Managing invasive alien plants on private land in the Western Cape: Insights from Vergelegen Estate

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Master of Science

By

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Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained within is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted this work for obtaining any qualification.

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Abstract

Invasive alien plants (IAPs) are a major threat to biodiversity and ecosystem services in South Africa and are particularly widespread and damaging in the Cape Floristic Region (CFR). Activities such as agricultural development, the establishment of forestry plantations and urbanization can change environments and provide opportunities for IAPs to spread. Large-scale government-funded management initiatives are underway to reduce the extent of invasions in this region, but they face many challenges. Among these challenges are the huge spatial extent of the invasions and difficulties in coordinating management efforts across large areas of invaded land in private ownership. Scarce funds for large-scale clearing operations need to be optimally used, but little information is available on which to base the planning of such complex undertakings.

This investigation used Vergelegen Wine Estate near Somerset West as a case study to investigate the factors that contributed to alien plant invasion on private land. I studied the effectiveness of one large project that set out to reduce alien plant cover, the challenges that the project faced, and the costs associated with long-term operations to clear IAPs on privately-owned land in the CFR. I documented the current (2016) extent of the problem at Vergelegen and estimated the time and resources that would be required to reduce the remaining invasions to a level where the minimum amount of resources are required to maintain the plants at a low density at low cost ('maintenance level'). Evaluation of this project provides insights into how to better manage IAPs on private land in the CFR.

I found a clear link between human activities, changes in land-use, and the spread and proliferation of IAPs. The area occupied by IAPs increased with increasing land-use change, from 8 % cover in 1938 to 40 % in 2004. The management interventions initiated in 2004 reduced dense stands of IAPs by 70 % over the next 10 years. The challenges associated with managing IAPs on private land included multiple interacting environmental and socio-economic factors. The total cost required to clear Vergelegen to a maintenance level was estimated to be between R55 and 80 million (2015-equavalent Rands; R49 million already spent prior to 2016, plus R6 – 30 million that still will be needed, depending on the scenario). Maintaining the estate was estimated to be R5.9 million per 15-year cycle, amounting to between 7.3 and 10.7 % of the cost to bring the estate to a maintenance level.

Using a wide range of research methods and techniques, I have shown that controlling IAPs at the scale of the operation at Vergelegen is possible, but at a significant cost to landowners. The effectiveness of projects, typically constrained by limited funds, could be increased by adopting an outcomes-based approach to ensure that objectives are achieved. Novel funding pathways need to be investigated by government to support clearing initiatives on private land that form part of larger priority areas to ensure success.

Opsomming

Indringerplante is 'n groot bedreiging vir biodiversiteit en ekosisteemdienste in Suid-Afrika en is veral wydverspreid en skadelik in die Kaapse Floristiese Streek. Aktiwiteite soos landbou-ontwikkeling, die vestiging van bosbouplantasies en verstedeliking kan omgewings verander en bied geleentheid vir indringerplante om te versprei. Grootskaalse regering befondsing inisiatiewe is aan die gang om die omvang van invalle te verminder in hierdie streek, maar hulle staar baie uitdagings in die gesig. Een van hierdie uitdagings is die groot ruimtelike omvang van die invalle en probleme in die koördinering van die bestuur pogings oor groot dele van binnegevalle land in private besit. Skaars befondsing vir grootskaalse skoonmaak operasies moet optimaal gebruik word, maar min inligting is beskikbaar waarop die beplanning van so 'n komplekse onderneming baseer kan word.

Hierdie ondersoek gebruik Vergelegen-wynlandgoed naby Somerset-Wes as 'n gevallestudie om die faktore wat bygedra het tot indringerplante op private grond te ondersoek. Ek het die doeltreffendheid van een groot projek, wat uit die staanspoor eerstens die indringerplantbedekking verminder, die uitdagings wat die projek in die gesig gestaar het, en die koste wat verband hou met lang termyn bedrywighede om indringerplantbedekking uit te wis op private grond in die Kaapse Floristiese Streek, bestudeer. Ek het die huidige (2016) omvang van die probleme by Vergelegen gedokumenteer, en die beraamde tyd en hulpbronne wat nodig sou wees om die res van die invalle op 'n lae digtheid teen 'n lae koste in stand te hou (onderhoud vlak). Evaluering van hierdie projek bied insig in hoe om beter bestuur toe te pas van indringerplante op private grond in die Kaapse Floristiese Streek.

Ek het 'n duidelike verband gevind tussen menslike aktiwiteite, veranderinge in grondgebruik, en die verspreiding en groei van indringerplante. Die indringerplante het verhoog met toenemende grondgebruiksverandering, vanaf 8 % dekking in 1938 tot 40 % in 2004. Die bestuur ingrypings vanaf 2004 het digte areas van indringerplante met 70 % oor die laaste 10 jaar verminder. Die uitdagings wat verband hou met die bestuur van indringerplante op private grond sluit in verskeie omgewings- en sosio-ekonomiese faktore. Die totale koste om Vergelegen tot op 'n onderhoud vlak te kry, se

kosteberaming was tussen R55 en 80 miljoen (2015 - ekwivalent; R49 miljoen reeds bestee teen 2016, plus R6 - 30 miljoen wat nog benodig sal wees, afhangende van die scenario).

Die onderhoud van indringerplante op die landgoed is na raming R5,9 miljoen per 15-jaar-siklus, teen bedrae van tussen 7.3 en 10.7 % van die koste om die landgoed tot op 'n onderhouds vlak te bring.

Met die gebruik van 'n wye verskeidenheid van navorsingsmetodes en tegnieke, het ek gewys dat die beheer van indringerplante op die skaal moontlik is by Vergelegen, maar teen 'n aansienlike koste vir grondeienaars. Die doeltreffendheid van projekte, tipies beperk deur beperkte fondse, kan verhoog word deur die aanneming van 'n uitkomsgebaseerde benadering en om so te verseker dat doelwitte bereik word. Befondsing opsies moet ondersoek word deur die regering met nodige ondersteuning, om die skoonmaak inisiatiewe en suksesse daarvan op private grond, wat deel van groter prioriteit areas vorm, te verseker.

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CHAPTER 1: GENERAL INTRODUCTION

Humans play an important role in modifying or regulating ecosystems. This includes the introduction of alien species, which allows them to breach biogeographical boundaries and to spread in regions they would probably not have reached under normal conditions (Jenkins, 1996; French, 2000; McNeely, 2000). Subsequently the spread of invasive alien plants (IAPs) has become a major problem throughout the world (Vitousek *et al*., 1997) and is considered as the second most significant threat to biodiversity following direct habitat destruction (Rubec and Ledd, 1996). The introduction of IAPs by humans has been taking place around the world for centuries (Pyšek and Richardson, 2008) and can be attributed to some species being important for food, shelter, fibre and sentimental reminders of homeland (Pyšek and Richardson, 2008). Distributions of invasive alien species are the result of human-mediated movements of species for many purposes (e.g., agriculture, forestry, mariculture, horticulture and recreation) and accidental introductions (van Wilgen *et al.*, 2008). New species combinations arise frequently in today's world in conditions of strong direct and indirect human impact. There are three main reasons for the existence of biological invasions (Hobbs *et al.*, 2006).

1. Human impacts resulting in local extinctions of most of the original animals, plant and microbial populations and/or the introduction of species that did not previously occur in that region.
2. Urban, cultivated or degraded land around ecosystems create a dispersal barrier for invasive alien plants.
3. Direct human impacts (e.g. through removal of natural soil, dam construction, harvesting, pollution) and indirect impacts (e.g. erosion) have resulted in major changes in the abiotic environment.

As alien species become naturalised in a new area the species usually experiences a lag phase of low population spread. During this phase the species may undergo evolutionary and ecological adaptations, before the species becomes invasive (Caley *et al.*, 2008; Pyšek and Richardson, 2008). The spread of IAPs is also altered by disturbance regimes such as floods and fires. The spread of IAPs transforms landscape, which are already fragmented by actively-managed areas, into dense monocultures of IAPs (Roura-Pascual *et al*., 2009).

South Africa includes eight terrestrial biomes; of which fynbos biome is regarded as the most highly invaded biome (Richardson *et al*., 2004). The main drivers promoting the establishment and spread of IAPs in the Cape Floristic Region (CFR) are both natural and socio-economic (Roura-Pascual *et al*., 2009). Natural drivers include climate change and disturbance regimes, while socio-economic forces emerge from human activities. There are dense stands of IAPs in the mountains, lowlands and along all the major river systems (Richardson *et al*., 2004), with the principal invaders being trees and shrubs in the genera *Acacia, Eucalyptus, Hakea,* and *Pinus.*

There are several examples of high-level strategies for dealing with the problem of invasive alien species, both globally (McNeely *et al.*, 2001) and nationally (Federal Interagency Committee, 1998; Anonymous, 1999). These strategies focus on reducing the risk of introduction, the control of existing invasions to mitigate impact, and the establishment of management and legislative capacity to guide management. However, in a systematic review and meta-analysis of invasive plant control research since the 1960s, Kettenring and Adams (2011) found that 71 % of studies did not consider costs. They also highlighted how most studies were undertaken at such small spatial and temporal scales that the results were not relevant to operational contexts that occur at landscape scales. For example, in terms of temporal scale they found that only 7 % of the studies applied control treatments for more than five years and 6 % monitored treatment sites for greater than five years. In terms of spatial scale, they found that only 20 % of the studies had a treatment plot size of greater than 1 m^2 and on only 9 % had treatment plots that were larger than 1 000 m^2. These findings were supported by Aronson *et al.* (2010a) who assessed the broader ecological restoration literature. Research initiatives usually have limited time – needing to match a grant cycle – and budgets to implement interventions. Additionally, much of their time and effort is spent ensuring the validity of the findings from their interventions, for example, randomly selecting sites to avoid selection bias and the establishment of controls to be able to make counterfactual inferences. On the other hand, interventions implemented in operational contexts might occur over larger spatial and temporal scales but very few of these interventions are monitored and measured.

Working for Water (WfW) is arguably the world's largest and most ambitious alien plant control programme (Koenig, 2009). Large numbers of alien plant species, including many trees and shrubs (Henderson, 2001), have invaded South African ecosystems (Henderson, 2007; Kotzé *et al.*, 2010). Some invasive trees, particularly those growing in riparian areas in its treeless biomes, reduce South Africa's scarce water supply relative to the lower biomass of the native vegetation (Görgens and van Wilgen, 2004). This was one of the main arguments behind the initiation of the programme in 1995, and hence its name. However, unlike other national control programmes that focus on prevention and early detection, WfW spends the bulk of its funds on labour-intensive control as part of a national poverty alleviation programme. This is partly because the programme is a public works project with the goal of creating employment in South Africa's impoverished rural areas (van Wilgen *et al.*, 1998; Koenig, 2009). Since its inception in 1995, WfW has spent approximately 3.2 billion South African Rand (ZAR) with indications that the area occupied by invasive alien plants may have been reduced by almost 50 % in some parts of the CFR (McConnachie *et al.*, 2016), but the programme has only reached a small proportion (4–13%) of the total invaded area (van Wilgen *et al.*, 2012).

A large percentage of invaded land in South Africa is privately owned. In 2008 WfW took a policy decision to phase out management interventions on private land, and to rather use incentives and disincentives to encourage private landowners to manage IAPs on their property themselves. WfW contributes to labour costs incurred by private landowners as an incentive and as a disincentive they can impose penalties on landowners if they fail to comply with legal requirements to control invasive alien plants. Many landowners support the idea of inclusive environmental governance involving public and private sectors and private land-owners, but few landowners have the knowledge and resources to deal with widespread dense stands of invasive trees and shrubs. There is thus an urgent need for monetary incentives, motivational tools, and regulatory enforcement if the desired outcomes are to be achieved (Urgenson, 2011).

1.1 Aims and objectives of the thesis

The significance of invasion by alien species to global conservation efforts has generated considerable empirical and theoretical advances (Hulme, 2003). However, it is not evident that the current scientific outputs have had any noticeable impact in reducing the rate of spread of biological invasions (Hulme, 2003). While this is partly because of the large scale of the problem, it also reflects that many of the approaches and perspectives addressing biological invasions, while excellent at highlighting the problems, have been less successful at generating solutions (Hulme, 2003). Thus, an evaluation of case studies is needed to identify and elucidate the challenges faced by managers and in specific in this study by private landowners, and to derive lessons that could help other private landowners to address the management of IAPs more effectively. This thesis evaluates one such project – probably the most ambitious and expensive IAP management effort ever undertaken on private land in South Africa. The case study involves the alien plant operations at Vergelegen Wine Estate (hereafter Vergelegen) in Somerset West, in the Western Cape Province. In 2004, when the programme was initiated, 70 % of the natural vegetation at Vergelegen (total area: 3200ha) was heavily invaded with alien trees and shrubs. As with all alien plant control operations, efforts at Vergelegen faced many challenges. These included dealing with wildfires, invasion from surrounding land, re-invasion following control, logistical issues relating to biomass removal, and financial constraints.

This thesis reviews the on-going management programme at Vergelegen in detail, starting by deconstructing the history of invasion by woody alien plants in the area by analysing historical data and aerial imagery, looking at management action over the last 10 years and the complexities involved with large-scale IAP clearing on private land, and finally proposing scenarios for alien plant control and recommendations for approaching the problem on private land within the CFR. The thesis aimed to contribute to the understanding of the complexity of managing IAPs on private land in the CFR and had the objectives outlined below, each of which is addressed in a separate chapter:

Objective 1: *To construct the spread of invasive alien plants on private land in the Cape Floristic Region: the case of Vergelegen*

This objective is presented in Chapter 2, which investigated the major factors that contributed to invasions of woody alien plants on a privately-owned farm in the CFR. The objectives of the chapter were to: (1) determine which land-use processes influenced the spread of alien species; and (2) document the invasion patterns and spread rates.

Objective 2: *To elucidate the challenges of managing invasive alien plants on private land in the Cape Floristic Region by drawing insights from Vergelegen Wine Estate (2004-2015).*

This objective is addressed in Chapter 3, which documents the cost, extent, and effectiveness of IAP clearing operations on Vergelegen and identifies the factors that affected progress towards the goal of reducing the cover of IAPs.

Objective 3: *To propose guidelines for optimizing alien plant management on private land in the Cape Floristic Region based on insights from Vergelegen Wine Estate*

This objective is addressed in Chapter 4, which investigates the magnitude of the current invasion on Vergelegen, documents the costs of control efforts over the past decade, and estimates the resources required to reduce the problem to a maintainable level. Scenarios based on current funding levels are constructed to explore options to guide future management. These findings are used to suggest changes to management strategies to improve the effectiveness of IAP-clearing operations on privately-owned land in the CFR.

The body of the thesis comprises the three chapters above. They are presented as stand-alone papers that have been prepared for publication in peer-reviewed journals. For this reason, there is substantial overlap, especially in the Introduction sections, of these chapters in describing the study site and features of the management operations at Vergelegen. All references are provided in a separate, combined list at the end of the thesis.

I undertook all the research and data analysis reported in these chapters, with guidance at all stages from my supervisors. I prepared first drafts of each chapter which were then discussed and edited by my supervisors. Because my supervisors will be co-authors of the published papers, “we” is used in these chapters, rather than “I”.

