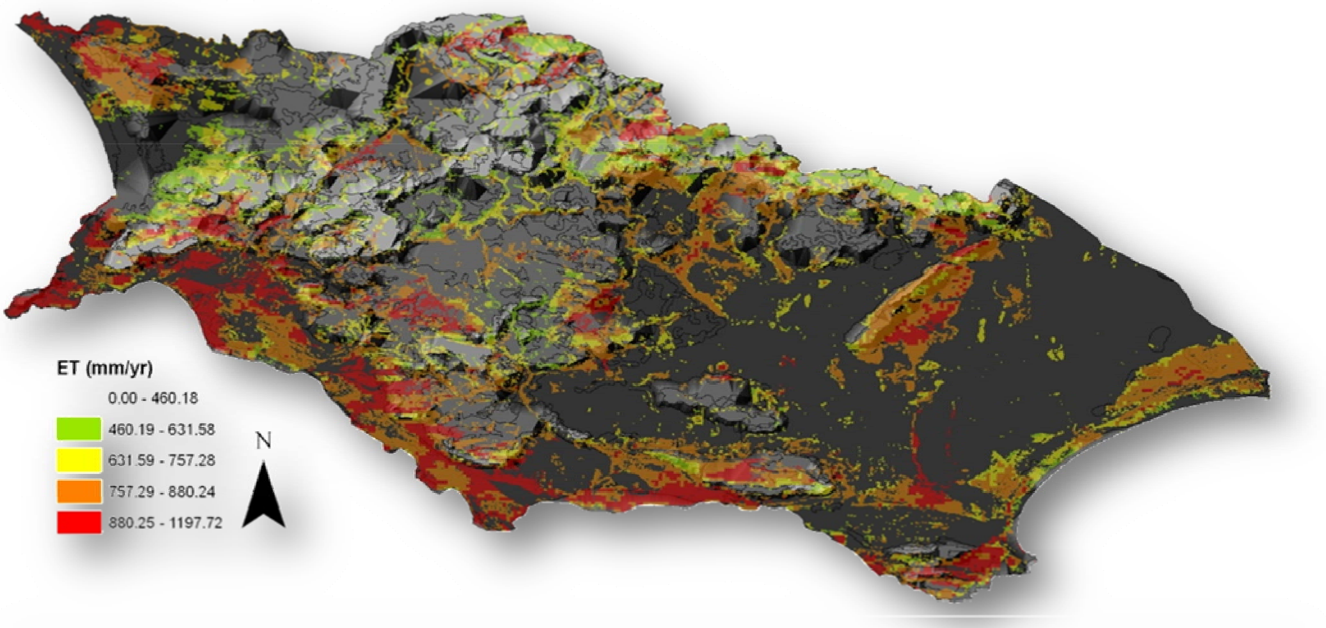
Chapter 4

Hydrological benefits of clearing invasive alien vegetation on the Agulhas Plain



Preamble from a personal point of view:

Let's recap the journey so far. The objective of this study was to quantify the hydrological benefits of clearing invasive vegetation. Unfortunately, the invasion map of the Agulhas Plain was outdated and as a result, chapter 2 was dedicated to exploring a technique to map invasive vegetation in a cost and time efficient manner. When the updated invasion map was compared to the original reference map, very low levels of agreement were found between the spatial distributions of invaded areas. Was it possible that stands of invasive vegetation could change so much in a 9 year period? And more importantly, what was driving these changes? The influence of fire and clearing on the spatial distribution of invasive vegetation was investigated in chapter 3. This brings us back to chapter 4. This chapter is the amalgamation of my journey. The alpha and omega if you will. It is the question that gave life to this study and the answer which puts it to bed. How much water are we talking about?

4.1. Abstract

The hydrological benefits of clearing invasive alien plants need to be quantified for management decisions and as an incentive for conservation. Effective management strategies can be implemented if hydrological priority areas can be identified and included in management plans. In this chapter, actual evapotranspiration data was derived from the SEBAL model and used to determine the amount of water that would be made available by clearing invasive alien vegetation and restoring the area to a natural state. The greatest hydrological benefit would be from clearing deep sands on the Agulhas Plain, but the return per hectare is highest for wetlands. A total of 36 million cubic metres of water could be made available annually from eradicating invasive vegetation. Overall, there is a definite hydrological benefit to clearing the Agulhas Plain.

4.2. Introduction

Water resources as an ecosystem service require valuation so that rational choices can be made regarding competing forms of land use (van Wilgen et al. 1998). This is relevant for the management decisions relating to invasive alien vegetation. Invasive alien plants (IAPs) pose the most significant threat to South Africa's species diverse fynbos vegetation and water resources (Binns et al. 2001; Lombard et al. 1997; Rebelo 1992; Rouget et al. 2003; van Wilgen 2010). The hydrological benefits of restoring natural capital by clearing IAPs need to be quantified. This information is necessary for management of the IAP problem, such as prioritization of eradication strategies, as well as for developing markets for water resources as an ecosystem service. Payment for ecosystem services (PES) has been recommended as a successful way of ensuring intervention and providing an incentive for conservation (Aylward & Barbier 1992; Palmer & Filoso 2009).

Invasive alien plants (IAPs) cause a significant reduction in streamflow (Enright 2000; Le Maitre et al. 1996). This is particularly evident in the Western Cape Province of South Africa where IAPs are estimated to reduce the annual runoff of water by up to 15.8% (Enright 2000). In addition to outcompeting the indigenous fynbos vegetation for essential resources, IAPs also change the natural landscape by destabilizing catchments and thereby increasing soil erosion, altering fire regimes and hydrological processes, as well as changing the physical and chemical composition of the soil (Joshi et al. 2004; Le Maitre et al. 1996; Tabacchi et al. 2000). The potentially detrimental impact of invasive alien plants on fynbos vegetation in South Africa was recognized as far back as the early 1900s, although it was not until 1945 that the hydrological implications associated with invasion became a concern and studies commenced to determine the impact of afforestation with exotic tree species on streamflow (van Wilgen et al. 1997).

Short term studies on the impact of afforestation on streamflow were able to show that streamflow increased after removing IAPs (Prinsloo & Scott 1999). This was a major justification for the Working for Water programme which was launched in 1995 with the aim of increasing water security by controlling IAPs (Dye & Jarmain 2004). Although there was evidence that invasive vegetation used more water than fynbos vegetation, these studies did not take longer-term hydrological changes into account, such as how much water the restored fynbos vegetation would use (Dye & Jarmain 2004). Because of the time frame required to obtain information on the water use by post-clearing vegetation, studies have relied upon hydrological models to estimate the impacts of clearing IAPs. Hydrological models are often based on critical assumptions and generalisations (Le Maitre et al. 2000). The uncertainty in the models used to estimate water use in the past has been identified as a knowledge gap (Dye et al. 2001; van Wilgen et al. 1998; Versfeld et al. 1998). It has been recognised that more detailed predictions of water use are required for land-use decisions (Dye et al. 2001) and that information is needed on the impacts of invasive alien vegetation and native vegetation on the hydrology of riparian and dryland conditions (Clulow et al. 2009; Dye et al. 2008). In particular, the need for a more advanced system for modelling evapotranspiration (ET) at a wide range of scales has been highlighted (Dye et al. 2001; Versfeld et al. 1998).

The Surface Energy Balance Algorithm for Land (SEBAL) is an energy balance model used to calculate actual ET (Bastiaanssen et al. 2005). This is a powerful model that combines remotely sensed data with field measurements to provide estimates of water use by vegetation at varying scales. A collaboration between Water Watch (www.waterwatch.nl) and the Council for Scientific and Industrial Research (CSIR, www.csir.co.za) assessed the actual ET over an 8 year period for the Western Cape and Kwazulu Natal using SEBAL. The model has been validated for South African conditions and is considered to be trustworthy (Hellegers et al. 2009). SEBAL ET data can be used to determine the hydrological impacts of IAPs and fynbos vegetation in riparian and dryland conditions. In addition, a landscape scale assessment can be provided for management and prioritization strategies for IAP control on the Agulhas Plain.

The objective of this study was to quantify the amount of water made available by restoring natural capital through IAP eradication on the Agulhas Plain. The study therefore addressed the following key questions: 1) Does invasive vegetation use more water than natural vegetation for all vegetation types and hydrogeological conditions? 2) Where should Working for Water target clearing operations from a hydrological perspective? 3) How much water could be made available by clearing the Agulhas Plain? The hydrological benefit of clearing invasive vegetation was calculated as the difference in evapotranspiration between invaded and natural areas. Differences between vegetation types and between hydrogeological conditions were explored to determine hydrological priority areas on the Agulhas Plain.

4.3. Method

4.3.1. Study site

The area of interest for this study is the Agulhas Plain (AP). The area is located between 19°30’ and 20°15’ south, and 34°30’ and 34°50’ east, covering 215 170 hectares at the southern-most tip of Africa (see Figure 4.1). The AP has been recognised as an area of high conservation importance for both terrestrial plants and wetland biota (Rebelo 1992). The area consists of a gently rolling, lowland landscape (Cowling & Holmes 1992) and is unique in that it has a wide range of wetland types within a relatively small area (see Figure 4.1). Freshwater springs, rivers, floodplains, estuaries, lakes, vleis and endorheic pans can all be found on the AP (Jones et al. 2000). The De Mond estuary and De Hoop vlei are both classified as RAMSAR sites (EWISA 2010). The average rainfall of the area is 478mm a year, most of which falls in the winter months between May and August. Of this rainfall, around 37mm are converted to runoff. This 7% precipitation to runoff ratio is below the national average of 8.6% (DEAT 1999). The summer is long and dry, typical of a Mediterranean climate. The vegetation on the Agulhas Plain consists of sclerophyllous fynbos shrubland (van Wilgen et al. 2008). The Agulhas Biodiversity Initiative (ABI) was launched in 2004 with the aim of addressing the threats to the biodiversity of the area and promoting sustainability. One of the most significant threats is invasion by alien plants (Binns et al. 2001; Lombard et al. 1997; Rebelo 1992; Rouget et al. 2003). It was found that 31% of the Agulhas Plain was invaded in 2009 (see Chapter 2). The three dominant invasive alien trees found on the AP are *Acacia*, *Pinus* and *Eucalyptus* species. *Acacia* species are predominantly found on the deep sandy lowlands and along river courses, particularly *Acacia mearnsii*. Pines and Eucalypts have invaded the uplands and mountainous areas.

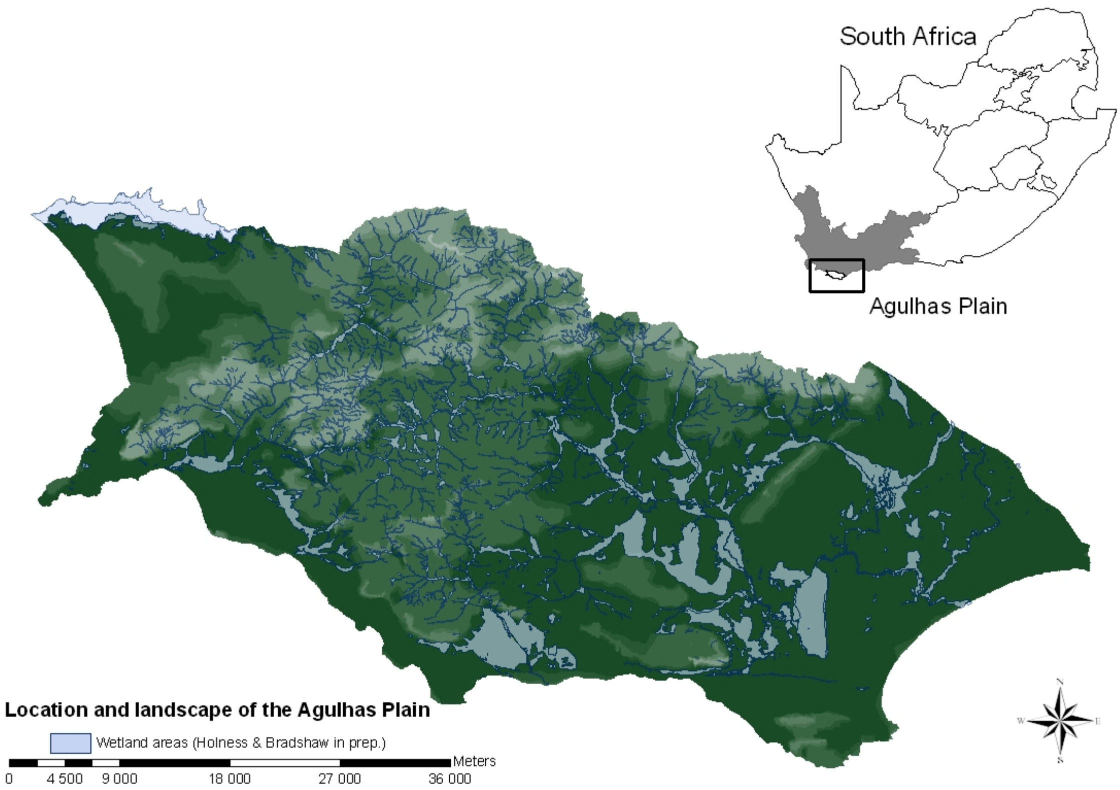


Figure 4.1: The Agulhas Plain is located at the southern-most tip of Southern Africa. It is unique in that it contains a wide diversity of wetland types. The area is considered a conservation priority area for both terrestrial plants at wetland biota.

4.3.2. Study design

Remote sensing was used to update the invasion map of the Agulhas Plain described in Chapter 2 using SPOT 4 derived NDVI. The spatial resolution of the SPOT 4 imagery was not sufficient to detect areas invaded below a 50% density. This shortcoming was not expected to have a significant influence on the ET predictions, as only the ET of dense stands could be detected with the 250x250m resolution of the Surface Energy Balance Algorithm for Land (SEBAL) data. No significant difference in the ET values resulting from a difference in scale was found (See Appendix D). The extent of invasion (above 50%) was found to be 31% with a total area of 66 772 hectares infested (Chapter 2). The updated invasion map was classified into three hydrogeological scenarios, namely: deep sands, wetlands and drylands (see Figure 4.2). Deep sands are formed by the intergranular aquifers along the coastal areas. IAPs growing on these deep sands can access groundwater and water use is therefore limited to the rate of evapotranspiration (ET) of the invasive vegetation and climatic conditions (temperature, vapour pressure deficit, solar radiation). Wetlands are defined here as riparian zones along rivers and wetland areas in the lowlands. A detailed map of the wetland areas was provided by Holness & Bradshaw (In prep.). In these areas, IAPs have access to groundwater and runoff. Again, the water use of IAPs growing in these areas is limited to the rate of ET and climatic conditions. Dryland or upland areas were classified as those shallow soils overlying the fractured hard rock aquifers in the uplands where IAP water use is limited to the amount of rainwater captured and retained by the soils and fractures in the underlying rocks. The evapotranspiration was derived for invaded and natural (un-invaded) vegetation types for each hydrogeological condition using SEBAL data (described in more detail in the next section). The difference in ET between invaded and natural areas was used to determine the amount of water that would be made available by clearing IAPs. This information can be used to determine which areas should be prioritized for eradication to maximise the hydrological return.

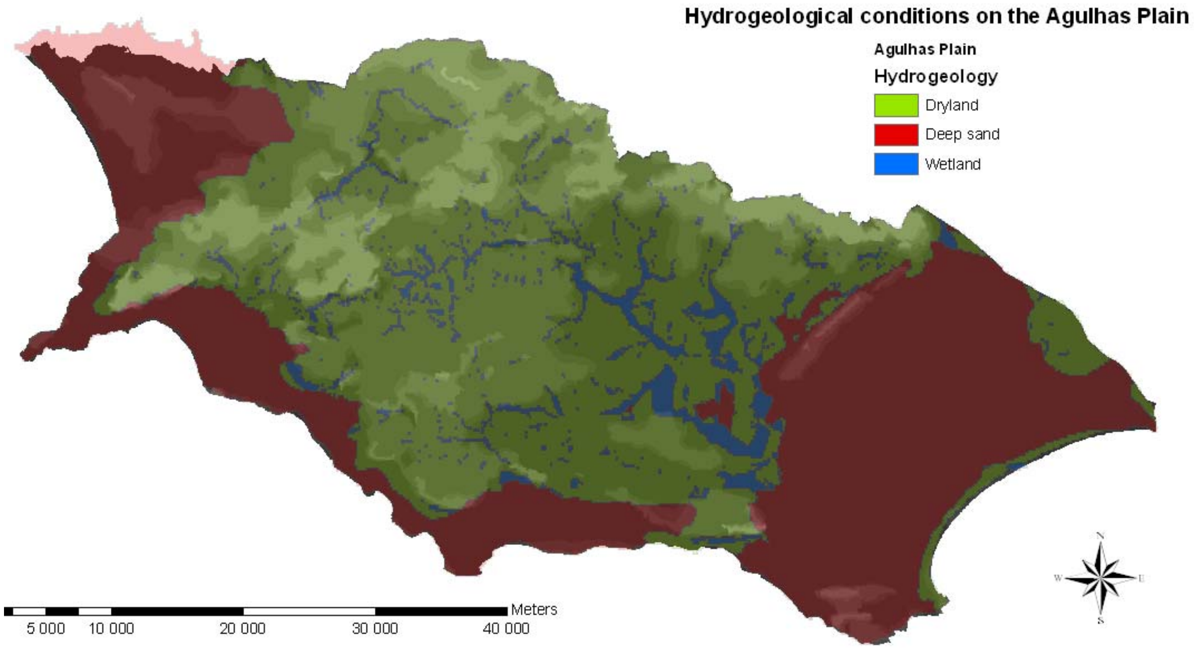


Figure 4.2: The Agulhas Plain was divided into three hydrogeological classes based on the aquifer and IAP accessibility to water. The red areas are deep sandy intergranular aquifers. Wetlands are delineated in blue, and the drylands consisting of fractured hard rock aquifers are illustrated in green.

4.3.3. SEBAL

Evapotranspiration data were obtained from a study done by Water Watch and the CSIR to monitor changes in evapotranspiration over KwaZulu Natal and the Western Cape (Meijninger & Jarmain In prep.). The Surface Energy Balance Algorithm for Land (SEBAL) was used to measure actual ET by combining remote sensing with field data. These inputs for the SEBAL model included shortwave and longwave radiation, surface albedo, air specific heat, air density, surface temperature, NDVI and surface thermal emissivity among others. MODIS imagery was used with a spatial resolution of 250m. There were several advantages to using SEBAL data. Firstly, ET information could be derived for invaded and natural areas for the same vegetation types and hydrogeological conditions. The ET values for natural vegetation are representative of a fully restored state of vegetation following IAP clearing. This was necessary baseline information to quantify the hydrological benefits of restoring natural capital. Secondly, water use could be evaluated at a landscape scale. A third advantage to using the SEBAL data was that a mean ET value was derived over the period of a year so that the impacts of seasonality were avoided. Lastly, and most significantly, the SEBAL data were already available from the Water Watch – CSIR study, and as a result, the time required for data analysis was reduced considerably.

4.3.4. Quantifying the hydrological benefits

The hydrological benefit of clearing IAPs was calculated as the difference in ET between invaded (above 50% density infestation) and natural (not invaded) areas. The amount of water made available by clearing IAPs was calculated for each vegetation type and hydrogeological condition, where possible. An average difference between invaded and natural areas was derived from these values for each of the three hydrogeological conditions and used to calculate where the greatest hydrological return for clearing would be on the Agulhas Plain. The hydrological benefit per hectare was also calculated, as well as the overall benefit of clearing all invasive vegetation from the Agulhas Plain. These calculations were based on two assumptions: firstly, the SEBAL ET values are representative of the vegetation types and hydrogeological conditions, and secondly, the difference in ET equates to the difference in runoff in the water balance equation. The Agulhas Plain can be seen as a closed catchment. The water balance equations states that runoff is equal to the amount of water entering a catchment through rainfall minus the amount of water leaving the catchment through evapotranspiration with some losses and gains for storage (groundwater). Over sufficient time, the losses and gains of the stored water even out and are negligible. Assuming rainfall is constant, a change in ET must result in an equivalent change in runoff.

4.4. Results

Invaded areas (indicated by red squares in Figure 4.3) were found to have a higher rate of evapotranspiration (mm/year) than natural (un-invaded, indicated by blue circles) areas for all three hydrogeological conditions (Figure 4.3). The highest rate of ET for invaded areas was for deep sands (855mm/yr), followed by wetland areas (810mm/yr). Interestingly, the reverse was true for natural sites. Natural vegetation in wetlands (725mm/yr) was found to have a higher ET than in deep sands (690mm/yr). Drylands had the lowest ET rate for both invaded (740mm/yr) and natural areas (680mm/yr).