CHAPTER 2: RECONSTRUCTING THE SPREAD OF INVASIVE ALIEN PLANTS ON PRIVATELY-OWNED LAND IN THE CAPE FLORISTIC REGION: VERGELEGEN WINE ESTATE AS A CASE STUDY

This paper was submitted for publication in *South African Geographical Journal.*

Abstract

Invasive alien plants (IAPs) are a major threat to biodiversity and ecosystem services in South Africa and are particularly widespread and damaging in the Cape Floristic Region (CFR). Activities like agricultural development, the establishment of forestry plantations and urbanization change environments and provide opportunities for IAPs to spread. We examine the factors that have contributed to alien plant invasions on a privately-owned farm in the CFR. The objectives of the study were: (1) to determine what land-use changes took place that could have influenced the spread of IAPs; and (2) to document the patterns of spread of IAPs. Aerial photographs from 1938, 1966, 1977, 1989 and 2004 were used to determine the types and rates of land-use change over time. Key land-use changes in the area involved agriculture, commercial plantations, urban development, and the spread of IAPs. The spatial analysis identified the main drivers of change. Agricultural development was the main land-use change driver and affected 40 % of the study area by 1977. Areas occupied by IAPs increased with land-use change from 8% cover in 1938 to 40% in 2004, and then declined to 15% in 2013 following the initiation of a major control initiative in 2004. The study illustrated a clear link between human activities, changes in land-use, and the spread and proliferation of invasive plants.

2.1 INTRODUCTION

Invasive alien species are a major threat to global biodiversity and ecosystem services (Mack *et al*., 2000). South Africa has been affected by invasive species from all major taxonomic groups (Irlich *et al*. 2014), but invasive alien plants are particularly widespread and damaging, especially in the Cape Floristic Region (CFR). Both natural and socio-economic factors have promoted the establishment and spread of invasive alien plants (IAPs) in the CFR. Natural drivers include fire, flooding and erosion, while socio-economic forces emerge directly from human activities (Roura-Pascual *et al*., 2009). Human activities enhance the economy of the region, but also exert pressures on the environment by increasing the rates of introduction and dissemination of IAPs. The spread of IAPs has transformed many landscapes in the CFR, where the species-rich natural vegetation has been replaced by dense stands of alien species of trees and shrubs (Wilson *et al.*, 2014). These invasions have many negative impacts in the CFR, including increasing transpiration losses resulting in reduced runoff and subsequent infiltration of water from catchments (Görgens and van Wilgen, 2004), modified disturbance regimes (e.g. increased fire intensity that leads to erosion, (van Wilgen and Richardson, 1985; van Wilgen and Scott, 2001) and reduced biodiversity (Raimondo *et al*., 2009). Rouget *et al*. (2003) estimated that dense stands of woody IAPs occurred over 2.6% of the CFR (2290 km^2).

The spread of IAPs in fragmented landscapes is a complex process, and is strongly influenced by human activities, which makes long-term predictions of spread difficult (With, 2002). Land-use change is well known to affect alien plant invasions (Hobbs and Huenneke, 1992). The CFR has undergone significant land-use changes over the past 300 years, largely through the expansion of urban areas and various forms of agriculture and forestry, and increasingly through the transformation of natural vegetation by dense stands of IAPs (Rouget *et al*., 2003).

Globally several initiatives have already been implemented to reduce the impacts of IAPs and to reduce their rate of spread. The most notable of these is the national Working for Water programme (WfW). WfW has invested substantial resources into the management of IAPs to reduce the extent of the invasion and to ensure the sustained delivery of water and the conservation of biodiversity (Roura-Pascual *et al*., 2009). Despite this investment, control operations have been applied to a relatively small portion of the estimated invaded area, and the invasions appear to have increased, and therefore remain a serious threat in many biomes, including the CFR (van Wilgen *et al*., 2012).A large percentage of invaded land in the CFR is privately owned and in 2008 WfW took a policy decision to phase out management operations on privately-owned land, replacing them with incentives and disincentives to encourage private landowners to manage IAPs on their property themselves. WfW's incentives provide funding to landowners to clear IAP's on their land; this includes 100 % cover of labour cost for the initial clearing, 75 % of the labour cost for the first follow-up clearing, 50 % of the labour cost for the second follow-up clearing, and 100 % of the cost of herbicides for initial clearing and three follow-up treatments. WfW also provides advice on clearing methods, training, and management support. Disincentives include the enforcement of national legislation under the Conservation of Agricultural Resources Act (Act No 43 of 1983) (CARA) and the National Environmental Management: Biodiversity Act (Act No 10 of 2004) (NEM:BA), both of which hold landowners accountable for the clearing of IAPs on their land.

Despite the assistance provided and the need to comply with legislation, the requirement for private landowners to manage invasive species on their property is poorly implemented and enforced, if at all, and many landowners put little effort into dealing with the problem due to a lack of knowledge and funds. The management of widespread dense invasions on privately-owned land requires an improved understanding of the ecological and socio-economic drivers that led to the current invasions, how attitudes have changed over time and whether interventions that are currently underway are effective in dealing with the problem.

This work reports on the findings of a study that examined the factors that led to the major plant invasions on a privately-owned farm in the CFR. The objectives of the study were: (1) to identify the land-use processes that influenced the spread of alien species; and (2) to document the invasion spread patterns.

2.2 METHODS

2.2.1 Study area

The 5332-ha study area (Figure 2.1) is in the Hottentots Holland Mountain Range Basin near the town of Somerset West in the Western Cape province of South Africa. The area falls within the Lourens River Protected Natural Environment and comprises privately-owned land (including 3200 ha of the Vergelegen Wine Estate) and has a history of agricultural activity dating back to the early 1700s. Records on agricultural practices and land-use changes are available from the 1700s onwards. In 2004, Vergelegen Wine Estate (hereafter Vergelegen) implemented a large-scale privately-funded programme to clear the fynbos vegetation on the estate of invasive woody plants and to rehabilitate the 2300 ha of natural vegetation that occurs within its boundaries. The area has a Mediterranean-type climate with a mean annual rainfall of 780mm. Altitude ranges from 70 to 1020 m.a.s.l. (meters above sea level).

The study area still contains large tracts of natural mountain fynbos, much of which has been invaded by woody alien plants. According to the South African National Biodiversity Institute's (SANBI) spatial biodiversity planning information, three main vegetation types occur in the area, namely Boland Granite Fynbos, Shale Renosterveld and Lourensford Alluvium Fynbos (Mucina *et al.*, 2014).

Boland Granite Fynbos is an endangered (with a high risk of extinction in the near future) vegetation type of which 45% has been transformed, mainly by vineyards, fruit and olive orchards. This vegetation type consists of medium-dense to open tree vegetation within a tall, dense proteoid shrubland. Shale Renosterveld is a critically endangered (with an extremely high risk of extinction in the immediate future) vegetation type, 87 % of which has been transformed by urban sprawl, cultivation and roads. Shale Renosterveld is characterised by tall, open shrubland interspersed with grassy plants. Lourensford Alluvium Fynbos is critically endangered; more than 91% of its extent has already been transformed by urbanization, cultivation, pine plantations and roads. This vegetation type is a low, medium-dense shrubland with a short graminoid understorey.

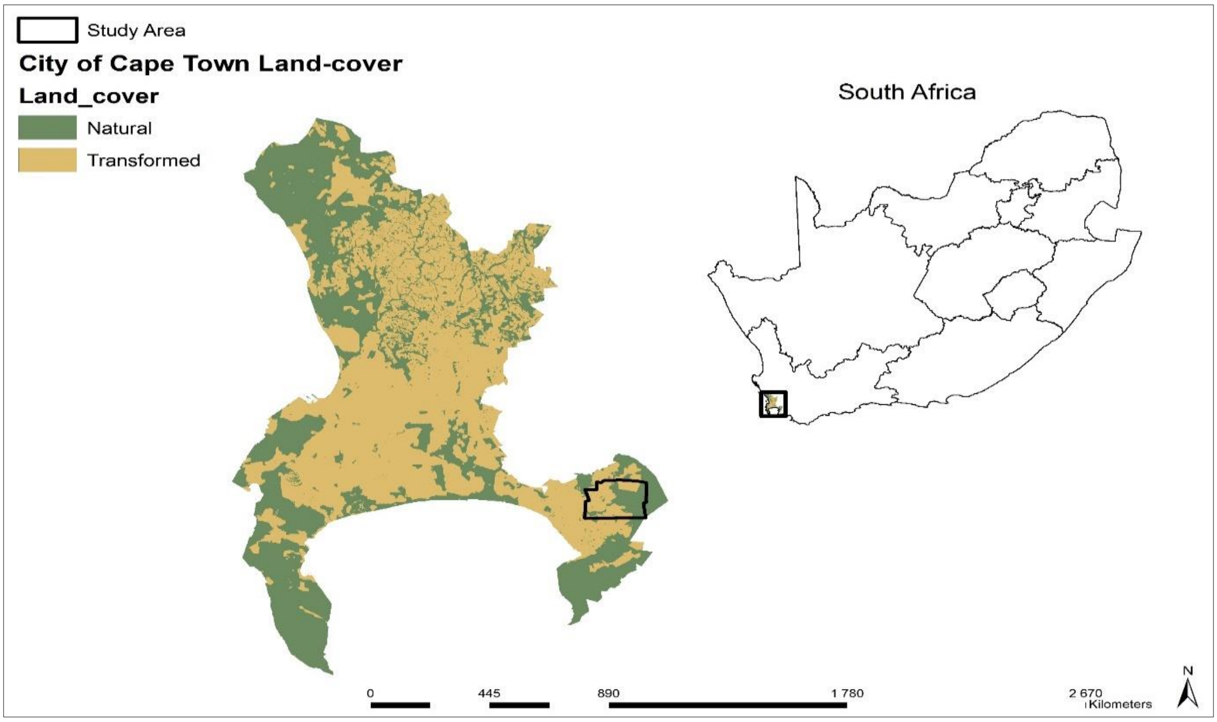


Figure 2.1: The study area at Vergelegen within the boundary of the City of Cape Town, Western Cape, South Africa. Dark shading indicates remaining natural vegetation (data from South African National Biodiversity Institute, 2012). The inset shows the location of the study area within South Africa.

The Mediterranean-climate and fertile soils provide suitable conditions for agricultural development which contributed to the transformation of the above-mentioned vegetation types. The remaining natural vegetation is heavily invaded by hakeas (*Hakea* spp.), pines (*Pinus* spp.) and wattles (*Acacia* spp.).

The study area includes the catchment of two streams; wetlands associated with these catchments increase the diversity of natural habitats and provide linkages between the higher mountain slopes and the remaining patches of natural vegetation within the agricultural parts of the study area. The scree slopes at the higher altitudes below the steep mountain cliffs support patches of indigenous forest, while the fynbos on the steep slopes supports a taller proteoid element. The vegetation on the flatter areas at lower altitudes consists of fynbos supporting a slightly different suite of species to the higher altitude slopes, and is conservation-worthy. A large portion of the catchment is heavily invaded with alien trees and shrubs.

2.2.2 Historical synopsis

A historical synopsis of land-use in the study area was compiled using two main information sources. The first was personal communication with farm managers in the area, some of whom have worked on the property for 25 years. This information was anecdotal but gave a good indication of where past agricultural lands and plantations were located. The second source was data in the Vergelegen library; this included books and other records with information regarding the property, its previous owners, and key developments in the area. Two books "*The story of two Cape farms*" (Fraser, 1981) and "*The story of Hottentots Holland*" (Leap 1970) yielded useful information on the socio-economic history of the study area and surrounding parts and included details on Vergelegen dating back 300 years. The historical synopsis served as background for interpreting key land-use changes.

2.2.3 Aerial photo geo-referencing

Aerial photographs of the study area were available for the years 1938, 1966, 1977, 1989, 2004 and 2013 from the Department of Land Affairs (Chief Directorate of Surveys and Mapping). These were used to quantify changes in land-use in the study area. The images were scanned into high-resolution digital format and then imported into a GIS (ARCMAP version 10) and standardized prior to interpretation. The geo-reference tool in ARCMAP was used to geo-reference the images with the 2013 satellite image as the reference, as is commonly necessary with scanned photographs, by correlating three or more objects from each image with the same object in a spatially referenced image.

2.2.4 Land cover classification and assessing the rate of change

The study area was subdivided into five categories: commercial agricultural land, commercial timber plantations, invaded land, natural vegetation, and urban areas. These five categories could be clearly separated when the photographs were carefully examined at a range of scales, due to clear differences in hue and texture. The imagery was overlaid with polygons to delineate different land-use categories.

Agricultural areas included orchards, vineyards, pastures, nurseries and horticultural areas, and associated land uses such as farmsteads, holding areas for livestock, tracks and roads, canals, and dams. Forestry plantations included systematically planted trees (*Pinus pinaster* and *P. radiata*) established for commercial timber production, as well as seedling trials and woodlots of sufficient size to be identifiable on aerial imagery. Urban areas included areas of intensive use with the land covered by structures, including suburban housing, roads, power and communication facilities, and industrial and commercial complexes, or areas converted to golf courses, smaller parcels of land (less than 1 ha) having less intensive use, and that were surrounded by urbanizing areas, were included in this category.

Once the agricultural, plantation and urban land had been identified, the remaining natural vegetation was divided into invaded and uninvaded areas (natural areas not invaded by IAPs). Invaded areas were those that contained stands of *Eucalyptus* spp., *Hakea* spp., *Pinus* spp. and *Acacia* spp. outside formal plantations and woodlots. The fact that most invasive woody species in study area were trees made the mapping of the natural areas easier, since there was a clear structural difference between invaded and natural vegetation in shape, hue and texture on acquired imagery (Richardson and Brown 1986).

Once the land use categories were mapped for each of the images (1938, 1966, 1977, 1989, 2004 and 2013), a 10m x 10m (one grid cell = $100m^2$) grid was overlaid, the geoprocessing clip tool in ARCMAP was then used to extract the category features from the land-use category polygons. We summed the grid cells to estimate the area of the respective land-use for each of the years for which aerial photographs were available to determine the total area covered by the various land-use categories.

2.2.5 Quantifying changes over time

A transition matrix is a fundamental starting point for the analysis of land change (Pontius *et al*., 2004). We used a cross-tabulation matrix to assess the total change in land use categories according to two pairs of components: net change, as well as gross gain and gross loss. To assess change, we compared each 10m x 10m grid cell with the same grid cell in the preceding data layer (for example, all cells in the 1938 data layer were compared to matching cells in the 1966 data layer). We recorded whether the cell remained in the same land use category, or changed to another category. The 1938 and the 1966 maps were compared to produce a cross-tabulation matrix that shows the percentage of the landscape within each combination of categories. The same was done for 1966-1977; 1977-1989 and 1989-2004 to view the changes for the time series that was available.

Each map comparison produced a table with the same arrangement of rows and columns (Table 2.1). The first step was to examine the column and row totals to determine the two largest categories. The diagonal entries in Table 2.1 show the persistence of each category. The persistence is used to calculate two types of change: gross gain and gross loss. The bottom row in Table 2.1 shows the quantity gained for each category and the right-hand column shows the category losses. The gains are the difference between the columns totals and persistence and the losses are the difference between two totals and persistence.

The transition matrix follows the format of Table 2.1, wherein the rows display the categories of time 1 and the columns display the categories of time 2. For example, the notation P_{12} denotes the proportion of the landscape that experiences a transition from category *1* to category *2*. Entries on the diagonal indicate persistence, thus $P_{11}j$ denotes the proportion of the landscape that shows persistence of category *1*. Entries off the diagonal indicate a transition from category *2* to a different category *1*. In the Total column, the notation *P1+* denotes the proportion of the landscape in category *1* in time 1, which is the sum over all *1*. In the Total row, the notation *P+1* denotes the proportion of the landscape in category *1* in time 2, which is the sum over all *1*. The additional column on the right indicates the proportion of the landscape that experiences gross loss of category *1* between time 1 and time 2. The additional row on the bottom indicates the proportion of the landscape that experiences gross gain of category *1* between time 1 and time 2.

Table 2.1: General cross-tabulation matrix for comparing two maps from different points in time (Pontius *et al.*, 2004).