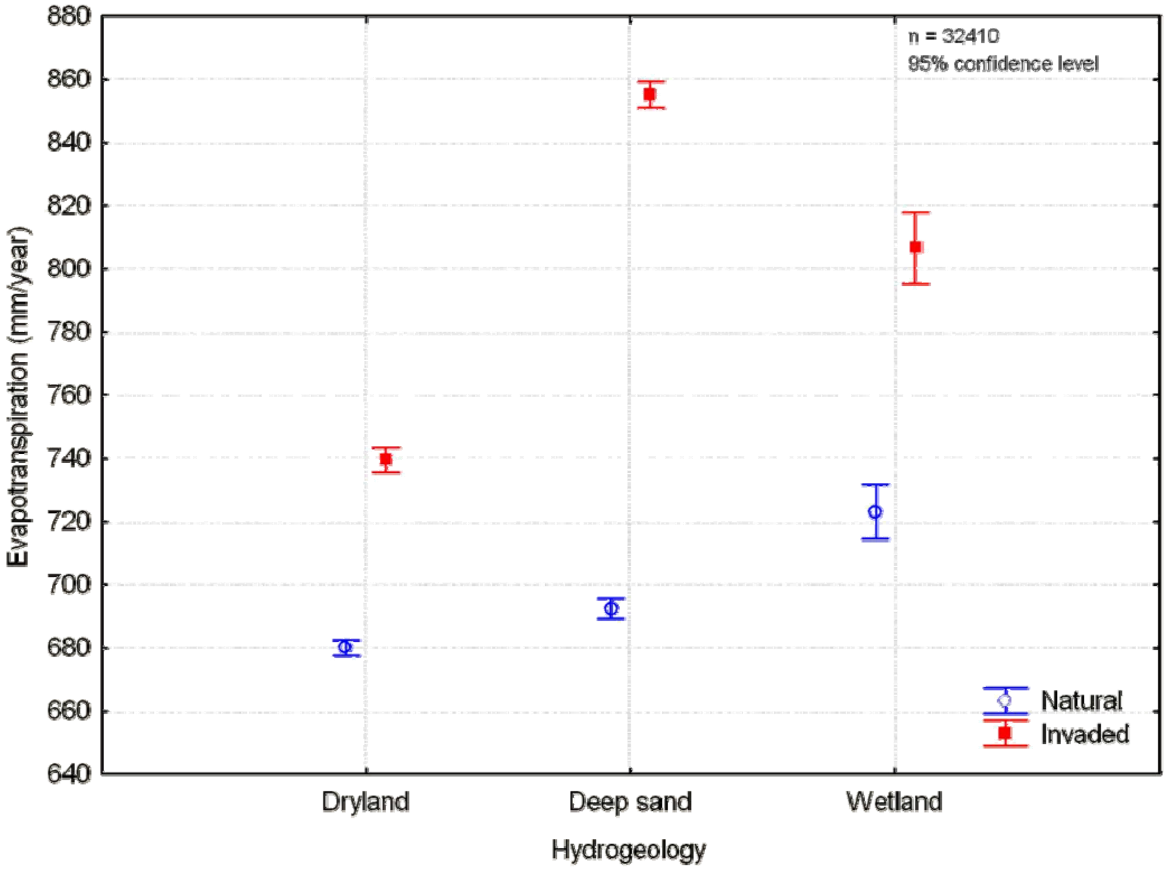


Figure 4.3: Invaded areas (red squares) have a higher rate of evapotranspiration than natural areas (blue circles) on the Agulhas Plain for all hydrogeological conditions. The difference in water use between invaded and natural areas is greatest for deep sands.

The hydrological benefit of removing invasive alien vegetation was calculated for each vegetation type and hydrogeological condition (Table 4.1). Deep sands held the greatest hydrological potential for most vegetation types with the exception of vegetation growing in moist conditions, such as in wetlands, vleis and along rivers. The highest hydrological return (mm/year) from clearing IAPs would be for sand dunes.

Table 4.1: The hydrological benefit (m3/ha/yr) is given for each vegetation type and hydrogeological condition. On average, deep sands have the greatest hydrological benefit. For ET values of invaded and natural areas, see Appendix C.

Vegetation type	Area (ha)	Dryland (m^3/ha/yr)	Deep sand (m^3/ha/yr)	Wetland (m^3/ha/yr)
Elim fynbos	3762.31	520	1260	770
Ericaceous fynbos	3864.19	430	0	0
Limestone fynbos	14994.86	840	1210	0
Mountain fynbos	16256.78	490	180	360
Renosterveld	19.12	570	970	0
Restioid fynbos	3440.30	930	1250	510
Rivers & floodplain	1322.21	0	-680	440
Sand dunes	482.86	1170	4620	0
Seasonal wetlands	1699.03	-190	-1120	480
Strandveld vegetation	10775.17	-270	1560	0
Vleis & salt pans	807.41	-410	-170	810
Average benefit		410	910	330

The average hydrological benefit (mm/yr) derived in Table 4.1 was used to quantify how much water would be made available (m^3/yr) should invasive vegetation be removed from the Agulhas Plain (Table 4.2). The benefit of clearing invaded drylands on the AP amounts to 11 810 682m^3 of water a year. The greatest benefit is from clearing invaded deep sands, which would make 23 310 711m^3 of water available annually. A considerably lower amount of water would be made available by clearing wetlands (1 135 549m^3), although it has the highest benefit (mm) per hectare (0.0094mm/ha). Overall, 36 256 943m^3 would be made available by clearing all invaded areas on the Agulhas Plain.

Table 4.2: The total amount of water that would be made available by clearing invasive alien plants under different hydrogeological conditions on the Agulhas Plain.

	Dryland	Deep sand	Wetland
Average benefit (mm/yr)	41	91	33
Total invaded area (ha)	28993	25678	3475
Total hydrological benefit (m^3/yr)	11810682	23310711	1135549
Benefit per hectare (mm/ha)	0.0014	0.0035	0.0094

Total benefit of clearing invaded areas on the Agulhas Plain: 36 256 943 m^3/year

4.5. Discussion

Streamflow reduction as a result of invasion by alien vegetation has been well documented in fynbos areas (Le Maitre et al. 1996; van Wilgen et al. 1997). The results of this study confirm that IAPs utilise more water than natural fynbos vegetation and show that there is a clear hydrological benefit to removing invasive vegetation on the Agulhas Plain. The quantifiable benefits of restoring natural capital presented in this study can be used to prioritize areas for clearing, as well as to motivate for the payment for ecosystem services.

Working for Water currently targets sparsely invaded uplands for clearing operations (Holmes et al. 2008; Richardson et al. 2007). Removing IAPs from the upper catchment areas promotes long-term sustainability by decreasing the chances of reinvasion, while optimising financial resources. According to van Wilgen (2010), there is insufficient capacity to control the IAP problem in South Africa. As a result, prioritization is essential for maximising benefits with limited funding (Dye et al. 2001). The criteria used for prioritization by WfW are: presence of priority IAP species, impact on hydrology, impact on biodiversity, impact on grazing, impact on harvested products, and the impact on fire hazards (van Wilgen 2010). This study explored the impact of clearing IAPs on hydrology and found that the greatest hydrological benefit would be derived from clearing IAPs on deep sandy aquifers. These areas encompass the low lying coastal areas of the Agulhas Plain and in most cases, do not coincide with the priority areas identified by WfW. Water use by IAPs growing on deep sand aquifers is limited by the physiology of the plants, the rate at which they can transpire and climatic factors (Dye & Jarmain 2004; Le Maitre 2004). This is because tall woody plants typically have deeper root systems and are able to access groundwater reserves (Le Maitre 2004). Evaporation is also increased by the taller, rougher canopies of IAPs (Le Maitre 2004). The deep sandy areas of the Agulhas Plain are densely invaded with *Acacia* species. Coastal dunes are particularly susceptible to invasion by *Acacia cycl*ops, but these stands are often not priorities as a result of their distribution away from the upper watershed areas (van Wilgen et al. 1998). Although significant amounts of water would be made available by clearing IAPs growing in deep sands, the long-term sustainability of the clearing operations is compromised as lowland areas are more susceptible to reinvasion by propagules transported downstream. Additionally, clearing dense stands of IAPs is expensive and requires intensive follow-up activities to prevent reinvasion (CapeNature, date unknown).

Although the eradication of invasive vegetation on the deep sands would have the greatest hydrological benefit, clearing invasive vegetation in wetland areas generates the greatest benefit per hectare (Figure 4.4). Wetland areas also overlap with WfW priority areas in the upper catchment areas. Clearing invaded wetland areas would optimise the hydrological gains for the input costs by WfW. Wetlands account for a small area of the Agulhas Plain and therefore fewer resources would be required to clear these areas.

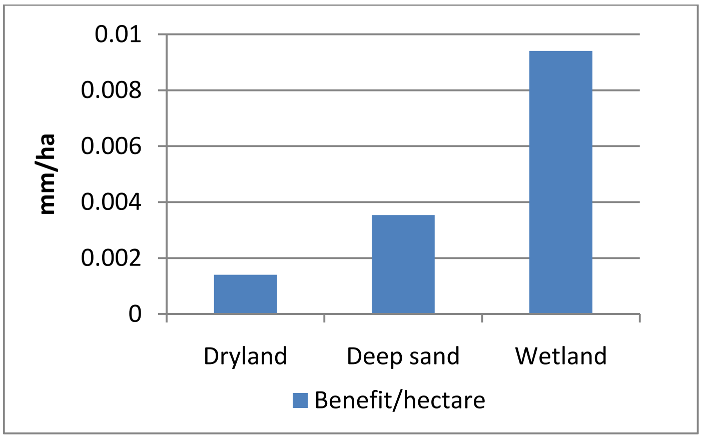


Figure 4.4: The benefit (mm) per hectare is highest for wetland areas.

This study provides hydrological data at a landscape scale. Previous estimates of water use have been site specific and have relied on hydrological models to extrapolate estimates to other areas and at different scales. The data from the SEBAL model used in this study is a measure of actual ET at a spatial resolution of 250 x 250m. This resolution is sufficient for management at a landscape scale. These data are valuable for IAP eradication programmes, such as Working for Water to make appropriate decisions that incorporate hydrological priorities into clearing strategies. The quantities of water made available by clearing IAPs justify eradication on the Agulhas Plain.

Restoring natural capital will make more water available for the wetland and estuary ecosystems on the Agulhas Plain. A total of 37 endorheic wetlands are found in the area, which range from fresh water to extremely saline (Jones et al. 2000). Water security is essential to maintain the unique chemical balance of these hydrological ecosystems and the fauna and flora associated with them. This is also true for the 29 palustrine wetlands also present on the Agulhas Plain (Jones et al. 200). The diverse wetlands (including two RAMSAR sites) support a wide array of biodiversity. A sufficient and constant supply of fresh water is essential for estuary ecosystems. Many fresh and salt water fish species breed in estuaries and the health and integrity of the ecosystem ensures the survival of fish populations. This is a concern as the ocean’s fish populations are already threatened by overfishing. Freshwater resources also play a role in nutrient cycling offshore. Nutrients are washed into the ocean supporting a variety of sea life. Not only does invasive vegetation reduce streamflow, but results in changes in nutrient cycling, having impacts downstream. Another benefit of an increased amount of water available following clearing is the dilution of pollution from agricultural practices on the Agulhas Plain. Several dairy farms dispose of their waste water into the local rivers. Additionally, fertilizers and other agricultural supplements enter the hydrological system and may become concentrated without the dilution effect. Increased water resources are also beneficial for human activities. The population of Bredasdorp is increasing over time and the town is becoming more dependent on groundwater resources. Removing IAPs increases the recharge of groundwater. This groundwater could potentially be used for agricultural practices as well.

To the best of our knowledge, this study is the first of its kind to quantify the actual hydrological benefits of restoring invaded areas to a natural state on the Agulhas Plain. This chapter also provides information on the impact of native and invasive vegetation on the hydrology of dryland and riparian areas as identified as a knowledge gap by Clulow et al. (2009) and Dye et al. (2008). SEBAL is an advanced system for determining actual ET at varying scales that has the potential to improve IAP management decisions and justify the restoration of natural capital.

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Chapter 5

Conclusions and recommendations

5.1. Key messages

This thesis explored the use of remote sensing to map invasive vegetation and provide the spatial data necessary for quantifying the hydrological benefits of clearing invasive vegetation on the Agulhas Plain. The key messages of the study are summarised below.

a) When selecting satellite imagery, the spatial resolution should be suited to the objective and scale of the study.

b) Invasive vegetation below a 50% density could not be detected at a spatial resolution of 20x20m.

c) The Normalised Difference Vegetation Index (NDVI) is the most accurate technique for mapping vegetation on the Agulhas Plain, explored in Chapter 2.

d) NDVI was not able to distinguish different species of invasive vegetation. Only medium and tall alien trees could be distinguished from the native fynbos vegetation. The spectral signature of invasive vegetation is easily confused with that of tall fynbos and natural forest. Wetland vegetation was also misclassified as invasive vegetation as a result of the high water content.

e) Disturbance data should always be included in the spatial analysis of invasive vegetation over time.

f) Disturbance events influence the spatial distribution of invasive vegetation.

g) No conclusions could be drawn regarding the influence of fire on invasion for the time frame of the study and at the spatial resolution of the imagery.

h) Changes in the spatial distribution of invasive vegetation over time, but not in the total extent of invaded land suggest that new areas are being invaded at the same rate at which they are being cleared. This is analogous to the Red Queen Hypothesis in evolutionary biology.

i) The greatest quantity of water would be obtained from clearing the invaded deep sands of the Agulhas Plain. These areas are densely invaded with *Acacia* species. From a hydrological perspective, deep sands should be a priority area. Working for Water target sparsely invaded uplands for long-term sustainability and deep sands are not a priority.

j) Clearing invaded wetlands yields the greatest hydrological benefit per hectare. These areas also overlap with Working for Water priority areas. Wetland areas combine hydrological benefits with long-term sustainability.

k) In total, 36 million cubic meters of water could be made available by clearing the Agulhas Plain. This amount of water certainly justifies future clearing operations.

l) There are significant hydrological benefits resulting from the restoration of natural capital. Increased water resources ensure the survival of the biodiversity associated with the unique wetlands and estuaries on the Agulhas Plain. Pollution of the hydrological system would be diluted and groundwater recharge will be increased enhancing water security.

5.2. Conclusions

5.2.1. Using remote sensing to map invasive vegetation

Invasive alien plants can spread at alarming rates. They have large seed banks and no natural pathogens and predators to prevent rapid multiplication (van Wilgen et al. 2004). Changes in the spatial distribution of invasive vegetation are an important consideration for land management agencies and up-to-date information is required to formulate appropriate strategies for IAP eradication and control. In South Africa, invasion maps are not updated often enough because of the time and expenses required to do so (WFWP 1999). Often, invasion maps are not available at the scale required to determine accurate spatial estimates of invaded areas (van Wilgen et al. 2001). Remote sensing has been suggested as a valuable technique for mapping and monitoring invasive vegetation as satellite imagery can be acquired for varying spatial and temporal scales and are cost effective. Remote sensing has been demonstrated to have potential for mapping invasive vegetation in South Africa (Cobbing 2006), and in particular, for fynbos areas (Hope et al. 2009). The aim of Chapter 2 was to explore which of three commonly used remote sensing techniques was most suitable for mapping invasive vegetation. In order to do this, several types of satellite imagery were considered. SPOT 4 imagery was chosen as it was available free of charge at a spatial resolution of 20x20m which could be used to map the extent of invasion of the Agulhas Plain at a landscape scale. SPOT 4 contains four bands, of which two are the red and near infrared bands required for mapping vegetation. Fewer bands also reduce the processing time of this imagery. Seven satellite images were acquired at the processing level 4 from the European Space Agency (ESA). Although this level of processing included geometric corrections, further orthorectification was needed using Landsat 7 ETM+ imagery as the reference dataset. Having an accurate reference dataset is an important consideration when working with satellite imagery. While imagery was obtained free of charge from ESA (excluding the costs required to download the imagery), the process of acquiring the images was time consuming. Once the research proposal was submitted, it took several weeks for permission to be granted to use the imagery. Another consideration when choosing the SPOT 4 imagery was weather conditions. The Agulhas Plain is a coastal area with frequent haze coming off the ocean. Haze and cloud cover can influence the data derived from satellite images (Kakembo et al. 2006). Images were chosen for the end of the dry season (February) when interference from haze could be kept at a minimum. Wetlands and riparian areas could also be easily distinguished from dryland areas as soil moisture was at its lowest. Evapotranspiration was also considered when choosing the period for the study. Vegetation responds differently to water availability and as such, a period was chosen when productivity was as close to average as possible. Evapotranspiration over the Agulhas Plain peaks in July-August with values closest to the mean in February and November.

5.2.2. Selecting a remote sensing technique for mapping and monitoring vegetation

Numerous remote sensing techniques are available for classifying land cover. When selecting a technique, the objective and scale of the study need to be taken into account. Three commonly used remote sensing techniques for mapping land cover were explored in Chapter 2. Tasseled cap and supervised classification performed better for overall classification of land cover classes, but the Normalised Difference Vegetation Index (NDVI) was found to be the most suitable for the classification of thicket and shrubland. The red and near infrared portions of the light spectrum are used to calculate NDVI and close to 90% of the information relevant to vegetation is contained in these two bands (Fatoki 2007). The shortcomings of this technique were that the spectral signatures of tall fynbos and natural forest are very similar to that of invasive vegetation and are easily confused. This problem has also been identified by Gibson et al. (2003) for South African conditions. Only medium and tall alien trees could be detected on the Agulhas Plain. Smaller invasive shrubs could not be distinguished from fynbos vegetation. Additionally, shadow in the mountainous areas resulted in an overestimation of invasion. Shadow has been known to influence NDVI values (Kakembo et al. 2006). The Agulhas Plain is a rolling lowland landscape (Cowling & Holmes 1992) and therefore interference from shadow was restricted to the mountainous area skirting the northern border of the AP. Invasive vegetation below a 50% density could not be detected as a result of the spatial resolution of the satellite imagery. Despite shortcomings in the detection of low density invasion, SPOT 4 derived NDVI is a useful technique for mapping invasive alien plants at a landscape scale. Changes in vegetation over time can also be detected. These data are certainly able to provide land managers with an idea of what happening at a landscape level. This information can be used to monitor and make decisions for where clearing efforts should be focused. It can be concluded that NDVI is a suitable technique for mapping invasive alien plants in the Cape Floristic Region for a gentle rolling lowland landscape such as the Agulhas Plain.

5.2.3. Conclusions from ground-truthing

Ground-truthing with a team of experts was done to assess the accuracy of the invasion map. SPOT 4 derived NDVI was found to accurately classify invasive vegetation on the lower plain area where there was limited interference from shadow. The extent of invasion in the mountainous areas was overestimated. It was found that there is much variation in density amongst invasive stands on the Agulhas Plain. This patchy distribution of invasive vegetation is a major challenge with regards to accurately assessing the density of invasion. Few densely invaded areas exist within a highly heterogeneous mosaic of varying densities of invasion.

5.2.4. The importance of including disturbance data in spatial analysis of invasive vegetation

The invasion map showed that 31% of the Agulhas Plain is invaded at a density above 50%. Cole et al. (2000) found that 27% of the area was invaded at that density in 2000. Despite a similar extent of invasion, a low level of correlation was found between the spatial distribution of invasive vegetation between the 2000 and 2009 invasion maps. Disturbance events as an explanation were explored in Chapter 3. When the 2000 and 2009 invasion maps were overlaid, 86 925 hectares were found to have become ‘uninvaded’ over time. These areas were mapped as invaded in 2000, but were classified as not invaded in 2009. A total of 84% of this discrepancy was accounted for by the 50% density detection problem. Fire and clearing events account for 43% of the remaining 16% of the area. The remaining 9% of the overall ‘uninvaded’ area could be a result of biocontrol reducing canopy cover below the detectable threshold. Biocontrol has been found to significantly reduce tree density for certain *Acacia* species (Morris 1997). Alternatively, inaccuracies in either of the invasion maps or in the fire or clearing data can explain this reduction in invasive vegetation over time. A key message in this chapter was that information on disturbance events is essential to include in monitoring changes in spatial distribution over time.

5.2.5. Reflections on Working for Water’s progress on the Agulhas Plain

Changes in spatial distribution of invasive vegetation over time, but not in the overall extent of invasion may indicate that Working for Water (WfW) is not making a detectable difference with their eradication efforts on the Agulhas Plain. This is analogous to the Red Queen Hypothesis in evolutionary biology where WfW is running (clearing) as fast as they can to stay in the same place. Increased efforts or more effective techniques are required for WfW to make progress with the eradication of IAPs on the Agulhas Plain. The study showed that areas that had been burnt and cleared had the lowest detectability over time. This is a standard technique used by WfW to cleared invasive vegetation with canopy stored seeds. These results vindicate using the ‘fell and burn’ method to eradicate invasive vegetation on the Agulhas Plain.

5.2.6. Reflections on the SEBAL model

The SEBAL model is the first of its kind in South Africa to provide actual evapotranspiration measurements at a landscape scale for whole provinces. Changes in water use can be detected and accurate predictions made regarding impacts on the hydrological cycle. This model certainly provides valuable information for land management agencies to make well informed decisions. Hydrological priority areas can be identified to optimize the allocation of limited resources. The SEBAL model will be a valuable instrument for justifying the restoration of natural capital by clearing invasive alien plants in South Africa.