	Time 2				Total time 1	Gross Loss
	Category 1	Category 2	Category 3	Category 4		
Time 1						
Category 1	P_{11}	P_{12}	P_{13}	P_{14}	P_{1+}	$P_{1+} - P_{11}$
Category 2	P_{21}	P_{22}	P_{23}	P_{24}	P_{2+}	$P_{2+} - P_{22}$
Category 3	P_{31}	P_{32}	P_{33}	P_{34}	P_{3+}	$P_{3+} - P_{33}$
Category 4	P_{41}	P_{42}	P_{43}	P_{44}	P_{4+}	$P_{4+} - P_{44}$
Total time 2	P_{+1}	P_{+2}	P_{+3}	P_{+4}	1	
Gross Gain	$P_{+1} - P_{11}$	$P_{+2} - P_{22}$	$P_{+3} - P_{33}$	$P_{+4} - P_{44}$		

2.3 RESULTS

2.3.1 Historical synopsis

In the early 1700s Dutch settlers discovered the fertile ground that was suitable for the cultivation of vines and a large variety of crops in the Helderberg Basin. Large areas were available for grazing for sheep and cattle. Willem Adriaan van der Stel transformed the area from “wilderness” to a highly productive farm by planting vineyards, a variety of grains, vegetable and flower gardens. Later he laid out orchards and orange groves and “enhanced” his land by planting camphor (*Cinnamomum camphora*) and oak (*Quercus* species) trees (Leap, 1970).

In the early 1800s the area under vines increased from 15 to 400 ha. Crops of wheat, oats, rye and barley yielded good returns. For almost 200 years Vergelegen belonged to Dutch families who were mainly subsistence farmers (Fraser, 1981).

Vergelegen changed hands in the early 1920s, at which point the vineyards were uprooted. Before 1938 areas invaded by alien trees and shrubs were predominantly situated in and around cultivated and transformed land in riparian areas. The dominant invasive trees were species of *Acacia* spp. and *Eucalyptus* spp. . Between 1938 and 1966 agricultural land-use grew with the introduction of contour ploughing and the planting of grass, clovers and trees, and natural vegetation declined accordingly (Table 2.2).

The property changed hands again in the early 1940s followed by the introduction of the large Jersey herd. Large dams were built, and fruit orchards, pastures and pine trees were planted during this period. Vergelegen Estate (Pty). Ltd and Vergelegen Timber (Pty). Ltd were formed in 1956, resulting in the planting of an additional 217 ha of *Pinus radiata* (event 1, Figure 2.2). A large dam was built in 1973 to provide water to growing crops and modern and efficient irrigation methods were established. Cash crops were planted at large scale in the early 1970s and the property started supplying a large national supermarket chain with vegetables in 1975. In the period of 1966 – 1977 the focus was on agricultural development, and the management of natural vegetation was neglected, which led to invasion by alien trees and shrubs.

Between 1978 and 1990, the farming enterprise at Vergelegen was in a sorry state of neglect. Although basic infrastructure, like buildings, roads and irrigation systems, dams, drainage and windbreaks, existed, most of it was not suitable for a viable farming enterprise. Cash crops were cultivated after the second half of 1987, but production was limited, because of inadequate irrigation systems. These were later abandoned due to poor economic returns. Agricultural land-use declined and the extent of invaded land increased. The rapid increase in the extent of invasion maybe directly correlated with the loss of agricultural land, since disturbed vacant land was invaded by herbaceous weeds and alien trees and shrubs. A large fire also occurred during this period (event 2, Figure 2.2).

Vergelegen was purchased by Anglo American Farms (Am Farms) in 1987 with the purpose of turning the property into a wine farm. Extensive soil and climate testing was undertaken and a plan was drawn up for the development of the area and a large winery was built. Suitable soils were identified and planted with vines and large portions of plantations were felled at the beginning of 1988 by Cape Timbers under contract to harvest the remainder of the viable commercial timber. The remainder of the plantations comprised of approximately 3-5 ha young trees (15-20 years) while the balance consisted of adult trees (older than 25 years) that were burnt in a large fire (event 2, Figure 2.2). The plantations were subsequently abandoned since the adult trees that burnt in the fire had no commercial value. Due to a lack of management, these areas became invaded by various alien plants species; contributing to the spread of pines to the surrounding natural vegetation. After 1989 agricultural land-use plateaued, and the area of invaded land increased (Figure 2.2). As part of the commitment of Am Farms to preserving natural and cultural heritage on its land, Vergelegen implemented a large privately-funded project to clear invasive plants in 2004 (event 4, Figure 2.2) with the goal of rehabilitating 2200 ha of natural vegetation. The decision was made after the occurrence 1997 wild fire that covered over 2800 ha of the study area (event 3, Figure 2.2).

Table 2.2: A summary of key events between 1938 and 2004 that contributed to changes in land use at Vergelegen. Percentages in brackets show the change in extent of each type of land use.

Historical Drivers					
Dates	**Agricultural**	**Plantations/Forestry**	**Fire**	**Urban**	**Outcomes**
1938-1966	1938 -Large dam built. 1941- Cattle re-introduced - one of the largest Jersey herds in South Africa, pastures planted, Contour ploughing. 1965- Orchard area increased with peach trees being planted. Large successful nursery was established and vines were re-planted at a small scale. 1966 - Introduced Friesland cows and a dairy was established. (16,5 % - 38,1 %)	1700 - Oak and Camphor tree plantations planted. 1921 - *Pinus radiata* afforested on a portion of the high lying land. First record of plantations in study area. 1956 - Pine trees were planted at large scale and Vergelegen timber limited formed. 217 ha. (4,1 % - 3,8 %)	No records available.	Farm Homesteads	**Agriculture ↑** **Plantations ↓** **Urban →** **Invaded Land↑** **Natural Vegetation ↓**
1966-1977	1973- Large dam was built due to the great need for water. Modern efficient irrigation methods implemented. Vegetables were grown at a large scale. (38,1 % - 41,7 %)	Pine plantations maintained and growing to 307 ha (3,8 % - 5,7 %)	3 Fires were recorded: 1976 - 2041 ha of which 70 ha were *Pinus radiata* plantations; 1500 ha natural veld; 236 ha agricultural; 216 ha invaded land 1974 - 1.569 ha Natural Veld 1971 - 12.321 ha Natural Veld	28 ha - Erinvale Estate Established.	**Agriculture ↑** **Plantations ↑** **Urban↑** **Invaded Land↑** **Natural Vegetation ↓**

1977-1989	1987 - Anglo American purchased Vergelegen with the intention of turning the estate into a world class wine farm. Different varieties of vines were planted. Orchards and cattle farming still forms a large part of the areas agricultural use. (41,7 % - 34,6 %)	Plantations decreased in size from 272 - 184 ha (5, 7 % - 5, 1 %)	3 Fires were recorded: 1978 - 19,3 ha (Natural Veld, not invaded) 1979 - 10,8 ha (Natural Veld, not invaded) 1985 - 13,6 ha (Natural Veld, not invaded)	Area increased to 31 ha	**Agriculture ↓** **Plantations ↓** **Urban ↑** **Invaded Land ↑** **Natural Vegetation ↓**
1989-2004	Following extensive soil and climate testing a detailed master plan was drawn up for the development of the area and large winery was built on Vergelegen. Orchards and cattle farming still forms a large part of the areas agricultural use. (34,6 % - 35,8 %)	Plantation decreased in size from 307 - 272 Ha. (5,1 %-3,4 %)	5 Fires recorded: 1991 - 9,7 ha (Plantation), 73,9 ha (Natural Veld) -Unknown Fire 1992 - 25,7 ha (Natural Veld), Controlled Burn. 1994 - 16,8 ha Helderberg Nature Reserve. (Controlled burn - removal of pine plantation for veld rehabilitation). 1997 - 2800 ha - 1600 ha invaded land; 403 ha agricultural; 650 ha natural veld; 164 ha plantations 1999 - 94 ha (Natural Veld)	Area increased 246 ha	**Agriculture ↑** **Plantations ↓** **Urban ↑** **Invaded Land ↑** **Natural Vegetation ↓**
2005-2013	Agricultural areas not expanding. All cash crops and pasture areas being rehabilitated, however *Pennisetum clandestinum* spp. pastures are still mapped as Agricultural land. (35,8 % - 28,9 %)	Plantations harvested and not replanted, fires also contributed to the significant decrease of this land-use. (3,4 % - 0 %)	3 Fires Recorded: 2007 - 16,2 ha (Natural Veld) 2009 - 2447 ha - 1800 ha natural veld; 570 ha invaded land; 38 ha agricultural land. 2011 - 4,6 ha (Natural Veld) Controlled burn.	No increase 246 ha	**Agriculture ↓** **Plantations ↓** **Urban →** **Invaded Land ↓** **Natural Vegetation ↑**

The land-use type most affected by the 1997 fire was invaded land that covered 1600 ha; other land uses impacted by the fire were agriculture - 403 ha; natural vegetation – 650 ha and plantations – 164 ha. After the fire the Vergelegen wine business funded a small project to clear and rehabilitate 140 ha of Boland granite fynbos. This project was successful and in 2002 the Board of Am Farms (owners of Vergelegen) committed to a 10-year project to clear the remaining 2200 ha. In 2004 a management plan for the clearing was compiled and implemented. This led to a rapid decline in the invaded area and an increase in the area under natural vegetation (Figure 2.3). In 2009 a large wild fire burnt 2500 ha of the study area (event 5, Figure 2.2). The land use categories impacted by this fire included, agriculture – 38 ha; invaded land – 570 ha and natural vegetation – 1800 ha. This fire burnt 900 ha of areas cleared between 2004 and 2009.

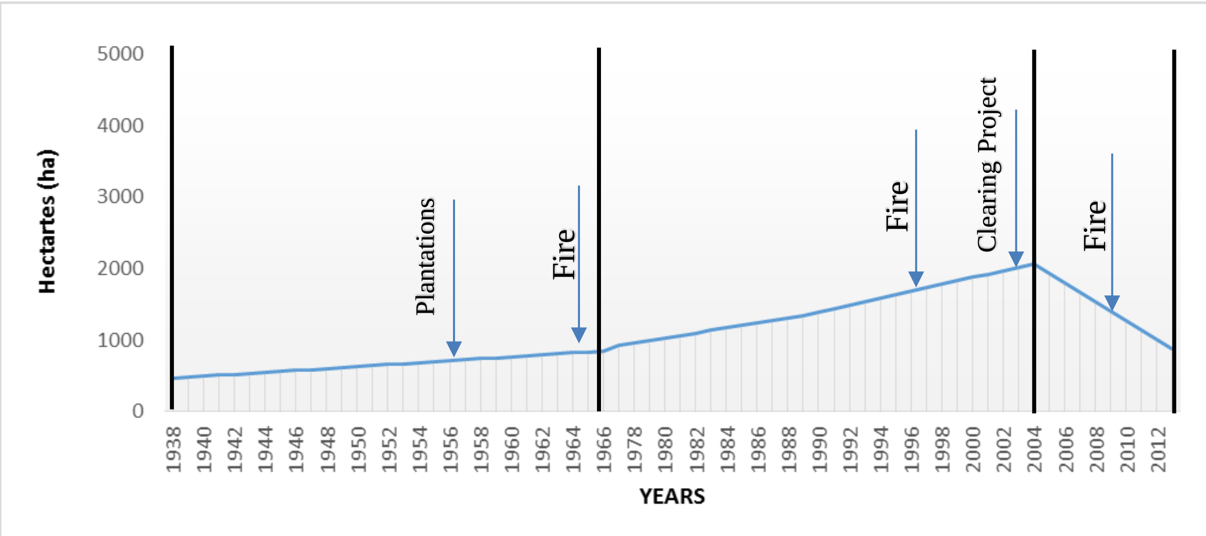


Figure 2.2: Changes in the area covered by invasive trees and shrubs at Vergelegen, Western Cape, South Africa, between 1938 and 2013. Vertical black lines indicate the date of assessment of invasions from aerial photographs. Dates of fires and other key events that influenced land-use and the extent of invasions are indicated (see Tables 2 and 4 for background information).

2.3.2 Trends in the area under different forms of land use

Large and continuous losses of natural vegetation (from 3770 to 928 ha) occurred between 1938 to 2004, after which natural vegetation increased to 2673 ha due to the implementation of the large clearing programme on Vergelegen (Figure 2.3).

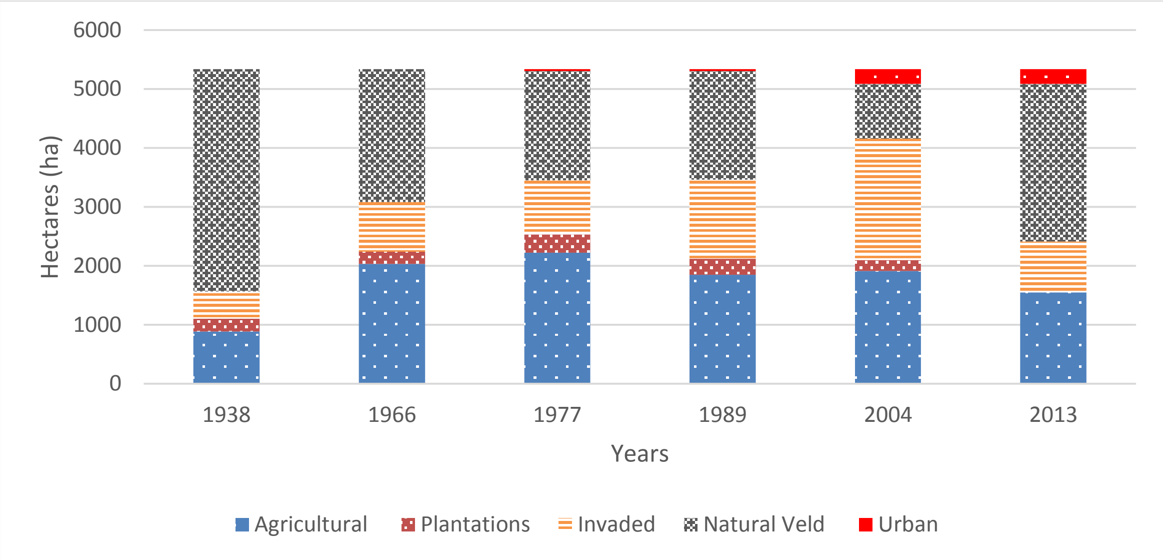


Figure 2.3: Land-use changes in the Vergelegen study area (Western Cape, South Africa) between 1938 and 2013.

Natural vegetation decreased by 29.1 % between 1938 and 1977, reflecting the intent to develop the area for agricultural purposes, and agricultural land increased in area by 23.3 % between 1938 and 1966. Natural vegetation experienced a net loss of 19.3 % (1989 – 2004), while invaded vegetation increased by 20 %. Agricultural land steadily increased from 881 ha in 1938 to 2222 ha in 1977 after which the extent of this land-use type declined to 1544 ha currently. Plantations were never large (at their peak reaching 306 ha in 1977; 5.7 % of the study area) and this land use increased most between 1966 and 1977 (Table 2.3), but the plantations were eventually phased out (Table 2.4). The areas surrounding the study area also contained commercial plantations (*Pinus pinaster; P. radiata)* from the early 1920's, and these would have acted as an additional seed source for invasions by pine trees. Urban land-use areas in the study area were small, only appearing in 1977 and growing from zero to 246 ha in 2015.

Table 2.3. The transition matrix reflects the probability of a land-use category staying the same or changing to another land-use category over time. The diagonal bold and italic percentages indicate the cells that remained unchanged over the period (land-use persistence). Cells highlighted in blue show the percentage cover at the specific time; cells shaded in grey show the percentage of cells that change from one land-use category to another. Gross loss indicates the percentage of the respective land-use category that changed to another category during a given period. Gross gain shows the percentage of cells that changed to the respective land-use category.

		1966						
	Land-cover categories	Agricultural	Plantations	Invaded	Natural Veld	Urban	**1938 % cover**	**Gross Loss**
1938	Agricultural	***14.8***	0.0	1.3	0.4	0.0	16.5	1.8
	Plantations	1.0	***1.3***	1.6	0.2	0.0	4.1	2.7
	Invaded land	3.9	0.1	***4.7***	0.0	0.0	8.7	4.0
	Natural veld	18.5	2.4	8.3	***41.6***	0.0	70.7	29.1
	Urban	0.0	0.0	0.0	0.0	***0.0***	0.0	0.0
	1966 % cover	38.1	3.8	15.9	42.2	0.0		
	Gross Gain	23.3	2.5	11.2	0.6	0.0		

		1977						
	Land-cover categories	Agricultural	Plantations	Invaded	Natural Veld	Urban	**1966 % cover**	**Gross Loss**
1966	Agricultural	***33.53***	0.33	3.43	0.27	0.53	38.09	4.56
	Plantations	0.11	***3.16***	0.54	0.01	0.00	3.82	0.66
	Invaded land	5.56	1.21	***8.99***	0.12	0.00	15.87	6.88
	Natural veld	2.43	1.05	4.34	***34.41***	0.00	42.22	7.81
	Urban	0.00	0.00	0.00	0.00	***0.00***	0.00	0.00
	1977 % cover	41.68	5.74	17.28	34.76	0.53		
	Gross Gain	8.15	2.59	8.29	0.35	0.00		

		1989						
	Land-cover categories	Agricultural	Plantations	Invaded	Natural Veld	Urban	**1977 % cover**	**Gross Loss**
1977	Agricultural	***31.47***	0.00	4.03	5.60	0.56	41.68	10.21
	Plantations	0.19	***2.78***	2.60	0.18	0.00	5.74	2.96
	Invaded land	2.59	0.64	***13.43***	0.64	0.00	17.28	3.85
	Natural veld	0.28	1.72	4.59	***28.19***	0.00	34.76	6.57
	Urban	0.01	0.00	0.52	0.00	***0.00***	0.53	0.00
	1989 % cover	34.57	5.12	25.17	34.57	0.57		
	Gross Gain	3.10	2.34	11.74	6.37	0.00		

		2004

	Land-cover categories	Agricultural	Plantations	Invaded	Natural Veld	Urban	1989 % cover	Gross Loss
1989	Agricultural	***26.71***	0.03	3.31	1.18	3.27	34.57	7.86
	Plantations	2.54	***2.26***	0.26	0.06	0.00	5.12	2.86
	Invaded land	3.98	0.85	***18.76***	0.94	0.67	25.17	6.41
	Natural veld	2.58	0.32	16.38	***15.22***	0.11	34.57	19.35
	Urban	0.00	0.00	0.00	0.00	***0.57***	0.57	0.00
	2004 % cover	35.80	3.45	38.72	17.40	4.63		
	Gross Gain	9.09	1.19	19.96	2.18	0.00		

2.3.3 Land-use change as a driver of invasion

A series of historical events has resulted in much of the natural vegetation becoming progressively invaded over the past 50 years (Table 2.4) with pines, wattles and eucalyptus trees being the most dominant. In the first instance, invasive trees were introduced to provide timber and firewood, and they spread from original plantings to the surrounding natural vegetation. Later, alien pasture grasses were sown, and these species also became invasive. Some invasive species (for example *Acacia cyclops*, *A. longifolia* and *Paraserianthes lophantha*) were not deliberately introduced, but arrived through other means. As agriculture expanded, new areas were disturbed by the creation of fields and through the construction of roads and dams, further promoting invasions. Grazing by cattle, from time to time in natural vegetation, also created conditions that would encourage invasions. Wildfires occurred at intervals, and resulted in further spread and densification of the invasive stands, especially those of serotinous trees and shrubs (hakeas and pines) whose winged seeds are released from fire-proof cones/follicles after fire (Richardson and Cowling, 1992). Abandoned plantations and agricultural lands were also very susceptible to invasions. This set of events (Table 2.4) provided diverse opportunities and mechanisms for the increase of invasions. The situation was only reversed when formal and co-ordinated control efforts were introduced in 2004.

Table 2.4: Events and mechanisms that promoted the establishment and spread of alien plants at Vergelegen, Western Cape, South Africa. ↑ denotes factors that favoured spread and densification of alien plants. ↓ denotes factors that slowed or hindered spread and densification.

Date	Event (see Table 2)	Mechanisms that promoted establishment and spread of invasive alien plants	Change in alien invasion
1700 – 1900	Planting of acacia woodlots. It is unknown when the woodlots were planted, but these species were brought into the study area to supply timber and firewood.	Based on the information available these woodlots were not managed or harvested after the early 1940's. Alien *Acacia* species produce large amounts of long-lived seeds that build up in the soil. Soil movement, whether due to humans of during rainfall events, could have led to the spread of *Acacia* species to new areas.	↑
	Planting of eucalyptus woodlots. Details on when the woodlots were planted are unclear, but it is well known that eucalyptus woodlots were planted for railway sleepers.	Based on the information available these woodlots were not managed or harvested after the early 1940's. Eucalypts could change the soil composition and increase fire intensity. Both factors could lead to the exclusion of indigenous species, and dominance by alien eucalypts.	↑
1921	1921 - *Pinus radiata* afforested on an unknown portion of the high-lying land. First record of plantations in study area.	Pines began to spread by means of winged seed from plantations to surrounding natural vegetation.	↑
1938	With the desire to increase the agricultural land-use, the farm's infrastructure was enhanced by constructing roads and dams.	Natural areas were disturbed due to the construction of roads and dams. These disturbances would have likely opened pathways for the invasion of alien plants. Herbaceous weeds invaded road verges, and seeds of Australian *Acacia* species, which were contained in gravel and soil used in road and dam construction, established along the roads, from where they started to spread into adjacent natural vegetation.	↑

1941	Cattle introduced - one of the largest Jersey herds in South Africa. Pastures were planted with indigenous and alien grasses, including Kikuyu *(Pennisetum clandestinum*) to provide grazing for the growing herd. Cattle were also allowed to graze occasionally in natural vegetation.	Natural vegetation was removed and top soils were disturbed to allow for the sowing of seeds for grazing pastures. Disturbed pastures were then colonized by weeds such as the alien species Patterson's curse (*Echium plantagineum*) and Scotch thistle (*Onopordum acathium*) and more recently the native *Senecio bupleuroides*. Disturbance of natural vegetation by grazing created opportunities for invasive alien trees and shrubs to establish in patches opened up by grazing.	↑
1956	217 ha of *Pinus radiata* were planted and a commercial forestry company (Vergelegen Timber Limited) was formed.	Vergelegen Timber Ltd. cleared 217 ha of natural vegetation and planted pines for timber production. The adult trees were harvested and these areas were re-planted. Disturbance associated with logging created further conditions to promote invasion. No management action was put in place to prevent the spread of seeds to surrounding natural vegetation. This allowed for the invasion of pine wind-dispersed seeds to spread into surrounding natural vegetation.	↑
1965	Peach orchards planted	Natural vegetation was removed and top soils were disturbed to allow for the planting of orchards. The disturbances to the soil and vegetation made the area more prone to plant invasion.	↑
1976	Fire - 2041 ha of which 70 ha were *Pinus radiata* plantations; 1500 ha natural vegetation; 236 ha agricultural and 216 ha invaded land burnt.	Seed release in serotinous pines and hakeas were triggered by fires, promoting the spread of these species to the surrounding natural vegetation. In addition, pines (and hakeas) that had established in natural vegetation also released seed, adding to propagule pressure and the further spread and densification of stands of invading pines and hakeas. Soil-stored seeds of *Acacia* species stimulated to germinate *en masse*, creating dense stands and out-competing natural vegetation. Agricultural land and plantations impacted by the fires were abandoned. These disturbed areas were then vulnerable to invasion by a suite of alien species that could establish in the absence of competition from natural vegetation.	↑

1977 – 1989	Portions of agricultural land were abandoned, or maintained but poorly managed	These disturbed areas were then very vulnerable to invasion by a large range of alien species being able to establish in the absence of competition from natural vegetation.	↑
1977	Plantation land-cover decreased after the 1976 fire, no new areas were planted and remainder of the plantations were harvested. The vacant land was never replanted.	Regrowth of dense stands of pines in abandoned plantation areas, and ongoing spread of pine seeds to adjacent natural vegetation.	↑
1997	Fire - 2800 ha - 1600 ha invaded land; 403 ha agricultural; 650 ha natural vegetation; 164 ha plantations	Seed release from pines and hakeas were triggered by fires promoting the spread of alien plants to the surrounding natural vegetation. Agricultural land and plantations impacted by the fires were abandoned and became invaded. Soil-stored seeds of *Acacia* species stimulated to germinate *en masse*, creating dense stands and out-competing natural vegetation.	↑
2004	Vergelegen implemented an alien plant control plan with the goal of clearing 2200 ha of invaded land over the next 10 years. After which a maintenance plan was set in place to prevent further spread of IAP.	A management plan was implemented in 2004. All woody alien species (predominantly pines, wattles and eucalypts) were targeted. Adult trees were removed by mechanical clearing including the use of chainsaws. Biomass was removed by block and stack burning. Cleared areas were followed-up on annually. Follow-up techniques used were dependent on species being treated; young pines were cut just above ground using machetes and/or loppers. Young wattles and eucalypts were treated either by doing stump treatment or foliar spray using herbicides.	↓
2009	Fire - 2447 ha - 1800 ha natural vegetation; 570 ha invaded land; 38 ha agricultural land.	Seed release from pines and hakeas was triggered by fires promoting the spread of alien plants to the surrounding natural vegetation. Agricultural lands impacted by the fires were abandoned and become invaded. Soil-stored seeds of *Acacia* species stimulated to germinate *en masse*, creating dense stands and out-competing natural vegetation.	↑

2.4 DISCUSSION

The CFR has lost up to 30 % of its natural habitats and is still being transformed by agriculture, commercial forestry, and urbanization (Roura-Pascual *et al*., 2009). Forestry activities and agriculture are important drivers of the introduction and dissemination of IAPs in the CFR (Rouget *et al*., 2003; Le Maitre *et al*., 2004; van Wilgen and Richardson, 2012).

This study provides the first systematic analysis of the spread of invasive trees and shrubs and the changes in land-use that have accompanied and facilitated these invasions on privately-owned land. Changes in land use at the Vergelegen study area over 75 years involved transformation of 80 % of the area's natural habitat by agriculture, plantations, urbanisation and alien plants by 2002. Analysis of historical aerial photographs was useful for quantifying this habitat transformation. Local knowledge helped with details regarding the extent of the invasion before clearing operations commenced in 2002.

Agriculture was the most significant human driver of natural habitat change in the study area, and 35 % of the area had been transformed to agricultural land by 2004. Socio-economic pressures lead to a strong focus on agricultural development between the 1920s and the 1990s. These findings of this study agree with those in other parts of the CFR where agricultural development has led to significant transformation of natural habitats (Kemper *et al*., 1999). Pine plantations formed only 6 % of the land-use in the study area at the peak of this land use. It is important to note that the areas surrounding the study site also contained pine plantations and that spread from these areas certainly contributed to invasions within the study area. To gain a better understanding of the importance of the neighbouring pine plantations in driving the spread of pines across the study area it would be useful to increase the study area size to incorporate all surrounding plantations.

The area of invaded land showed the most net gain over time of all the land use categories and covered 40 % of the study area in 2004. Alien plants that invaded the area were predominantly *Acacia*, *Eucalyptus,* and *Pinus* species. The wattles and eucalypts are largely confined to lower-elevation areas close to rivers areas whereas most pine invasions are on higher-elevation slopes. The earliest invasive stands were located around the Vergelegen homestead and in transformed areas (agricultural land and plantations), and these spread across the study area over time. Poorly managed agricultural land was prone to plant invasion and management neglect was the most significant driver for invasion in the lower-elevation parts of the study area. Pine species invaded the higher slopes, spreading from both the plantations within the study area and through long-distance dispersal of seeds from remote plantings; fires were a key driver of these invasions. Fynbos is a fire-adapted ecosystem and alien species such as pines are well adapted to proliferate under these conditions. Three large fires have been recorded in the study area since the 1950s (Figure 2.4); as shown in other parts of the CFR (Richardson and Brown, 1986; Rouget *et al*. 2001), the availability of a seed source and several fires can result in the transformation of large tracts of fynbos shrubland into dense woodlands or forests of pines.

Urbanization had the smallest impact on invasion since only 5% of the area was transformed by this land-use. However, some areas in the CFR have been heavily transformed by urbanization, namely Cape Flats Fynbos and Blackheath Sand Fynbos (Wood *et al*., 1994), and this form of land use change is a substantial driver of habitat loss in the region.

For conservation planning and action, it is important to be able to assess how, where and when future land-use change can lead to future spread of IAPs. Understanding how different facets of human-induced land-use change mediate the spread of invasive plants can help managers in applying effective prioritization to optimize control actions. The results of this study suggest that invasions proceed in a predictable fashion in tandem with human-mediated land use changes that provide and alter seed sources and disturbances that are crucial drivers and dispersal mechanisms of invasions of alien trees in the fynbos. Fire is the dominant ecosystem processes in fynbos, and it is a major driver of invasions. Even in increasingly fragmented and human-modified landscapes, intense fires are the dominant forcing function that greatly complicates attempts to reduce the extent of alien plant invasions. Fires can never be excluded from these ecosystems, and the timing, frequency, intensity, and other features of the fire regime are essentially impossible to predict, and therefore to manage. Prescribed burning is potentially a valuable tool for managing woody plant invasions in fynbos (van Wilgen *et al.,* 1994), but its application is becoming increasingly difficult in areas such as our study site where managers are reluctant to risk damaging human structure should prescribed burns escape (van Wilgen *et al.*, 2012b). Consequently, fire is increasingly acting as a stochastic force that stimulates proliferation of the invaders; very often fires annul the gains made in mechanical clearing operations.

Successful management of large areas of dense stands on invasive trees and shrubs such as those that have established at Vergelegen over the past 75 years is a huge challenge. Knowledge of the interacting factors that have contributed to these invasions is of some use for planning effective management operations.

CHAPTER 3: THE CHALLENGES OF MANAGING INVASIVE ALIEN PLANTS ON PRIVATE LAND IN THE CAPE FLORISTIC REGION: INSIGHTS FROM VERGELEGEN WINE ESTATE (2004-2015)

This paper was submitted for publication in *Transactions of the Royal Society of South Africa.*

Abstract

Alien plant invasions are a major threat to biodiversity and ecosystem functioning in South Africa's Cape Floristic Region (CFR). Large-scale government-funded management initiatives are underway to reduce the extent of invasions in this region. Among the many challenges are the huge spatial extent of the invasions and difficulties in coordinating management efforts across large areas of invaded land in private ownership. Very little information is available on the success of privately-funded alien plant control initiatives. This study investigated the effectiveness of one large project in reducing alien plant cover, the challenges faced, and the costs associated with long-term clearing operations on privately-owned land in the CFR. Results for the study area (Vergelegen) show that the cover of dense invasive plant stands declined by 70 % over 10 years since management operations began, but that operations cost 3.6 times more than was originally estimated (ZAR 43.6 vs 12.19 million respectively). The challenges associated with managing invasive alien plants (IAPs) on private land are very similar to those faced on state-owned land, with the efficiency of management being constrained by multiple interacting environmental and socio-economic factors. However some success in managing IAPs can be achieved by adhering to basic principles, including careful planning with clear achievable goals in mind, a commitment to stable long-term funding, and regular monitoring. Most private land owners cannot afford the substantial investment of resources that would be required to clear large stands of IAPs and to ensure that cleared areas are maintained to prevent re-invasion, and finding ways to fund this remains a challenge.