5.2.7. Prioritizing IAP eradication efforts

Actual evapotranspiration (ET) values were derived from the SEBAL model for the Agulhas Plain. A mean value for invaded and natural vegetation types and hydrogeological conditions were obtained. The ET data showed that invaded areas use more water than natural areas for all conditions. The greatest hydrological benefit is for clearing invaded deep sand areas. Although the most water would be made available by clearing the dense *Acacia* stands on the deep sands, Working for Water target sparsely invaded upland areas for long-term sustainability. A solution for this conflict in priority areas would be to target wetland areas in the uplands. Clearing wetland areas yields the greatest hydrological benefit per hectare and prevents the spread of invasive propagules downstream.

5.2.8. Much to do about water

In conclusion, significant quantities of water will be made available by clearing invasive alien vegetation on the Agulhas Plain. The benefits of restoring natural capital will improve water security for wetlands and estuaries, dilute pollution, recharge groundwater and support biodiversity. The results of this study justify the restoration of natural capital and can be used for improved management of clearing operations, and to develop markets for ecosystem services.

5.3. Recommendations

Recommendations for future research in this field include:

- The management implications of burning invasive vegetation in fire-adapted fynbos areas are recommended for further investigation. The impact of fire on invasion needs to be understood and managed. Invasive vegetation may also influence fire regimes thereby threatening fynbos communities by altering the frequency, intensity and seasonality of fire. Additionally, measures for preventing and reducing invasion following burning should be explored.

- Further research is recommended to predict the impacts of climate change on terrestrial hydrology and invasion. Changes in the climate are thought to favour woody species which may promote invasion and enhance the productivity of these species. The implications of these changes on terrestrial hydrology are poorly understood.

- Developing markets for the payment for ecosystem services has been suggested as the only way to incentivise conservation and restoration of natural capital. Studies such as this one, provide environmental data, however this data needs to be translated into a common language for economists to interpret. Although quantifying the amount of water that will be made available by clearing invasive vegetation is enough to justify IAP eradication, this data needs to be translated into yield to make economic sense. As no dam or means of measuring yield exists for the Agulhas Plain, it is recommended that a similar study is performed where yield can be measured. Alternatively, data on the volume of the aquifers on the Agulhas Plain should be obtained.

- Finally, it is recommended that the effects of dilution and nutrient cycling on fish populations in wetland and estuary ecosystems be explored in more detail. Runoff, effluent discharge and groundwater pollution from farms on the Agulhas Plain are significant factors in water quality. The dilution effect and nutrient cycling are ecosystem services and can be used to motivate for invasive alien plant eradication. The estuaries are a breeding ground for many fish species. These breeding grounds require sufficient clean freshwater to maintain healthy fish stocks. Invasive vegetation may have detrimental impacts on fisheries by reducing freshwater resources, affecting water quality, changing nutrient cycles and threatening biodiversity and food sources.

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Appendix A

A1: Images showing the reasons why invasive species are introduced to new areas.

A2: An illustration of how invasive alien plants are spread across the landscape.

A3: The impacts of invasive alien plants on the Agulhas Plain.

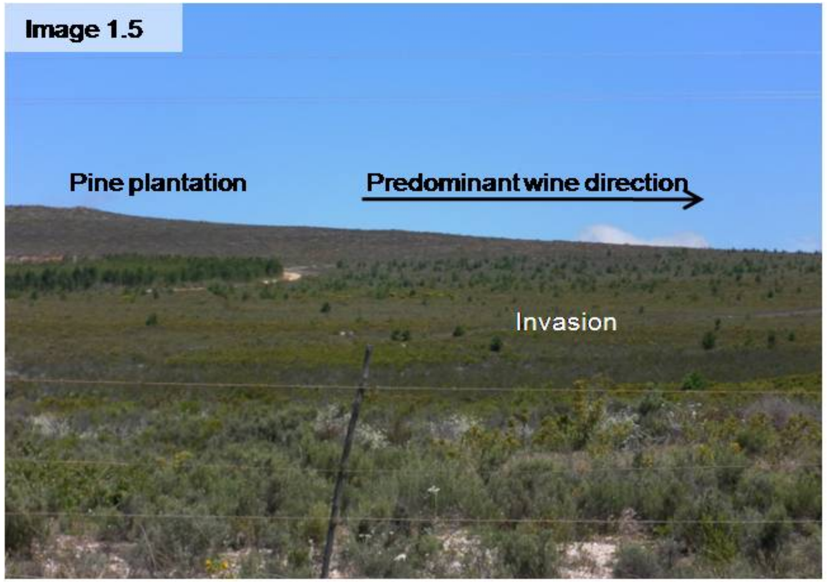
A4: SPOT 4 imagery of the Agulhas Plain (spatial resolution of 20m).

A5: SEBAL evapotranspiration data with the invasion map overlaid.

A6: Biomass on the Agulhas Plain (tons/ha) obtained from the SEBAL model.

Invasive alien plant species were introduced to the Agulhas Plain as shelter belts and fodder for cattle (Image 1.1), for dune stabilization (Image 1.2), as a source of timber (Image 1.3) and as ornamentals (Image 1.4).

Figure A1: Reasons for the introduction of invasive species



Invasive alien plants spread rapidly over time. Some species are dispersed by wind (Image 1.5), while others are dispersed by water (Image 1.6). Human activities such as quarries (Image 1.7) may transport propagules over large distances. Fire and disturbance may also promote invasion (Image 1.8)

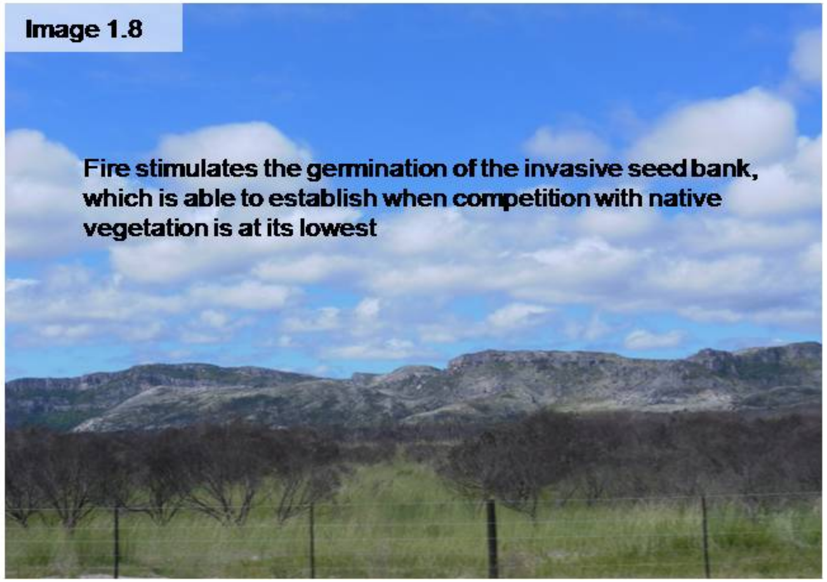


Figure A2: These images show how invasive propagules are distributed across the Agulhas Plain.

Invasive alien plants have invaded 31% of the Agulhas Plain. There are simply not enough resources available to control the problem so information is needed to prioritize areas for optimizing eradication efforts.

Figure A3: The impacts of invasive vegetation are illustrated by these images of the Agulhas Plain.

Figure A4: The SPOT 4 image of the Agulhas Plain

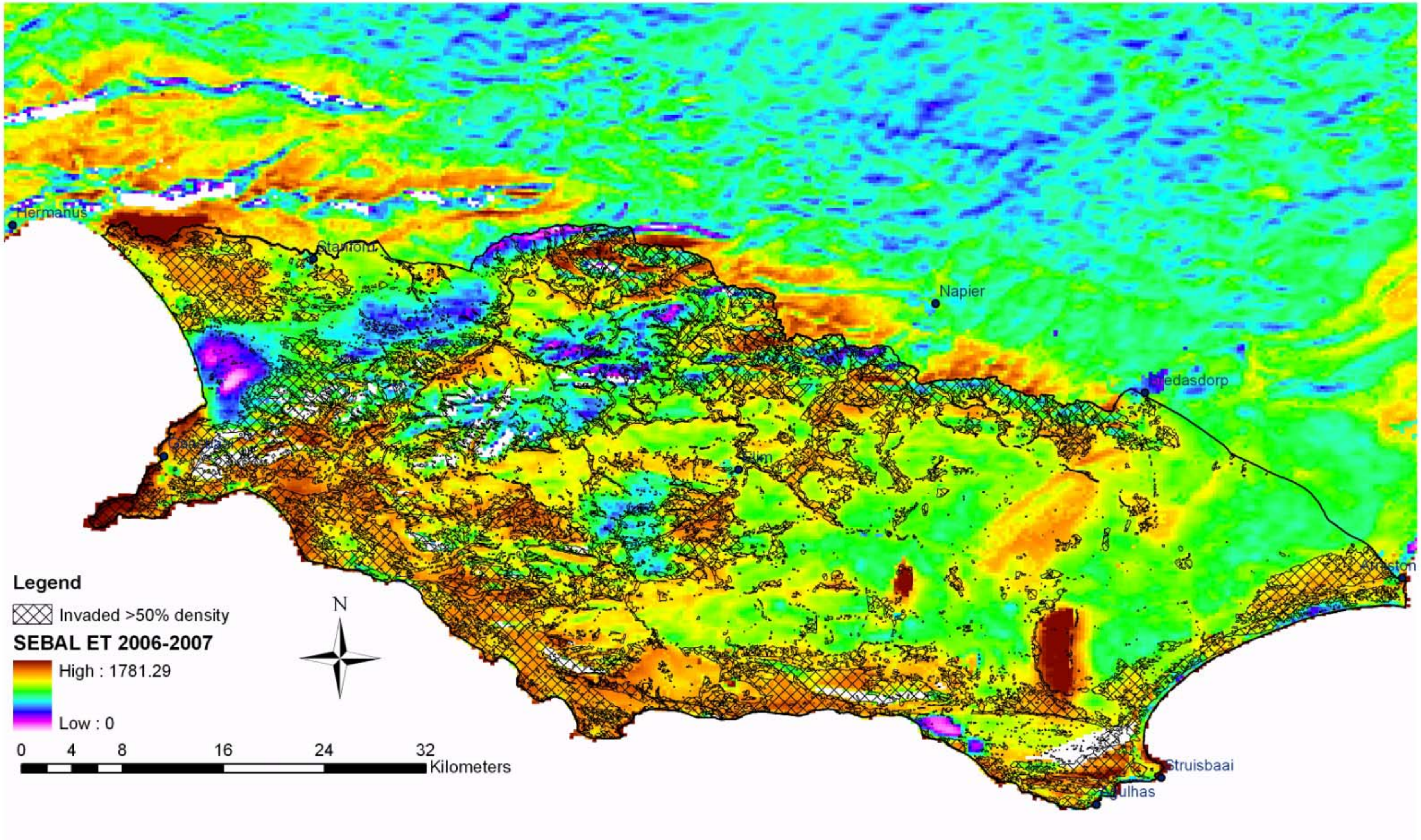


Figure A5: Actual evapotranspiration was obtained from the SEBAL model (mm/yr). The shaded areas indicate invasion above 50% density.