3.1 INTRODUCTION

Invasive alien plants (IAPs) pose a significant threat to the biodiversity and functioning in many of the world's ecosystems (Mack *et al.*, 2000; Pimentel *et al.*, 2005). Many alien plant species, including many species of trees and shrubs, have invaded South African ecosystems (Richardson *et al.*, 1997; Henderson 2007; Kotzé *et al.*, 2010). Some of these plants reduce scarce water supplies and negatively affect biodiversity and the functioning of ecosystems (Le Maitre *et al.*, 2000; van Wilgen *et al.*, 2008). Millions of Rand have been spent on preventing and mitigating the impacts of these invasions (van Wilgen *et al.*, 2012a). The government-funded programme 'Working for Water' (WfW) was launched in 1995 to address this problem and is the largest conservation project in Africa (van Wilgen, 2009) and the world's most ambitious programme for managing IAPs (Koenig, 2009). Despite important advances, a major obstacle faced by WfW is the complex interactions among factors that influence the dynamics of the invasive species, and the interplay with a wide range of socio-political issues. This is especially challenging in the fire-prone fynbos vegetation of the Cape Floristic Region (CFR) (Roura-Pascual *et al.*, 2009; van Wilgen *et al.*, 2016b). The CFR is subjected to many external pressures (e.g. urbanization, land-use change and climate change) that threaten the long-term persistence of its biological diversity (van Wilgen *et al.*, 2016a). The remaining natural habitats are threatened by the expansion of woody IAPs (Rouget *et al.*, 2003; Latimer *et al.*, 2004). Despite the large investment of resources, it is unclear whether the extensive control operations are substantially reducing the problem and alleviating the threats to the region's biodiversity (van Wilgen *et al.*, 2016b).

A large percentage of invaded land in the CFR is privately owned. In 2008 WfW took a policy decision to phase out management interventions on private land, and to rather use incentives and disincentives to encourage private landowners to manage IAPs on their property themselves. WfW contributes to labour costs incurred by private landowners as an incentive, and as a disincentive the government can impose penalties on landowners if they fail to comply with legal requirements to control IAPs. Many landowners support the idea of inclusive environmental governance involving public and private sectors and private land-owners, but few landowners have the expertise and resources to deal with widespread dense stands of invasive trees and shrubs. There is an urgent need for monetary incentives, motivational tools and regulatory enforcement if the desired outcomes are to be achieved (Urgenson, 2011).

We know of no thoroughly documented accounts of large-scale, privately-funded initiatives to control IAPs in the CFR or elsewhere. An evaluation of case studies is needed to identify and elucidate the particular challenges faced by private landowners, and to derive lessons that could help other private landowners to address the management of IAPs more effectively. This paper evaluates one such project – probably the most ambitious and expensive IAP management effort ever undertaken on private land in South Africa. The case study involves the alien plant operations at Vergelegen Wine Estate (hereafter Vergelegen) in Somerset West, in the Western Cape Province. In 2004 when the programme was initiated, 70% of the natural and semi-natural vegetation at Vergelegen (total area: 3200ha) was heavily invaded by alien trees and shrubs. As with all alien plant control operations, efforts at Vergelegen have faced many challenges. These have included dealing with wildfires, invasion from surrounding land, re-invasion following control, logistical issues relating to biomass removal, and financial uncertainty and constraints. This paper sets out to document the cost, extent and effectiveness of this operation, and to identify the factors that affected progress towards the goal of reducing the cover of IAPs.

3.2 METHODS

3.2.1 Study area

Vergelegen Wines (Pty) Ltd. (3200 ha in extent) (Figure 3.1) is located in the Hottentots Holland mountain range near the town of Somerset West in the Western Cape Province of South Africa. The area falls within the Lourens River Protected Natural Environment and is privately-owned. It is subjected to a Mediterranean-type climate with a mean annual rainfall of 750mm, 46% of which falls in the winter months of June through August. Altitude ranges from 70 to 1020 m a.m.s.l. About a third of the study area has been converted to crop agriculture (mainly vineyards), while the rest has remained as natural vegetation of three main types: Boland granite fynbos, shale renosterveld and Lourensford alluvium fynbos (Mucina *et al.*, 2014).

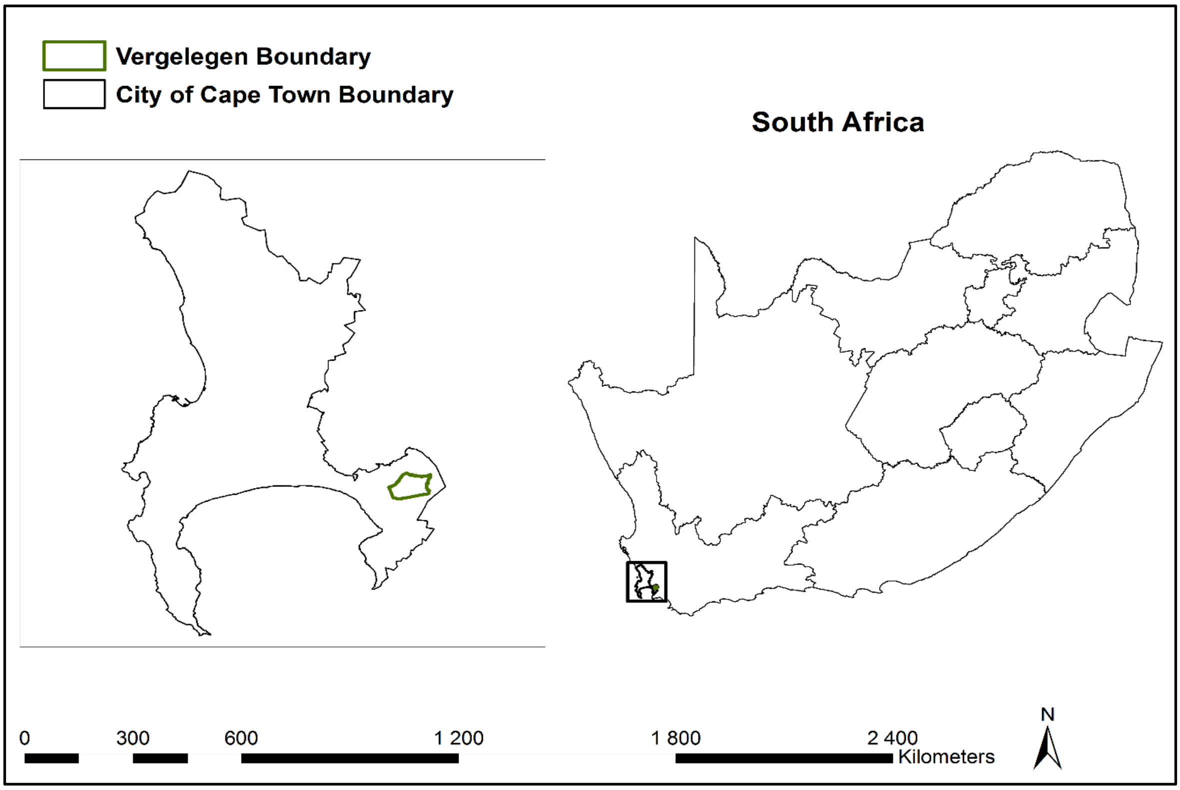


Figure 3.1: The study area at Vergelegen within the boundary of the City of Cape Town in the Western Cape Province, South Africa.

3.2.2 History of control efforts

The history of alien plant control on Vergelegen between 2004 and 2015 was reconstructed by reviewing monthly management reports from Vergelegen environmental project managers, the minutes of meetings of Vergelegen environmental managers and reports from several independent consultants who developed the alien plant control management plan, and subsequent audit reports. This information was used to set out a historical synopsis of the key stages of the clearing operations.

3.2.3 Measuring control effectiveness

3.2.3.1 Changes in alien plant density over time

The change in alien plant cover between 2004 and 2015 was estimated in order to assess the effectiveness of the control programme. Six categories of alien tree canopy cover were used in the 2002 management plan: occasional (< 1% cover); very scattered (1 - 5% cover); scattered (5 - 25% cover); medium (25 - 50% cover); dense (50 - 75% cover); and closed (> 75% cover). The 2002 plan used roads and contours to divide the area into 26 management units based on the workload (estimated time and funding required to clear the invasive trees in that unit) (Figure 3.3).

The density of invasive trees and shrubs in 2015 was estimated from March 2015 aerial imagery obtained from the City of Cape Town. The density of invasive trees was noted for each management unit for comparison with 2002 estimates.

3.2.3.2 Management progress

The original alien control management plan established three main clearing phases:

1. Initial clearing: Felling of all invasive trees and, in some cases, removal of all felled biomass.

2. Follow-up: Follow-up clearing once every 1.5 to 2 years to remove any plants that may have been missed in the initial operation and any seedlings/saplings.

3. Maintenance control: Ongoing removal of emergent IAPs from an alien plant population that has been reduced to a level that can be contained at a relatively low cost in perpetuity.

However, based on the experience gained and the site-specific issues that came to light, the management plan was adjusted in 2013 to include nine management phases (Table 3.1). This made no difference to the annual work already set out by the management plan; it merely allowed for five follow-up treatments (1 treatment per year), and a maintenance phase, and provided a logical flow to monitor the alien plant control programme progress. We established the progress within each management phase for each of the years that the project was active, starting before clearing operations in 2004 up to and including the 2015 operations. The progress as originally planned in 2004 was then compared to the actual project flow between 2004 and 2015.

3.2.3.3 Estimating the cost of clearing

We obtained the annual budgeted costs for clearing and follow-up from the 2002 management plan, and compared these estimates to the actual expenditures from monthly project costing reports. These reports detailed the actual amounts spent on clearing, follow-up, management, equipment and other associated costs. All costs were inflated to 2015 values using the annual consumer price index to compare the differences in cost between the budget as set out in the original management plan in 2002 and the actual costs incurred.

Table 3.1: Nine management stages of the alien plant control programme implemented on Vergelegen Wine Estate.

Phase	Management phase	Description of management phase
1	Treatment not yet initiated	No management action taken. This includes areas where initial clearing has not taken place yet, agricultural and hospitality areas.
2	Initial Clearing	Initial clearing is the initial control action that drastically decreases the exciting alien plant population. The preferred treatment was cut stump where stems are cut as low as practical. Herbicides are applied as recommended for the specific species being treated.
3	Biomass treatment	Biomass removal is a critical part of the alien control programme there are varies methods to remove biomass created by clearing alien plants in fynbos, however prescribed burning was the most effective and practical means of controlling biomass created by the Vergelegen alien control programme. This stage includes areas within the clearing project that are located on higher slopes. Biomass was not removed in these areas due to the risk of run-away fires. Follow-up is still taking place annually, with increasing costs.
4	Follow-up 1	Follow-up is the control of seedling, root suckers and coppice growth that occurs after initial clearing. WfW has a 3 follow-up policy before they hand over the treated area to the relevant land owner. However on the Vergelegen project we worked on 5 follow-up treatments since new alien plant seeds were introduced from the surrounding invaded area.
5	Follow-up 2	
6	Follow-up 3	
7	Follow-up 4	
8	Follow-up 5	
9	Maintenance Phase	Maintenance phases includes areas that have less than 2 % invasion present annually, these areas require minimal resources to control plant invasion.

3.2.3.4 Comparison of budgeted and actual costs

We determined a cost variance ratio between the planned and actual costs for the alien control programme. The cost variance ratio (CVR) was determined as $CVR = \frac{(Actuals\ Cost - Planned\ Cost)}{Planned\ Cost}$ for each of the 26 management units (MUs). The MUs were further divided into three categories based on their accessibility and difficulty in terms of conducting management operations: easy, moderate and difficult. “Easy access” included MUs that were surrounded by roads, in and around agricultural areas, old agricultural lands and old plantations. “Moderate access” MUs were those where at least one side of the area was accessible by road. “Difficult” MUs were those with no road access where at least 15 minutes of walking was required to reach work sites; these occurred at higher elevations and most were on steep and/or rocky terrain. The CVR was used to determine whether the variance between planned and actual cost increased with the increase in difficulty of access. To test whether there was an impact of the difficulty of control at a location on the cost variance, cost variances estimates were recalculated as log (1+the cost variance estimate) in an effort to normalise the data. An ANOVA was used to look at the impact of access on the cost variance, with Tukey's post-hoc test used to look for differences between any of the treatments.

3.3 RESULTS

3.3.1 History of control efforts

A survey of alien vegetation density was conducted in 1997 by a consultant (“Consultant A”) after a fire burnt the area in 1997. The fire was considered to be difficult to control due to the large fuel build-up that had occurred as a result of the dense cover of IAPs. The purpose of this survey was to assess the density of IAPS in the burned areas, with a view to prioritising areas for clearing, identifying suitable removal methods, and designing management strategies. The plan suggested that management should be initiated as soon as possible to prevent the areas from becoming a solid forest of IAPs over the next 20 years (“Consultant A”). The implementation of this plan was delayed by 5 years due to a lack of funding.

During a series of meetings with City of Cape Town reserve managers and consultants who urged Vergelegen to take action in 2002, the impacts of IAPs were reconsidered by the Vergelegen board members, and a follow-up management plan was drawn up by a consultant ("Consultant B"). This plan included a complete estimation of costs and an area prioritization plan. The estate was mapped and divided into 26 management units (MUs) using distinct land marks as boundaries. Funding was made available in 2004 and a project manager ("Project manager A") was appointed. The first management efforts on the estate focused on areas with lower densities of IAPs, and areas earmarked for the creation of fire breaks. This was done by appointing a local woodcutting contractor who had been working on the estate harvesting fire wood. Her team of six people was trained to use chainsaws and herbicides for the control of IAPs and also in how to conduct prescribed burning. Besides the contracting team that cleared IAPs, a Razerback machine (Figure 3.2) was used to clear IAPs in easily accessible areas. The Razorback is a heavy machine which is driven into and against the material to be cut. The material is cut while the machine is moving forward and is pulverised by the heavy and sharp cutters (e.g., a 4m tall pine tree can be shredded in 37 seconds, leaving only a stump remaining). The mulch produced by this machine does not create a large fire hazard as it decomposes rapidly, resulting in good recovery of the natural vegetation. The unit was unfortunately only available during wet winters and although successful, was not used extensively due to very heavy winter precipitation and also the high costs involved.

In 2006, as part of Vergelegen's quality control requirements, an independent consultant ("Consultant C") was appointed to audit the implementation of the 2002 management plan to assess compliance and effectiveness. Consultant C's report provided an independent assessment of whether the approved funding had been spent correctly. Seven site inspections were done and on-site meetings were conducted with project manager A. Key findings of the audit were that the original plan had no clear site-prioritization specifications e.g. that lower-elevation areas, and light to medium density stands should be prioritized over dense stands. The audit recommended that expenditure on each MU (or part of an MU) should be noted and accounted for separately to ensure the accumulation of costing knowledge for each MU to allow for an informed system of budgeting.

Figure 3.2: Invasive alien plants (IAPs) on Vergelegen and some of the approaches used to manage them: (a) General view of the extent of IAPs (dark areas) on Vergelegen in 2006; (b) mountain slopes covered by burnt stands of pines (mainly *Pinus pinaster*); (c) Contracting team clearing a dense *Pinus pinaster* stand; (d) Area cleared of *Pinus pinaster* by the razorback; (e) Dense stand of *Eucalyptus* species; (f) Dense stand of wattles (mainly *Acacia mearnsii*; (g) Razorback clearing a dense stand of alien plants; (h) Stacks of biomass created by the clearing programme; (i) Prescribed burning to remove biomass.

The audit also reported a failure to adhere to the schedule of follow-up after initial clearing. There were 2-3 year gaps between initial clearing and follow-up treatments, while the plan called for follow-ups in the first growing season following the clearing (Consultant C, Audit report, 2006). The audit also found very poor compliance with the original management plan drawn up by Consultant B. However, according to project manager A, the non-compliance was intentional as the original plan was never considered in the work schedule and work priorities were rethought and applied based on the local knowledge of project managers. The audit pointed out that even though the project manager did not follow the 2002 management plan, some success was achieved in the clearing of important fire breaks, the "testing" of the Razorback, and outsourcing of the clearing activities to local entrepreneurs including the provision of training, skills transfer, and the acquisition of equipment. The sale of timber to offset the cost of clearing also contributed to offsetting the project costs.

Between 2006 and 2009, the project team was increased to 40 people, comprising 12 chainsaw operators and 28 workers who focussed on stacking and follow-up. As the work progressed to the higher and steeper slopes, the workforce had to contend with greater amounts of burnt vegetation from the 1997 fire. This slowed the clearing and follow-up processes. Biomass was reduced by conducting stack and block burns, but burning was only conducted in winter because of the risk of run-away fires at other times of the year. Other forms of biomass removal included the harvesting of wattle and eucalypt wood for fire wood, and viable pine timber was sold to saw mills. Approximately 1027 ha of invaded land was cleared between 2006 and 2009.

In February and March of 2009 another large fire swept across the Helderberg Basin, including the 1027 ha of Vergelegen that had been cleared in preceding years. This event precipitated the need to revisit the management plan to prioritise follow-up weeding in areas burnt in the fire. To advise on the alteration of the management plan, consultant C was appointed to adjust the management plan to accommodate the unplanned wildfire. The post-fire assessment indicated that the project focus needed to shift to areas cleared before the fire since the fire had triggered mass germination of soil-stored seeds.

The follow-up areas were prioritised as follows:

- Areas immediately around buildings and other infrastructure, to avoid regrowth that would constitute a fire hazard in future;
- Areas identified as asset protection zones;
- Areas of low-density invasions, where the returns on investment would be much higher (Higgins et al. 2000);
- Areas that could provide access for security reasons, or to initial clearing sites;
- The tops of slopes, watercourses, and steep, long bare slopes, to inhibit the spread of seeds downhill or downstream, where they would invade new areas; and
- Disturbed sites, to remove seedlings that had emerged as a result of mass germination of the soil-stored seeds of wattles.

In 2009, a second project manager (project manager B) was appointed to focus on all the areas cleared before the 2009 fire, and additional funding was made available after a successful insurance claim. Two new contracting teams were appointed, each comprising 10 workers.

In 2011, Vergelegen management appointed additional teams to speed up the initial clearing programme. An area of 446 ha was to be cleared, most of it on the higher slopes that supported a dense cover of pines with mixture of wattles and eucalypts along drainage lines.

Vergelegen is owned by Anglo American who are primarily a mining company operating in a volatile social and financial environment. In 2012 the decision was made to temporarily stop all initial clearing after Anglo American experienced financial constraints following a series of strikes in the mining industry. The focus of the project shifted towards follow-up treatments in already cleared areas and to biomass removal.

Table 3.2: A summary of key events during operations aimed at clearing invasive alien plants at Vergelegen (1997 – 2015).

Date	Event	Reason for event	Outcome and significance
1997	1. WfW Cleared 230ha of the mountainous area 2. Survey of invasive alien plant density (Consultant A)	1. Details on who implemented and paid for this event were not recorded.	2. Intended to provide input for deciding on priorities and methods for management, but was not implemented.
2002	Management plan (including cost estimations and prioritization) drawn up by a consultant (Consultant B)	After the 1997 fire the intensity of the fire and the re-growth of IAPs after the fire forced Vergelegen to look at options to reduce the impacts associated with IAPs	The estate was divided into 26 management units (MUs). Provide the goals of the management plan.
2004	Appointment of a project manager to oversee implementation of plan	Experienced project manager was required to oversee the project implementation	Start of the implementation of the management plan.
2004 - 2009	Appointment of local woodcutting team of 6 people	Local wood cutting was appointed to promote local community business growth and job creation	Local woodcutter and her team were trained by the estate in the use of chainsaws and herbicides. This team was used to do alien clearing on the property.
2005 - 2006	Use of Razorback - a tracked machine in this case a bulldozer with mover and mulcher in front of the machine, the razorback would drive into dense IAP stands, cut and mulch the material, leaving it broadcasted over the cleared site.	Need for feasible way to control plants and biomass effectively	Mechanical clearing of accessible areas.
2006	Appointment of a consultant (Consultant C) to audit implementation of management plan	To audit work completed between 2004 - 2006	Identification of inconsistencies and deviation from best practice. Recommendation that MUs should be contracted out to contractors to supplement the in-house team.
2006 – 2009	Increase clearing team numbers from 6 to 40	To increase speed of clearing operation.	Problems encountered – need to clear steep areas; accumulation of biomass; need to burn outside of ecologically optimum season.
2009	Large wildfire	Unplanned event	Large area burnt, including 1027 ha that had been cleared.

2009	Appointment of consultant C to assess implications of fire	Audit work completed before the fire and assess impacts of fire on the clearing programme	Need to shift priorities.
2009	New management plan drawn up in response to perceived need to shift priorities	To provide a new approach to the project and to help deal with IAP regrowth after the 2009 fire	Provide the goals of the management plan.
2010	New project manager appointed; additional contracting teams appointed	To assist with project implementation	Two new teams and project manager was assigned to the insurance project (All areas cleared before the 2009 fire).
2011	Three additional contracting teams appointed	To increase the speed of initial clearing and assist with follow-up	Contractor numbers significantly increased from 60 to over 200 workers to increase the speed of the initial clearing operation.
2012	Funding for initial clearing funding curtailed	Initial clearing funding was stopped.	Further initial clearing was stopped, and available funds were allocated to follow-up operations
2013 - 2015	Project priority shift	The increase in contracting teams increased the speed of the clearing operation but also increased the biomass and the size of areas requiring annual follow-up.	Work prioritization shifted to follow-up and biomass removal.

3.3.2 Changes in alien plant density over time

The control operations were successful in achieving large reductions in the cover of IAPs over the study period (Figure 3.3). In 2004, 70% of the area was covered by alien plants in the closed cover category, but this was reduced to 0% by 2015. The area covered by alien plants in the dense and medium cover categories increased 4 to 9%, and from 0 to 7% respectively by 2015. Alien plants in the scattered, very scattered, and occasional cover categories increased from 4 to 27%, 17 to 19 % and 5 to 39 % by 2015, respectively. Between 2004 and 2015, the overall extent of closed-cover stands of IAPs decreased by 70%, 16% of which changed to occasional cover, 26% to very scattered cover, 38% to scattered cover, 7% to medium cover and 12% to dense cover. The area covered by alien plants in the dense category in 2004 had decreased to either medium or occasional cover by 2015, in about equal proportions. The lack of significant change from dense to medium cover can be attributed to the presence of biomass created by the clearing operations which made follow-up treatment time-consuming, costly and in many cases ineffective. The lower density classifications including occasional (38%), very scattered (18%) and scattered (26%) increased significantly between 2004 and 2015. The remaining dense (9%) areas were those where initial clearing had not yet been initiated.

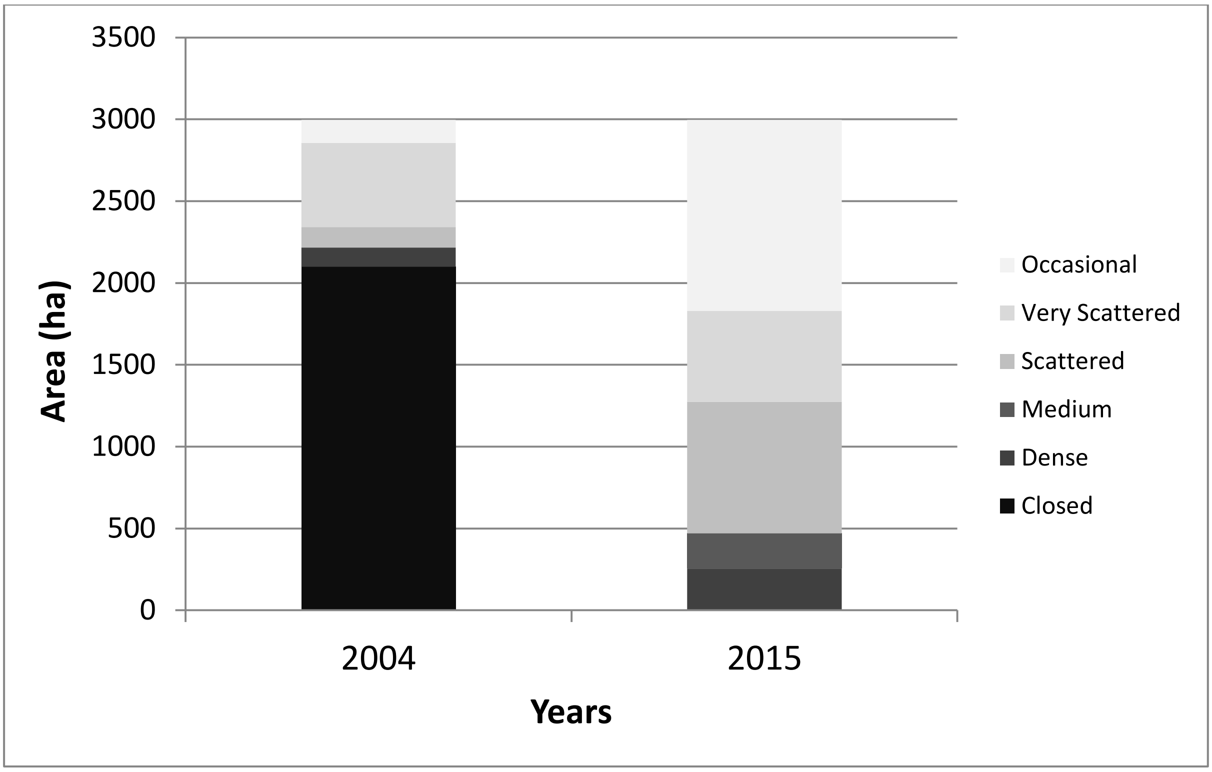


Figure 3.3: Area occupied by invasive alien plants in six cover classes at Vergelegen in 2004 and 2015. The classes are occasional (< 1% cover); very scattered (1 - 5% cover); scattered (5 - 25% cover); medium (25 - 50% cover); dense (50 - 75% cover); and closed (> 75% cover).

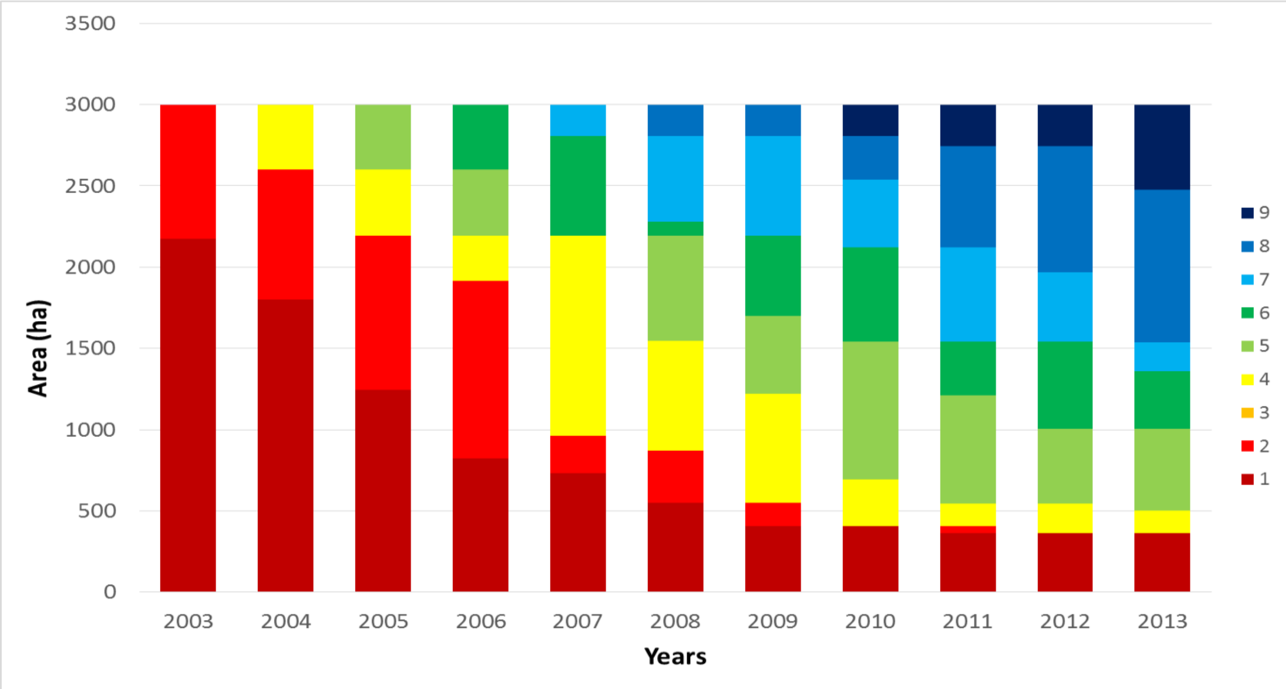
3.3.3 Management progress

The clearing operations did not proceed according to the original management plan, which proposed a starting date of 2003 and called for completion of operations by 2013 (Figure 3.4A). The original plan estimated that 72 % of the initial clearing should have been completed by 2006, but only 23 % of the area had been cleared at this time. The numbers of follow-up treatments required for each of the MU's were inconsistent, and ranged from one to five (Figure 3.4A). Based on the original plan, areas that had a medium to closed cover of pines species were allocated one to three follow-ups whereas areas invaded by wattles were allocated five follow-ups. Biomass removal was not included as a management phase in the original 2002 management plan, and no consideration was given to ways of dealing with the large volume of dead biomass that was created by initial clearing operations.

The project was initiated in 2004 after funding was made available (Figure 3.4B). Between 2004 and 2009, a ~1000 ha was cleared, but only 500 ha of this received one follow-up treatment between 2006 and 2009. In addition to alien plant control operations funded by Vergelegen, a relatively small area (230 ha) was cleared and followed up by WfW up to an including 1997. This work focused on high altitude areas on the boundary of the property. A large fire wild fire burnt the cleared areas in 1997, and WfW teams did not return to Vergelegen. Information regarding the cost and time spent on Vergelegen by WfW is not available, as the work was carried out on an ad-hoc and unplanned basis.

After the 2009 fire additional teams were appointed to work solely on follow-up which allowed all cleared areas to receive one follow-up treatment per year. In 2011 the rate of initial clearing increased after additional teams were appointed. The last initial clearing efforts stopped in 2012, when funding for the project was terminated. However, to prevent the cleared areas from becoming reinvaded, follow-up and biomass reduction treatments were continued. No work has thus been carried out on approximately 180 ha that were proposed for clearing in the 2002 management plan.

A



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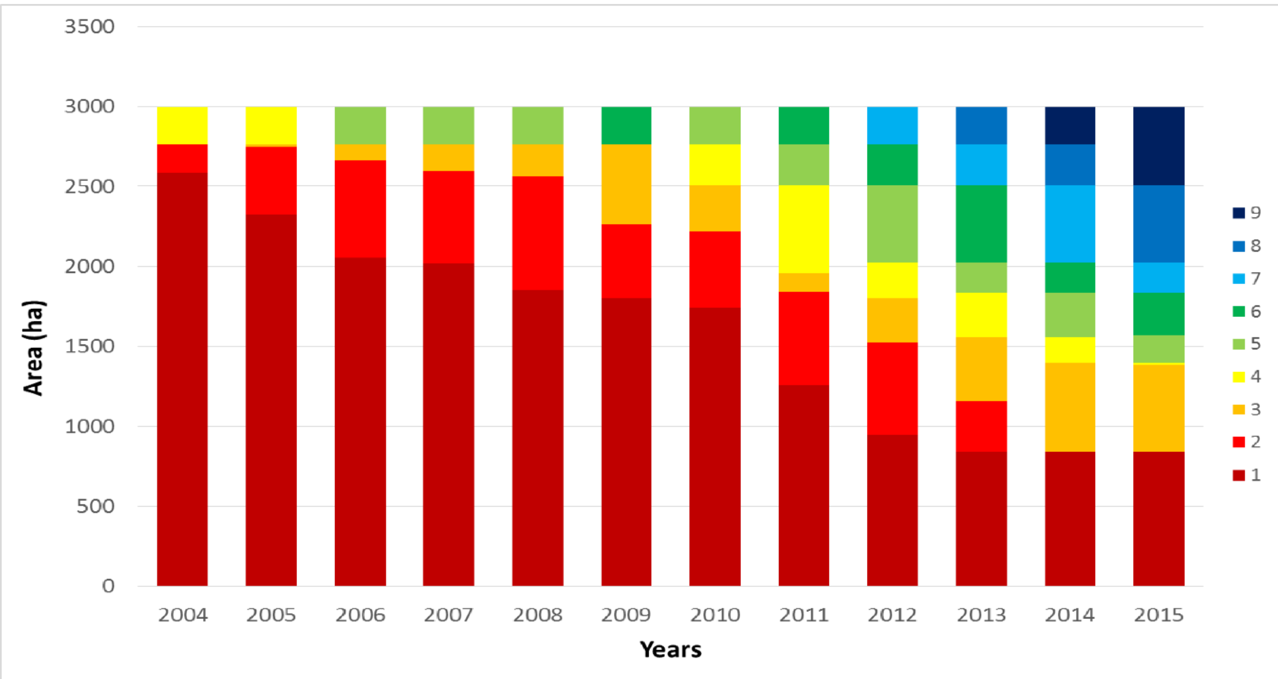


Figure 3.4: The planned and actual project flow through nine implemented management phases over 12 years (See Table 2 for phases). A: The planned project flow from 2003 to 2013. B: The actual management phases achieved between 2004 and 2015.