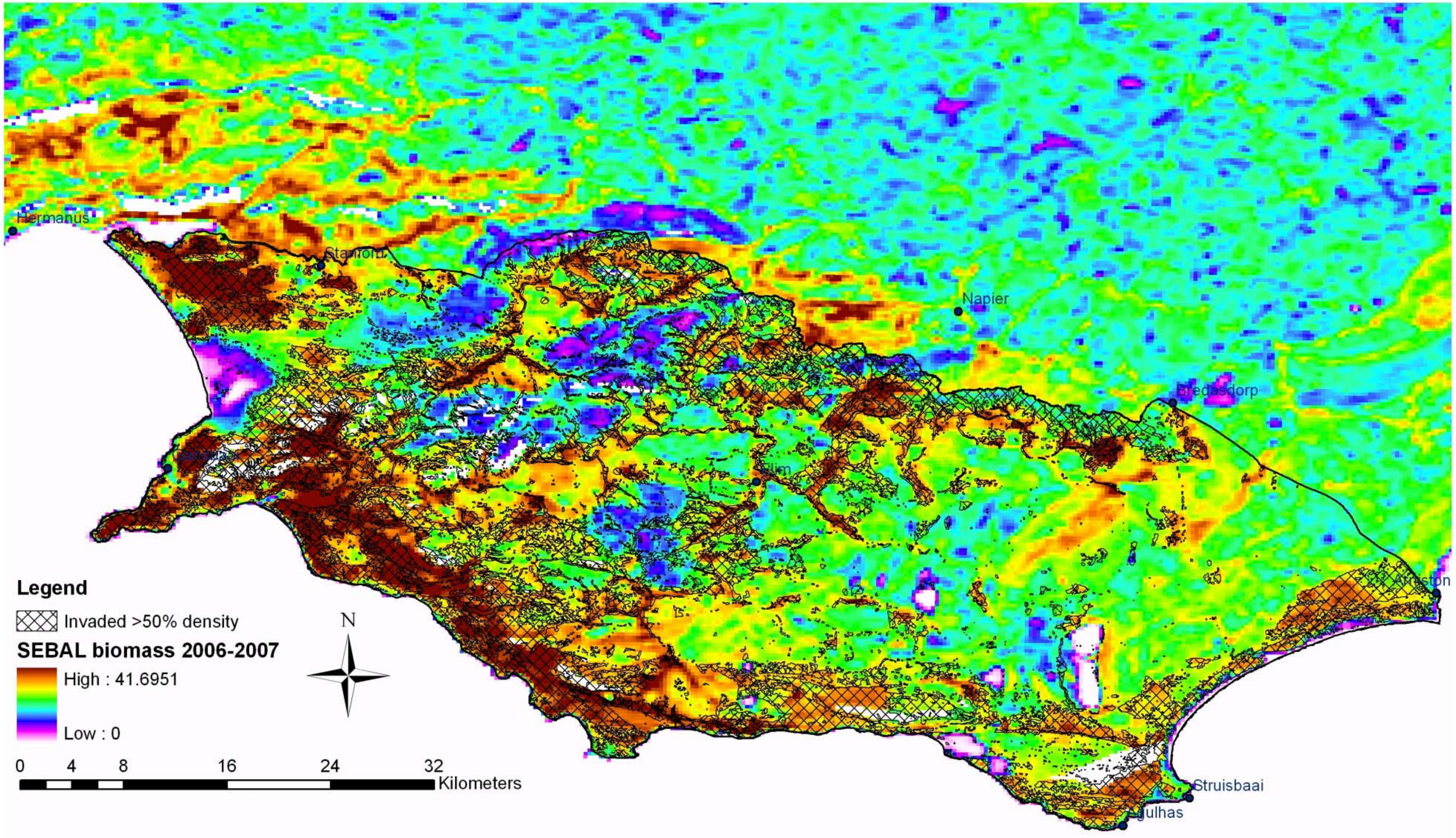


Figure A6: Biomass data derived from the SEBAL model given in tonnes per hectare. The shaded areas indicate areas invaded above 50% density.

Appendix B

B1: Chapter 2 cross tabulations

B2: Chapter 3 cross tabulations

B3: Chapter 4 evapotranspiration values

Table B1: Cross tabulations of RS techniques against the NLC 2000 reference dataset. These results were used to determine which RS technique was most accurate at mapping vegetation on the AP.

	Supervised Classification						Total	User's accuracy
NLC2000	Unclassified	Bare soil	Cultivated	Shrubland	Thicket	Waterbodies		
Bare soil	0	87	8	2	11	2	110	79%
Cultivated	0	20	2221	292	193	3	2729	81%
Shrubland	0	51	814	1284	948	8	3105	41%
Thicket	0	37	481	989	1982	8	3497	57%
Waterbodies	1	17	192	143	144	62	559	11%
Total	1	212	3716	2710	3278	83	10000	54%

	Tasseled Cap						Total	User's accuracy
NLC2000	Unclassified	Bare soil	Cultivated	Shrubland	Thicket	Waterbodies		
Bare soil	2	96	0	5	7	1	111	86%
Cultivated	0	209	1951	380	159	30	2729	71%
Shrubland	1	385	277	1357	955	130	3105	44%
Thicket	5	515	127	658	1970	222	3497	56%
Waterbodies	13	44	106	149	138	108	558	19%
Total	21	1249	2461	2549	3229	491	10000	55%

	NDVI						Total	User's accuracy
NLC2000	Unclassified	Bare soil	Cultivated	Shrubland	Thicket	Waterbodies		
Bare soil	44	23	17	16	10	1	111	21%
Cultivated	1	26	1777	755	159	11	2729	65%
Shrubland	5	6	305	1522	1243	24	3105	49%
Thicket	2	11	176	1089	2051	168	3497	59%
Waterbodies	5	7	117	189	220	20	558	4%
Total	57	73	2392	3571	3683	224	10000	39%

Table B2.1: The original cross tabulation and derived User's accuracy used to compare the 2000 and 2009 invasion maps

Cross tabulation		Invaded2009 NO	Invaded2009 YES	Total
Invaded2000	NO	3581	2118	5699
	YES	598	586	1184
Total		4179	2704	6883

User's accuracy		Invaded2009 NO	Invaded2009 YES
Invaded2000	NO	63%	37%
	YES	51%	49%

TableB2.2: The original cross tabulation and derived User's accuracy for burnt and cleared areas

Cross tabulation for burnt areas			Invaded2009 NO	Invaded2009 YES	Total
NO	Invaded2000	NO	2526	1762	4288
		YES	390	480	870
	Total		2916	2242	5158
YES	Invaded2000	NO	1055	356	1411
		YES	208	106	314
	Total		1263	462	1725

User's accuracy for burnt areas			Invaded2009 NO	Invaded2009 YES
NO	Invaded2000	NO	59%	41%
		YES	45%	55%
YES	Invaded2000	NO	75%	25%
		YES	66%	34%

Cross tabulation for cleared areas			Invaded2009 NO	Invaded2009 YES	Total
NO	Invaded2000	NO	3276	1864	5140
		YES	524	567	1091
	Total		3800	2431	6231
YES	Invaded2000	NO	305	254	559
		YES	74	19	93
	Total		379	273	652

User's accuracy for cleared areas			Invaded2009 NO	Invaded2009 YES
NO	Invaded2000	NO	64%	36%
		YES	48%	52%
YES	Invaded2000	NO	55%	45%
		YES	80%	20%

Table B2.3: The original cross tabulation data and derived User's accuracy of the combined burning disturbance data

	Cleared	Burnt	Invaded 2000	Invaded2009 NO	Invaded2009 YES	Total
Cross tabulation	NO	NO	NO	2281	1559	3840
			YES	351	462	813
			Total	2632	2021	4653
		YES	NO	995	305	1300
			YES	173	105	278
			Total	1168	410	1578
	YES	NO	NO	245	203	448
			YES	39	18	57
			Total	284	221	505
		YES	NO	60	51	111
			YES	35	1	36
			Total	95	52	147

	Cleared	Burnt	Invaded 2000	Invaded2009 NO	Invaded2009 YES
User's accuracy	NO	NO	NO	59%	41%
			YES	43%	57%
		YES	NO	77%	23%
			YES	62%	38%
	YES	NO	NO	55%	45%
			YES	68%	32%
		YES	NO	54%	46%
			YES	97%	3%

Table B3: The benefit if clearing an areas was calculated as the difference between the invaded and natural evapotranspiration, given here in m3/ha/yr.