3.3.4 Estimated cost of clearing

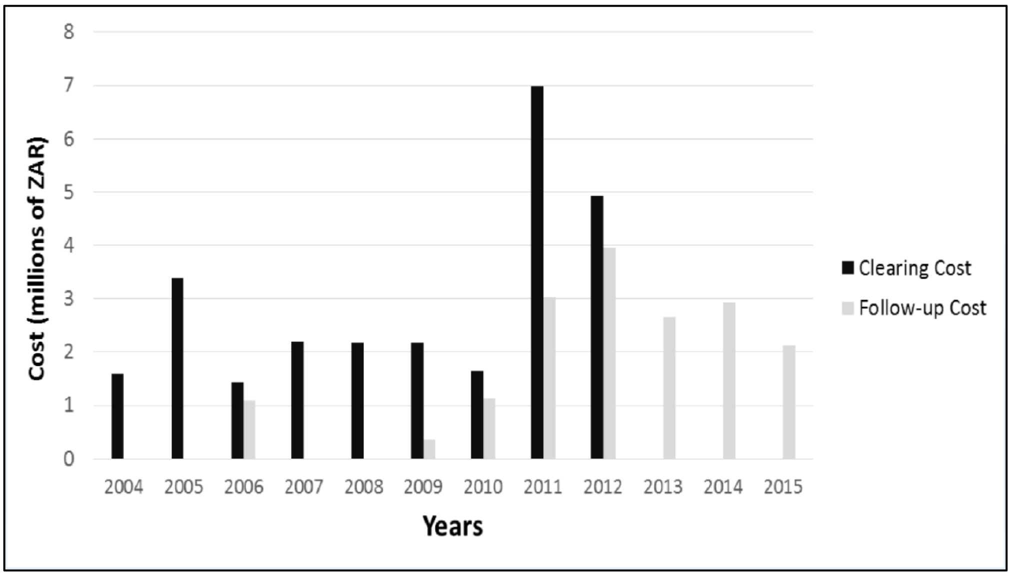
The 2002 management plan estimated to combined cost of clearing and follow-up to be ZAR 12.19 million over the next 12 years (ZAR 6 million was budgeted for initial clearing with an average cost of ZAR 2332/ha, and ZAR 6.19 million was budgeted for follow-up treatments). The annual costs were estimated at ZAR 1.3 million in 2003, reducing to ZAR 180 000 in 2013 (Figure 3.5A).

In reality, the original plan was not rigorously followed, and the cost of control was much higher than planned. Between 2004 and 2009 funds were allocated mainly to initial clearing, with very little going to planned follow-up operations (Figure 3.5B). After the 2009 fire, follow-up treatments were given priority, with the remaining funds going to further initial clearing. The actual amount spent on initial clearing between 2004 and 2015 was ZAR 26.4 million (more than four times the budgeted amount) with an average of ZAR 13 241/ha. The actual amount spent on follow-up was ZAR 17.2 million (three times the budgeted amount) (Figure 3.6).

3.3.5 Variance between budgeted and actual costs

The difficulty of control in a management unit did not affect the cost variance estimate ($F_{2,19}$ =1.44, p= 0.26) and no pair-wise comparisons were significant after Tukey's post-hoc test (at p= 0.05).

A



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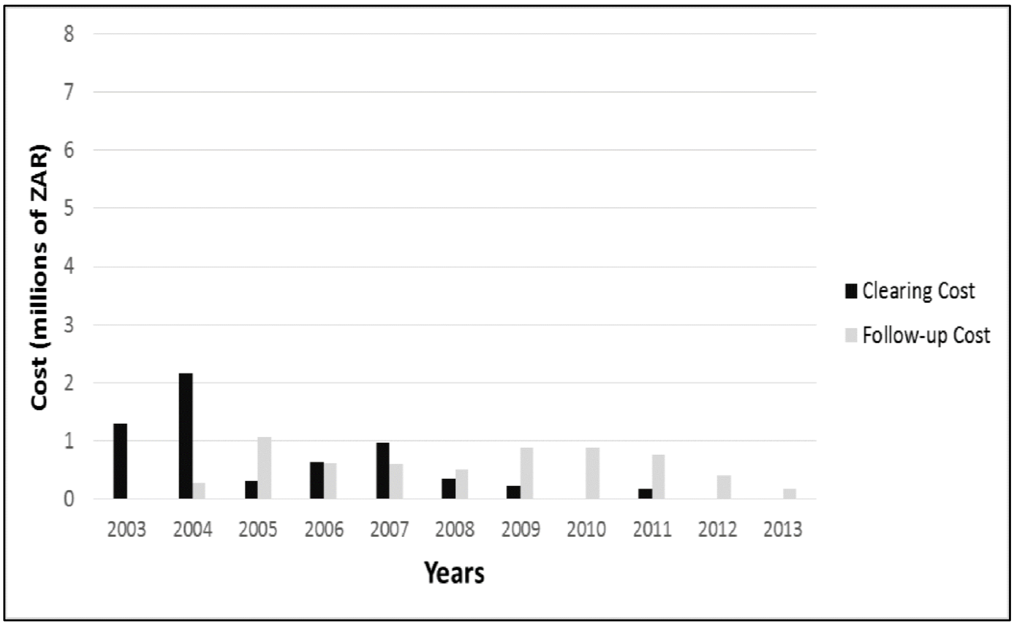

Figure 3.5: Actual annual project costs compared to budgeted costs in ZAR (South African Rand). A: The budgeted costs per year between 2003 and 2013. B: The actual amount spent per year for initial clearing and follow-up between 2004 and 2015.

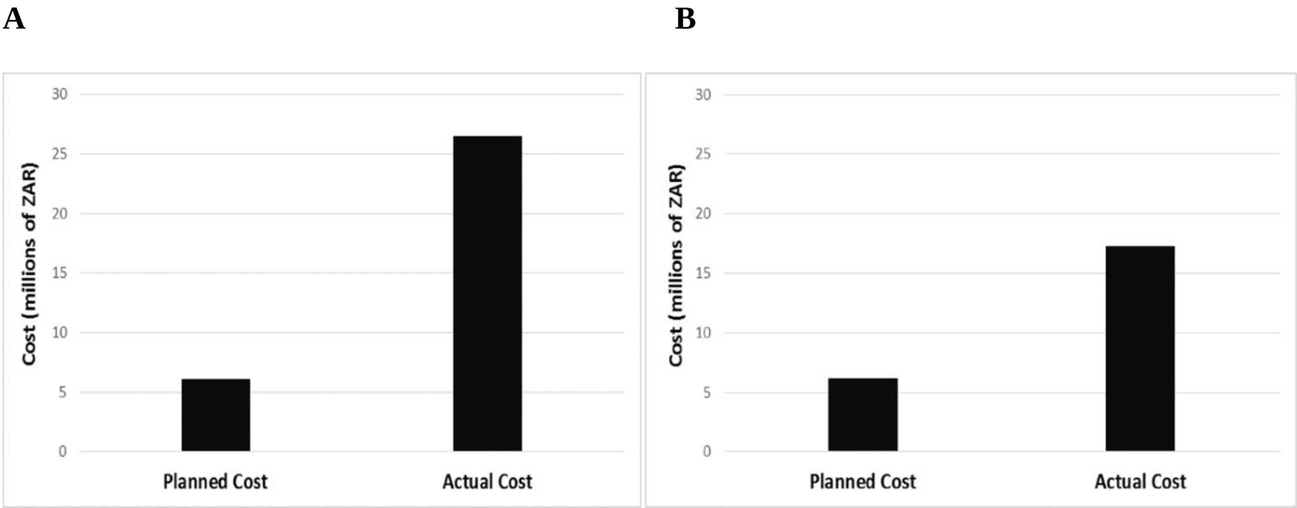

Figure 3.6: Total planned and actual costs spent on initial clearing of invasive alien plants and follow-up operations at Vergelegen. A: The planned costs for initial clearing between 2003 and 2013 versus the actual costs of clearing between 2004 and 2015. B: Planned costs for follow-up in the original management plan versus the actual cost for follow-up between 2004 and 2015.

3.4 DISCUSSION

Attempts to reduce the extent of invasion by IAPs on Vergelegen Estate have achieved substantial success. Dense invasions have been reduced from 73 to 8% of the area, but the cost was much greater that was originally envisaged, and populations of IAPs remain, albeit at much lower densities than at the start of operations. Should the funding for the operation be terminated, or even reduced, the substantial gains achieved to date will be lost and the area will return to its former heavily-invaded state (van Wilgen *et al.*, 2016a,b; Fill *et al.*, 2017). The experience at Vergelegen has clearly demonstrated the complex nature of the environment in which IAP control projects have to operate, a feature that characterises similar projects elsewhere (Roura-Pascual *et al.*, 2009; Woodford *et al.*, 2016). In this sense, the problems that confront private landowners are not substantially different from those faced by projects implemented by WfW on public land in the CFR. Key problems include the lack of foundational knowledge on which to base estimates of the cost of achieving long-term goals; the lack of effective methods to control IAPs; the fluctuating nature of funding due to competing demands for scarce resources; the occurrence of unplanned events, especially wildfires; and unforeseen complications, such as the generation of large amounts of woody biomass. Even with access to substantial funding, the state has only been able to reach a small proportion of all invaded land under its control in the CFR (van Wilgen *et al.*, 2012a), and the goal of achieving sustainable control may require a focus on priority areas, leaving others unmanaged (van Wilgen *et al.,* 2016a). One feature of the Vergelegen case that separates it from similar operations in the region is the existence of a formal management plan, and a commitment to auditing the plan, that has been absent from state-funded control operations in the CFR to date (van Wilgen *et al.*, 2012b).

The private landowner at Vergelegen, Anglo-American, is a large corporation with access to substantial financial reserves. This corporation has a stated commitment to managing the natural environment and cultural heritage of the estate. The same is not true for many other private landowners. This begs the question of whether most private landowners will ever be in a position to make effective contributions to gaining control of IAPs at the landscape scale in the CFR, as they are expected and are legally obliged to do in terms of regulations under the National Environmental Management: Biodiversity Act (Act 10 of 2004). The government has sought to address this challenge by introducing “landuser incentives” to provide support to landowners to pay for the labour required for the initial clearing and follow-up operations. Under this arrangement, landowners provide additional resources, and commit to preventing re-invasion of cleared areas. However, the goal of this assistance (to extend the control of IAPs beyond the state-owned areas, thus gaining control over much larger areas) may not be realised, for all of the reasons outlined above, and especially because the funds available for such incentives are limited. It is clear that additional sources of reliable funding are needed to address these problems on a wide scale on private land in the

CFR. One possible solution would be to implement a system of payment for ecosystem services (PES), in which off-site users of services (e.g. water) are charged a levy which could be used to support control projects in areas that generate the services (Blignaut *et al.*, 2007). If the goal of achieving control of IAPs on privately-owned land is to be achieved, it is imperative to agree upon, and to implement, such PES programmes.

CHAPTER 4: OPTIMIZING ALIEN PLANT MANAGEMENT ON PRIVATE LAND IN THE CAPE FLORISTIC REGION: INSIGHTS FROM VERGELEGEN WINE ESTATE

Abstract

Managing invasive alien trees and shrubs is extremely challenging, particularly for private landowners who have limited funds to devote to clearing operations and who often lack practical knowledge. Scarce funds for large-scale clearing operations need to be optimally used, but little information is available on which to base the planning of such complex undertakings. Vergelegen Wine Estate is undertaking probably the largest privately-funded alien plant control programme in South Africa with the goal of clearing invasive plants on 2200 ha of the 3200 ha estate. This paper documents the current extent of the problem on Vergelegen and estimates the time and resources that would be required to reduce the remaining invasions to a maintenance level. We consider a range of scenarios of funding, rates of spread and management effort, and provide recommendations on how to approach the problem most effectively. Alien trees and shrubs in the genera *Acacia*, *Eucalyptus* and *Pinus* were estimated to cover 10 % of the estate at various densities in 2016. The estimated cost to clear the remaining invasion was between R6 and R30 million under various scenarios. Only maintaining the current levels of funding, or doubling funding, and assuming spread rates of between 5 and 8 %, could bring the invasion under control over an acceptable period and at a reasonable cost. Once a maintenance phase is reached, the cost of maintaining invasions at low levels in perpetuity would drop to 10 % of the historic control costs. Our findings suggest that controlling plant invasions at the scale of the operation at Vergelegen would be possible, but at a significant cost to landowners. The effectiveness of projects, typically constrained by limited funds, could be increased by adopting an outcomes-based approach to ensure that objectives are achieved. Novel funding pathways need to be investigated by government to support clearing initiatives on private land that form part of larger priority areas to ensure success.

4.1 INTRODUCTION

Invasive alien plants (IAPs) pose a significant threat to biodiversity and ecosystem services globally (Vitousek *et al.*, 1996, Vilà *et al.*, 2011), including in the Cape Floristic Region (CFR), a biodiversity hotspot in South Africa. More than 1000 indigenous plant species are threatened due to IAPs in the CFR (Raimondo *et al.*, 2009), and invasive trees and shrubs cause a substantial reduction in surface water runoff from catchments which could precipitate major economic consequences (van Wilgen *et al.*, 2008). Considerable resources have been allocated to combat the problem in recent decades (van Wilgen *et al.*, 2012b), following the launch of a large programme to clear invasive alien plants in South Africa in 1995 (Koenig, 2009).

A major obstacle faced by project managers working on invasive plant control anywhere in the world is the complex interactions among factors that influence the dynamics of the invasive species, and the interplay of these with a wide range of socio-political issues. Management is especially complex and challenging in the fire-prone fynbos vegetation of the CFR which is subjected to many external pressures, including urbanization, human activities, climate change and plant invasion (Roura-Pascual *et al.*, 2009).

Effective management of alien plant invasions requires detailed planning before management operations can be initiated. Such planning needs to be based on an understanding of the spatial extent of the problem, features of the invading species and the invaded environment, the nature and dynamics of threats to biodiversity and other features, and of the factors that potentially affect the effectiveness of management interventions. Only with such information can objective decisions be made regarding the prioritisation of sites for control, selecting the best methods, and devising ways of monitoring outcomes to ensure effectiveness (Downey, 2010a). Planning must also cater for evaluating performance and implementing changes where necessary. Despite the substantial financial investments that have gone into controlling IAPs in the CFR, recent studies have suggested that current management operations may not be reducing the overall extent of the problem in the region (van Wilgen *et al.*, 2016; van Wilgen *et al.*, 2012). At best, the rate of spread of invasive species at a catchment scale has been slowed down, but not stopped, and in many places spread continues despite clearing efforts (McConnachie *et al.*, 2012; Fill *et al.*, 2017).