Drylands	Invaded ET	Natural ET	Benefit of clearing drylands
Elim fynbos	7735	7217	518
Ericaceous fynbos	6012	5583	428
Limestone fynbos	7340	6497	843
Mountain fynbos	6793	6301	492
Renosterveld	6742	6174	568
Restioid fynbos	8254	7325	929
Rivers & floodplain	0	0	0
Sand dunes	6652	5482	1170
Seasonal wetlands	7457	7647	-189
Strandveld vegetation	7253	7527	-274
Vleis & salt pans	5729	6140	-411
Average	6997	6589	407

Deep sands	Invaded ET	Natural ET	Benefit of clearing deep sands
Elim fynbos	7856	6596	1259
Ericaceous fynbos	0	0	0
Limestone fynbos	8189	6976	1213
Mountain fynbos	8180	7997	183
Renosterveld	7437	6471	966
Restioid fynbos	8640	7391	1249
Rivers & floodplain	7298	7980	-682
Sand dunes	7945	3328	4618
Seasonal wetlands	7850	8968	-1118
Strandveld vegetation	8173	6611	1563
Vleis & salt pans	8105	8277	-171
Average	7967	7059	908

Wetlands	Invaded ET	Natural ET	Benefit of clearing wetlands
Elim fynbos	8154	7388	765
Ericaceous fynbos	6663	0	0
Limestone fynbos	0	6912	0
Mountain fynbos	7272	6917	356
Renosterveld	0	8054	0
Restioid fynbos	7755	7248	507
Rivers & floodplain	7994	7557	437
Sand dunes	0	0	0
Seasonal wetlands	7478	7002	476
Strandveld vegetation	0	0	0
Vleis & salt pans	7637	6825	812
Average	7565	7238	327

Appendix C

C1: The question of scale when combining remote sensing and hydrological modelling

C2: Correlations between biomass and water use

The question of scale when combining remote sensing and hydrological modelling

Hydrological systems are highly complex and modelling them can be time consuming and labour intensive (Liu & Zheng 2004). Remote sensing is a logical and effective means of acquiring accurate hydrological data at large scales (Engman 1996). Remote sensing and environmental data were combined in a study performed by the Council for Scientific and Industrial Research (CSIR) to model the evapotranspiration over the provinces of Kwa-Zulu Natal and the Western Cape using the SEBAL model and MODIS imagery. Although SEBAL can be used at various scales, the resolution of the model ultimately depends on that of the input. As satellite imagery is the primary input source, the spatial resolution is an important consideration. MODIS imagery has a medium to coarse spatial resolution (250m) which is advantageous in that it reduces processing time, but at the same time reduces the scale of the model. The invasion map of the Agulhas Plain was mapped using SPOT 4 imagery which has a spatial resolution of 20m. Combining the two data sets could potentially influence the evapotranspiration values for each category of vegetation type and hydrogeology. The SPOT 4 invasion map (20m scale) was scaled up to 250m using the dominant vegetation type and hydrogeology and the ET values derived. These data were compared to the ET values derived for the 20m scale map. There was little difference between the ET estimates at the two scales for the drylands and deep sands. There was however, a difference in the ET values for wetland areas (Figure 5.3) when the two scales were compared. This was not unexpected as wetland areas account for a small portion of the Agulhas Plain. These areas are in most cases, long narrow strips along rivers which are not detected at a 250m resolution. Overall, no significant difference was found between the two scales and as such, the 20m scale was used for this study.

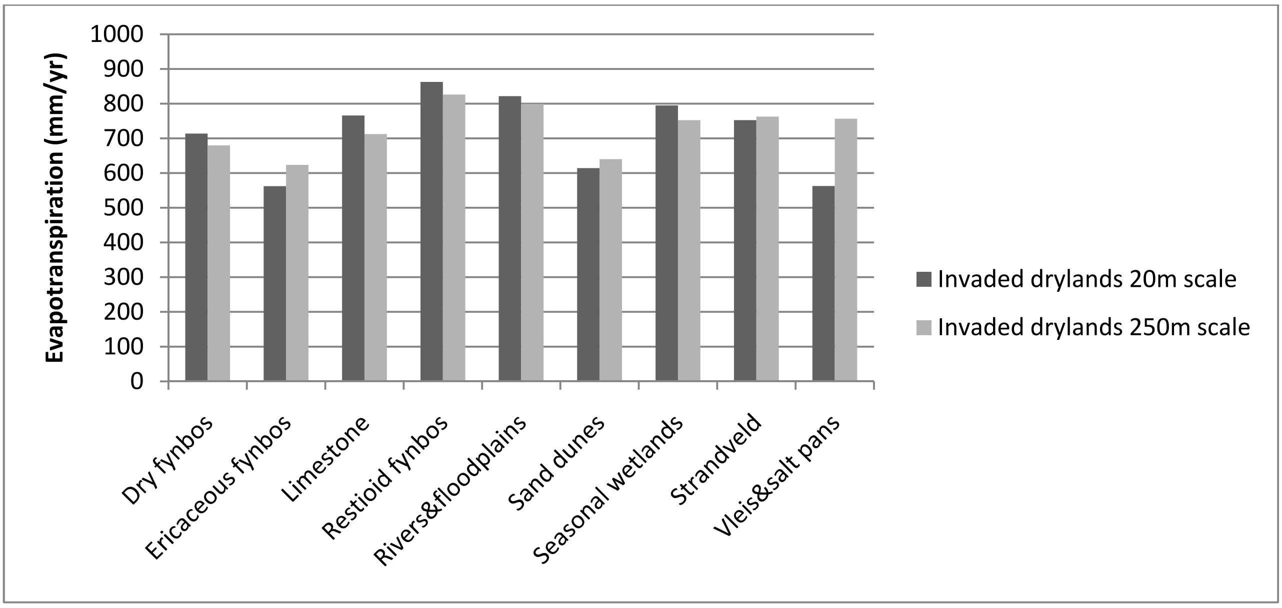


Figure C1: The histogram shows the evapotranspiration estimates (mm/yr) for dryland areas at a 20m and 250m scale. No significant difference exists for the vegetation types.

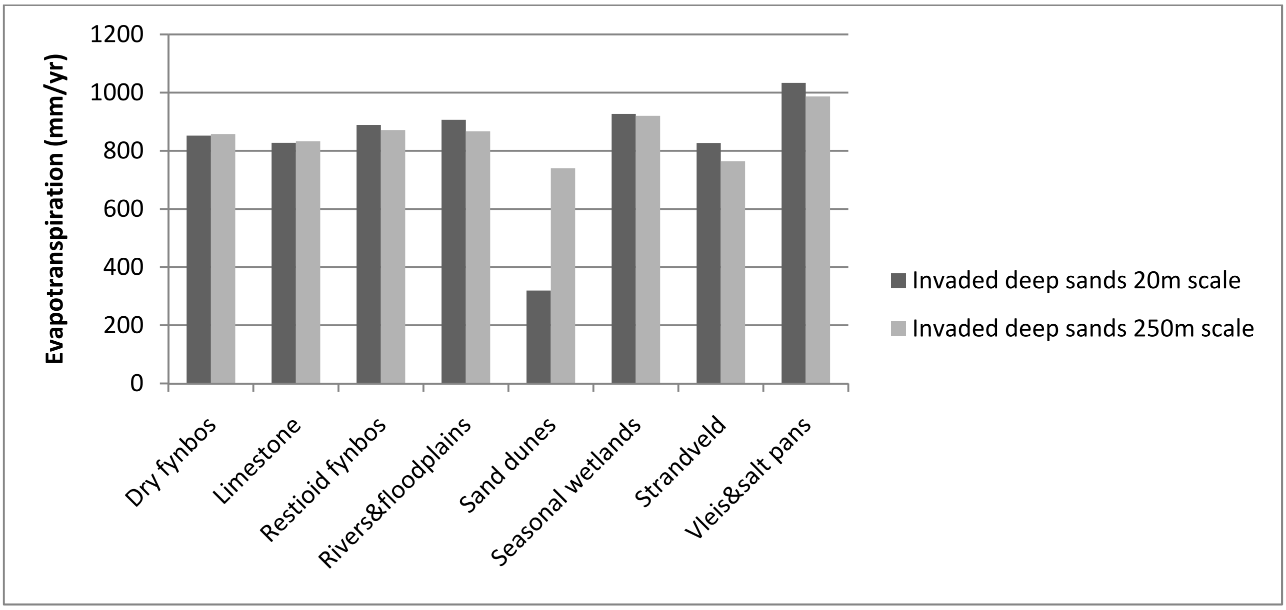


Figure C2: The histogram compares evapotranspiration data obtained at two scales. The data indicate that there is no significant difference between the evapotranspiration values (mm/yr) for all vegetation types except for sand dune vegetation.

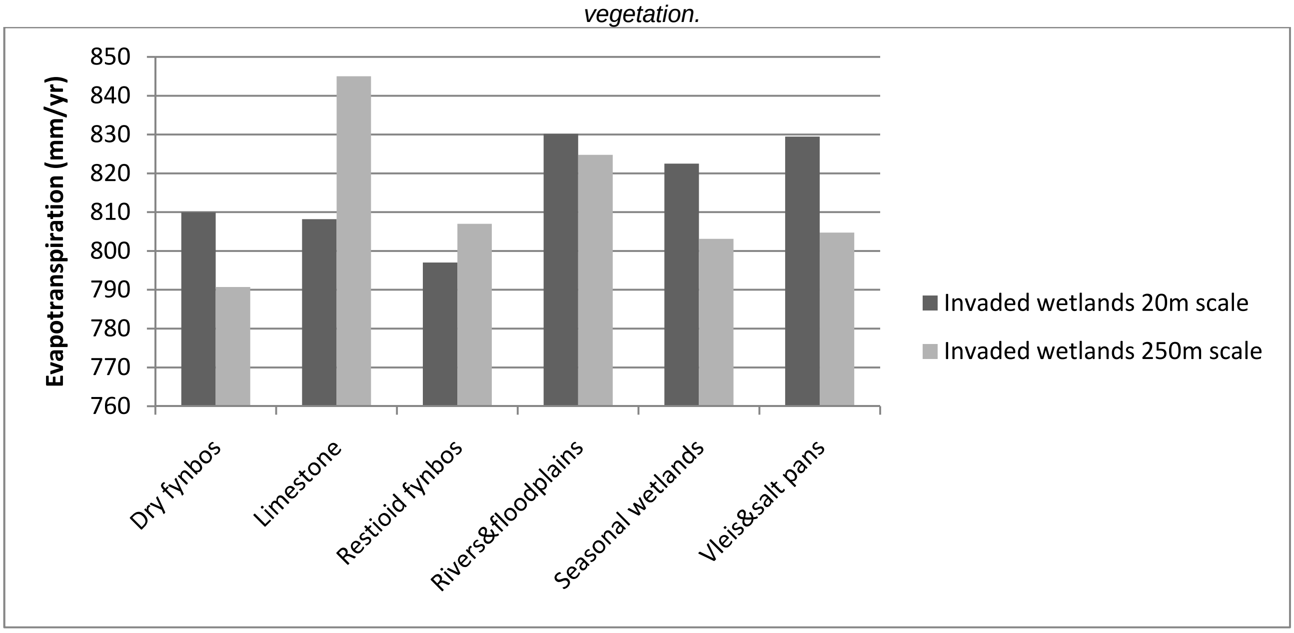


Figure C3: The difference in scale for wetland areas resulted in some difference in the evapotranspiration values (mm/yr) for different vegetation types.

Correlations between biomass and water use

A study by Le Maitre et al. (1996) demonstrated the correlation between biomass and water use. This was confirmed in this study using biomass and evapotranspiration data from the SEBAL study as seen in Figure 5.4. The graph shows a positive correlation (R=0.78947) between biomass (tons/ha) on the x-axis and evapotranspiration (mm/yr) on the y-axis. Areas with high ET, but low biomass such as wetlands and waterbodies may have a confounding effect on the data, and as such, only data for dryland areas was included in this analysis. Le Maitre et al. (1996) used the correlation between biomass and water use to develop a hydrological model whereby a reduction of streamflow could be estimated based on the biomass of invasive vegetation. This model was used to estimate the streamflow reduction for the Agulhas Plain.

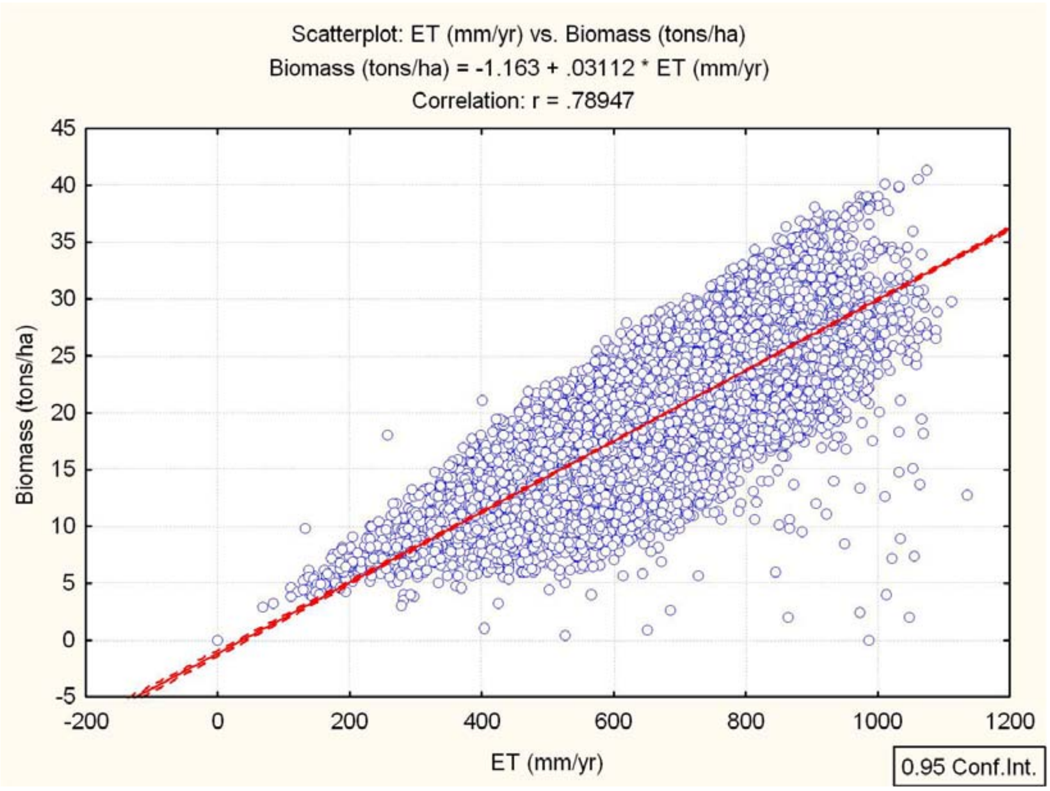


Figure C4: The graph shows a positive correlation (R=0.78947) between evapotranspiration in 2007 (ET07, given in mm/yr) and the biomass (tons/ha) for the same year.

The results of the model estimated that 82 million m^3 of water would be made available by clearing invasive vegetation on the Agulhas Plain (see Appendix D). The SEBAL model estimated a gain of 36 million m^3 of water for the area. There is a considerable difference in the results of the two models. The streamflow reduction model is an empirical model based on small catchment studies used to model changes in water balance. The SEBAL model has a relatively coarse spatial resolution, but is a measure of actual evapotranspiration based on site specific environmental data. The streamflow reduction model was found to overestimate water use as a result of the model being based on high rainfall catchments. The incremental flow (mm) reductions estimated by this model are too large and not comparable to the SEBAL data. As such, the streamflow reduction model was left out of the study. The results of the streamflow reduction model are available in Appendix D.

Appendix D

Preamble from a personal point of view:

Things didn't quite pan out as expected in Chapter 4. The original plan was to use two different hydrological models at different scales and compare the results. This would be a means of assessing the different approaches against each other. What we found was that the results were not comparable and as such, we stuck with what we deemed the more accurate and suitable model for the study. It would have been a pity to let that work go to waste, and as such, I have included it as an appendix.

Streamflow reduction by invasive alien plants on the Agulhas Plain

Introduction

Invasive alien plants (IAPs) cause a significant reduction in streamflow (Enright 2000; Le Maitre et al. 1996). This is particularly evident in the Western Cape Province of South Africa where IAPs are estimated to reduce the annual runoff of water by up to 15.8% (Enright 2000). In addition to outcompeting the indigenous fynbos vegetation for essential resources, IAPs also change the natural landscape by destabilizing catchments and thereby increasing soil erosion, altering fire regimes and hydrological processes, as well as changing the physical and chemical composition of the soil (Joshi et al. 2004; Le Maitre et al. 1996; Tabacchi et al. 2000). The potentially detrimental impact of invasive alien plants on fynbos vegetation in South Africa was recognized as far back as the early 1900s, although it was not until 1945 that the hydrological implications associated with invasion became a concern and studies commenced to determine the impact of afforestation with exotic tree species on streamflow (van Wilgen et al. 1997). These studies were able to show that streamflow increased after removing IAPs (Prinsloo & Scott 1999). This was a major justification for the launch of the Working for Water (WfW) programme which was launched in 1995 with the aim of increasing water security by employing underprivileged people to control IAPs (Dye & Jarmain 2004). Although WfW is regarded as an effective social and economic development tool (Binns et al. 2001), there is limited scientific evidence to validate the clearing of invasive alien plants from a hydrological viewpoint (Dye et al. 2001). The aim of this study was to estimate the hydrological benefits of clearing invasive alien plants on the Agulhas Plain.

Method

Study site

The area of interest for this study is the Agulhas Plain (AP). The area is located between 19°30’ and 20°15’ south, and 34°30’ and 34°50’ east, covering 215 170 hectares at the southern-most tip of Africa (see Figure 4.1). The AP has been recognised as an area of high conservation importance for both terrestrial plants and wetland biota (Rebelo 1992). The area consists of a gently rolling, lowland landscape (Cowling & Holmes 1992) and is unique in that it has a wide range of wetland types within a relatively small area (see Figure 4.1). Freshwater springs, rivers, floodplains, estuaries, lakes, vleis and endorheic pans can all be found on the AP (Jones et al. 2000). The De Mond estuary and De Hoop vlei are both classified as RAMSAR sites (EWISA 2010). The average rainfall of the area is 478mm a year, most of which falls in the winter months between May and August. Of this rainfall, around 37mm are converted to runoff. This 7% precipitation to runoff ratio is below the national average of 8.6% (DEAT 1999). The summer is long and dry, typical of a Mediterranean climate. The vegetation on the Agulhas Plain consists of sclerophyllous fynbos shrubland (van Wilgen & Richardson 1985). The Agulhas Biodiversity Initiative (ABI) was launched in 2004 with the aim of addressing the threats to the biodiversity of the area and promoting sustainability. One of the most significant threats is invasion by alien plants (Binns et al. 2001; Lombard et al. 1997; Rebelo 1992; Rouget et al. 2003). It was found that 31% of the Agulhas Plain was invaded in 2009 (see Chapter 2). The three dominant invasive alien trees found on the AP are *Acacia*, *Pinus* and *Eucalyptus* species. *Acacia* species are predominantly found on the deep sandy lowlands and along river courses, particularly *Acacia mearnsii*. Pines and Eucalypts have invaded the uplands and mountainous areas.

Study design

The study area was classified based on 1) hydrogeology (drylands, wetlands or deep sands), 2) vegetation structure of the IAPs (medium alien trees or tall alien trees), and 3) the type of vegetation that had been invaded (ericoid-restioid fynbos, short ericoid fynbos, tall moist fynbos, or seeps and marshes). The Le Maitre et al. (1996) biomass models were used to determine the biomass of each category (Table D1).

Table D1: The biomass models developed by Le Maitre et al. (1996) were used to determine the biomass of each vegetation category. Biomass (b) is derived from the age (a) of the vegetation.

Biomass model category	Biomass model
Restioid fynbos	$b=1370\log_{10}(a)-187$
Ericoid-restioid fynbos	$b=932\log_{10}(a)-108$
Tall moist fynbos	$b=9540\log_{10}(a)-636$
Short ericoid fynbos	$b=4820\log_{10}(a)-575$
Seeps and marshes	$b=372\log_{10}(a)+22$
Medium alien trees	$b=9610\log_{10}(a)-636$
Tall alien trees	$b=20000\log_{10}(a)-7060$

The age (a) of the vegetation is determined as the number of years since the vegetation was burnt. An age (a) of 7.5 years was used for dryland areas based on the average number of years between fires in fynbos areas. Wetland areas are not burnt as often due to their location in protected gullies and high moisture content, and as such, an age of 15 years was deemed suitable. The vegetation growing on deep sands has access to groundwater and therefore a higher biomass. Although the vegetation is burnt every 7.5 years (on average), an age of 15 years was used to compensate for the higher biomass. The streamflow reduction for invaded and natural (not invaded) areas was calculated from the biomass estimates using Equation D1.

Equation D1: Streamflow reduction

$$Streamflow\ reduction\ (mm) = 0.0238x\ biomass\ \left(g/m^3\right)$$

The total reduction in streamflow by IAPs on the AP was calculated as the streamflow reduction multiplied by the area invaded. The amount of water made available by clearing invasive vegetation (i.e. - the hydrological benefit) was calculated as the difference between the streamflow reduction by invaded areas and that of natural areas.

Results

The difference between invaded and natural areas is greatest for wetland areas for all vegetation types (Table D2). On average, 2344m^3 of water would be made available by clearing a hectare of invaded wetlands. Deep sands also offer a considerable hydrological benefit from clearing with an average of 2129m^3 of water made available for every hectare of invasive vegetation cleared.

Table D2: The greatest hydrological benefit (m^3/ha) from clearing invasive vegetation is derived from wetlands.

Streamflow reduction (m^3/ha)	Drylands	Deep sands	Wetlands
Ericaceous	1872	2428	2717
Renosterveld	1174	1450	1740
Restioid	1800	2324	2613
Rivers&floodplains	0	2553	2843
Sanddune	1872	2428	0
Seasonal wetland	1958	2553	2843
Strandveld	1872	2428	0
Vleis&salt pans	1958	2553	2843
Dry fynbos	1872	2428	2717
Limestone	205	144	433
Average	1620	2129	2344

Interestingly, the lowest hydrological benefit is from clearing invaded limestone areas. Tall fynbos and natural forest were grouped into the category. Water use by natural woody vegetation is not expected to be significantly different from invasive woody vegetation, which may explain the limited benefits derived from clearing these areas.

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