Most land in South Africa that is invaded by alien plants is privately-owned, and without the collaboration of private landowners in alien plant management operations, invasions in the CFR will probably never be brought under control (van Wilgen *et al.*, 2012, 2016). Urgenson (2011) showed that most landowners and other stakeholders in the CFR support the notion of inclusive environmental governance involving both the public and private sectors. However, most of these landowners lack the substantial resources that would be required to sustain the operations needed to address the problem. Private landowners often have very limited information on the costs and levels of effectiveness of different approaches used to reduce invasive cover, and many interventions that have been undertaken have been ineffective.

Vergelegen Wine Estate (hereafter Vergelegen) has invested substantial resources to reduce the impacts of IAPs. As far as we know this is the largest privately-funded project directed at IAP control in South Africa, and approximately R 49 million has been spent since systematic operations started in 2004, R 26.4 million on initial clearing, R 17.2 million on follow-up operations to remove seedlings that emerge after clearing, and R 6.2 million on other facets of management (van Rensburg *et al.*, 2016b). This amount was spent on invasions over an area of approximately 2000 ha, but invasions persist, albeit at lower densities, and some areas have yet to receive an initial clearing. About 52 % of the funds were spent on areas invaded mainly by Australian *Acacia* species (1000 ha), 29 % was spent on *Eucalyptus* species (188 ha) and 18 % was spent on *Pinus* species (813 ha). The average total cost per hectare (including initial clearing and follow-up treatments) was the highest for *Eucalyptus*, followed by *Acacia* species and *Pinus* species.

The main goal of the project at Vergelegen was to clear 2200 ha of IAPs from undeveloped areas with natural vegetation to reach a “maintenance level” of plant invasion. The concept of a maintenance level recognises that alien species cannot be eradicated once they are well established over large areas, but that operations should aim to reduce invasion (in terms of extent and abundance) to a level where the invasions can feasibly be contained at a relatively low cost in perpetuity (Goodall and Naude 1998; van Wilgen *et al.*, 2016).

In 2012 all initial clearing operations at Vergelegen were halted due to a drastic reduction in funding. This reduction was because of funding constraints within Anglo American Farms (owners of Vergelegen) that resulted in widespread cost-cutting. At that stage, approximately 200 ha of land that still required initial clearing remained untreated, and some funding was made available for follow-up treatments on land that had already received initial treatment. Previous studies conducted on Vergelegen have examined (1) the factors that contributed to invasive plant spread (van Rensburg *et al.*, 2016a); and (2) the costs and effectiveness of past management actions (van Rensburg *et al.*, 2016b).

This paper describes the extent of invasions on Vergelegen in 2016, and provides an estimation of the resources required to reduce the problem to a maintenance level under different scenarios of spread and funding. We then estimate the resources that would be required to maintain the cleared areas. We use these findings to propose changes to the control operations that would potentially improve management effectiveness. Although the study focuses only on Vergelegen, findings should be relevant to many other cases in the CFR and will be useful for developing guidelines for an improved national strategy for incorporating privately-owned land into overall invasive species management plans.

4.2 METHODS

4.2.1 Study site

The study was conducted on the Vergelegen Wine Estate (which covers approximately 3200 ha, Figure 4.1), near Somerset West in the Western Cape Province. According to the South African National Biodiversity Institute's (SANBI) spatial biodiversity planning information, three main vegetation types occur in the area: Boland granite fynbos, shale renosterveld and Lourensford alluvium fynbos (SANBI BGIS, 2009). The area falls within the Lourens River Protected Natural Environment and has a Mediterranean-type climate with a mean annual rainfall of 780 mm. Altitude ranges from 70 to 1020 m a.m.s.l. The area has been invaded by alien trees, especially species in the genera *Acacia* (wattles), *Eucalyptus* (eucalypts) and *Pinus* (pines). The wattles and eucalypts are mainly confined to lower-elevations close to riparian zones, whereas most pine invasions are on higher-elevation slopes. The earliest invasive stands were located around the Vergelegen homestead and in transformed areas (agricultural land and plantations). These spread across natural vegetation in the study area over time. Poorly managed agricultural land was prone to plant invasion and management neglect exacerbated the problem of invasion in the lower-elevation parts of the study area. Pine trees invaded the higher slopes, having spread from both the plantations within the study area and through long-distance seed dispersal from remote plantings; periodic fires facilitated these invasions by triggering seed release and dispersal and creating a favourable environment for germination and growth. The study area has been burnt in three large wildfires since the 1950s. Work in other parts of the CFR has shown that repeated fires facilitate seed release and spread of pines, leading to the transformation of large tracts of fynbos shrublands into dense pine forests (Richardson and Brown, 1986; Rouget *et al.*, 2003). An alien plant control programme was initiated at Vergelegen in 2004 with the goal of clearing 2200 ha of invaded land due to the growing concern of increased fire intensity and frequency and the loss of natural habitat. The programme was managed by Vergelegen environmental project managers, who in turn employed contractors to clear the invaded areas.

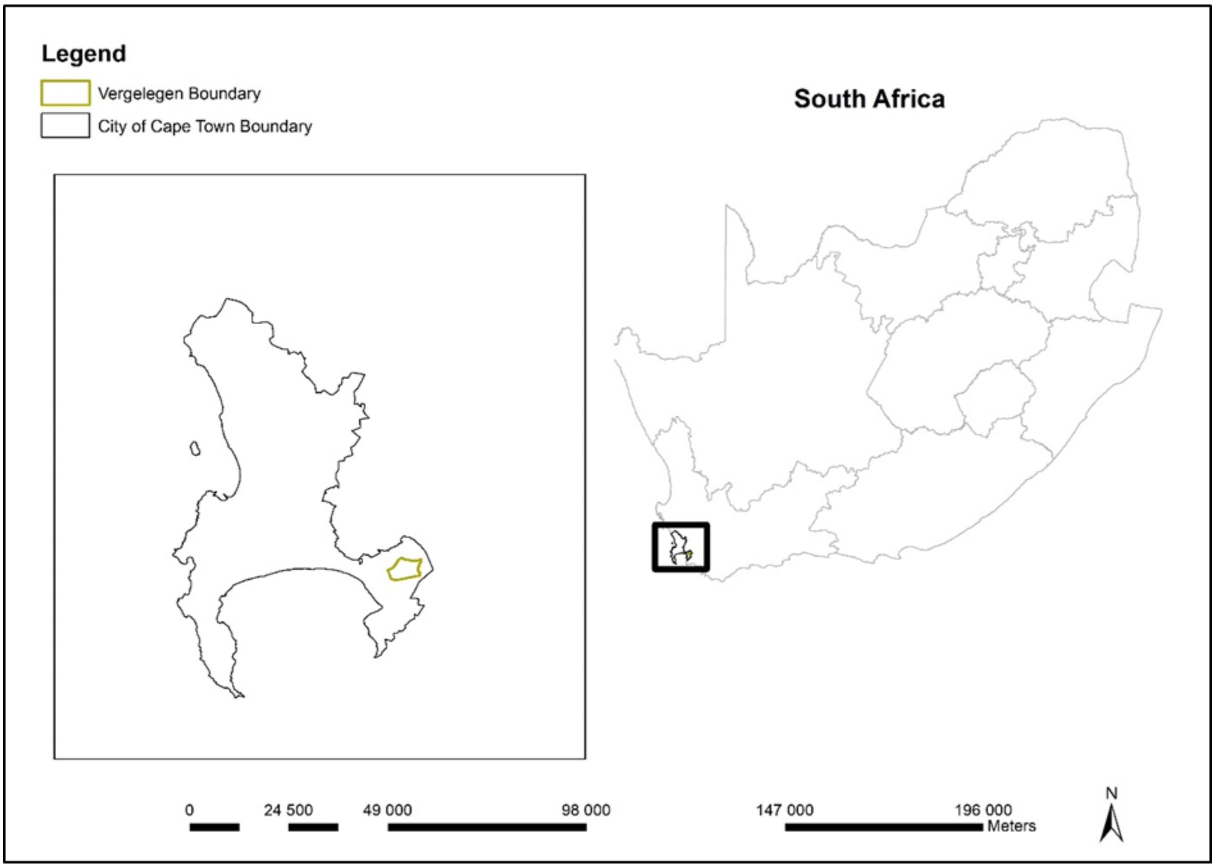

Figure 4.1: The study area at Vergelegen within the Cape Town Metropole in the Western Cape Province, South Africa.

4.2.2 Extent of alien plant invasion

Vergelegen was divided into 26 management units (MUs). In each of the MUs we estimated the cover of invasive alien trees and shrubs in the genera *Acacia*, *Eucalyptus*, and *Pinus* in 2016. The three genera account for almost all the remaining invasive alien plants on Vergelegen after 11 years of invasive alien plant management. We estimated the area covered by IAPs in each MU using aerial photographs and on-the-ground verification, and divided each MU into six classes based on the cover of trees, as follows: occasional (< 1 % cover);

very scattered (1 – 5 % cover); scattered (5 – 25 % cover); medium (25 – 50 % cover); dense (50 – 75 % cover); and closed (> 75 % cover).

4.2.3 Projected future control costs

We used the "norms and standards task field verification sheet" used by the Working for Water programme (Neethling and Shuttleworth, 2013) to estimate the effort (person days) that would be required to treat all the remaining plant invasion. Treatments included initial and follow-up clearing. The effort and methods are listed in the norms and standards for different taxa, and for different densities of invasive trees and shrubs. The effort required was adjusted to account for the time needed to reach sites (by road and then on foot), and for slope (costs rise as slope increases). Slope was determined using 5-m contour lines in ArcMap version 10. To find the slope of the MUs, the horizontal distance (run) as well as the vertical distance (rise) between two points on a line parallel to the feature was determined. The percentage slope was estimated by:

$$\%\,Slope = \frac{Rise}{Run}\,x\,100$$

Effort calculations are built into the task verification sheet and once required fields are populated the estimated person days were calculated. MU boundaries were demarcated as spatial data layers and we used the distance between the centre point of the management unit and the closest road to estimate walking time (assuming a walking speed of 3 km/h), and between the road access to the MU and the Vergelegen headquarters to estimate driving time (assuming a driving speed of 60 km/h) (van Wilgen *et al.*, 2016). The norms and standards were used to determine the estimated cost of initial clearing efforts and five follow-up treatments (the selection of the number of follow-up treatments required was based on experienced gained by the environmental project managers on Vergelegen over the last decade). The cost was estimated for each MU and for a range of future scenarios to cater for different levels of annual funding and rates of spread (Section 4.2.5). We first estimated the "base cost", which is the amount funding that would be required to clear the remaining invasion and to carry out the required follow-up treatments. To achieve control at the base cost would require all invaded areas to be cleared, and followed up, in one year. This is clearly not possible, both because the clearing and follow-up treatments must be spread over several years, and because available annual funding would almost certainly be below the base cost. We therefore assumed that remaining invasions would continue to spread until they were cleared.

4.2.4 Scenarios for future control

The removal of invasive alien plants from Vergelegen is aimed at reducing the alien plant cover to a maintenance level where limited resources would be required to sustain a low level of cover. The current alien plant control programme is divided into nine management phases (Table 4.1). After initial clearing, the dead biomass that results from the clearing operation is burnt between April and September as specified on the required burning permit granted by the City of Cape Town. Once biomass has been removed, these areas receive five annual follow-ups to reach a maintenance phase.

Table 4.1: The current management phases implemented in the Vergelegen alien plant control programme.

Phase ID	Management phase	Description of management phase
1	Treatment not yet initiated	No management action taken. This includes areas where initial clearing has not taken place yet, agricultural and hospitality areas.
2	Initial Clearing	Initial clearing is the initial control action that drastically decreases the exciting alien plant population. The preferred treatment was cut stump where stems are cut as low as practical. Herbicides are applied as recommended for the specific species being treated.
3	Biomass treatment	Biomass removal is a critical part of the alien control programme there are varies methods to remove biomass created by clearing IAP in fynbos, however prescribed burning was the most effective and practical means of controlling biomass created by the Vergelegen IAP control programme. This stage includes areas within the clearing project that are located on higher slopes on Vergelegen, biomass was not removed in these areas due to the risk of run away fires. Follow-up is still taking place annually, however increasing costs.
4	Follow-up 1	Follow-up is the control of seedling, root suckers and coppice growth that occurs after initial clearing. WfW has a 3 follow-up policy before they hand over the treated area to the relevant land owner. However on the Vergelegen project we worked on 5 follow-up's since new IAP seeds were introduced from the surrounding invaded area.
5	Follow-up 2	
6	Follow-up 3	
7	Follow-up 4	
8	Follow-up 5	
9	Maintenance Phase	Maintenance phases includes areas that have less than 5% invasion present annually, these areas require minimal resources to control plant invasion.

We investigated the outcome of four funding scenarios: 1 = the current level of funding continues; 2= current funding is doubled; 3= current funding is reduced by 50 %; 4= future funding is erratic and unpredictable. The reasoning behind these scenarios was that (1) that the current funding level would continue, as a starting point for planning; (2) doubling the current funding level could reduce the time required to reach a maintenance phase, assuming that this would save funds in the longer term; (3) that funding could be reduced by 50 % due to a scarcity of funds, reflecting the current economic climate; and; (4) that the funding could be erratic, as has happened in the past (e.g. Vergelegen clearing project funding was terminated in 2012 due financial constraints, and re-instated in later years). For the last scenario, we proposed random costing scenarios that could theoretically simulate a realistic alien plant control project funding scenario.

4.2.5 *Scenarios for spread rates*

We used two spread rate scenarios (5 % and 8 %) to simulate the annual spread of alien tree stands that have not yet been cleared. We estimated a probable rate of spread for invasive alien plants using a data from Vergelegen and surrounding farms in which the distribution of alien plant invasion was estimated at intervals between 1938 and 2004. For example, alien plant cover increased from 463 ha in 1983 to 2065 ha in 2004, an annual rate of increase of 5.2 %. For the purposes of this study we did not consider species-specific spread rates and only considered a general rate of increase for all IAP species. Fork *et al.,* (2015) investigated the rate of spread of non-native eucalypt woodlands in central California using time-series analysis, and estimated that planted eucalypt groves increased 271 % in size, on average, over six decades, invading adjacent areas, which equates to an annual spread rate of 4.5 % per year. In the case of *Pinus*, Higgins *et al.,* (2000) used successive aerial photographs to estimate the rate of spread of *P. pinaster* at four sites in the CFR. They used a linear regression of the natural logarithm of the area versus time, and estimated doubling times at between 10 and 30 years, or 3–8 % per year. Considering that the dominant species remaining on Vergelegen are *Eucalyptus* and *Pinus* species (4.3.1) we chose 5 % and 8 % as realistic spread rates for use in our scenarios. The areas surrounding Vergelegen are heavily invaded by IAPs; we thus assume that after a "maintenance phase" has been reached the cleared areas will continue to be re-invaded. We therefore added a 5 % and 8 % spread rate to the annual maintenance cost.

4.2.6 Maintenance control scenarios and cost estimates

Once the initial clearing and follow-up treatments have been completed, we assumed that the level of invasion would have been reduced to less than 2 % cover overall. The ecosystem management of the 2200 ha cleared since the projects inception in 2004 should then go over to a maintenance phase, which would aim to keep invasions at less than 2 % cover in perpetuity.

Maintenance-level management would require several interventions, including:

- Prescribed burning on a 15-yr rotation, with the dual purpose of rejuvenating the vegetation and by reducing the risk of having large wild-fires (van Wilgen, 2009). To achieve this, the farm will be divided into 6 blocks of 376 ha, each of which would come up for burning when it reaches a post-fire age of 15 years. Given that much of the farm is currently the same post-fire age, the age at which blocks are burnt could vary between 10 and 16 years, so that burns can be staggered over several years.
- Treatment of any pine and hakea plants in the burning block. Any pine or hakea plants occurring in the burning block should be felled 1 – 2 years prior to burning. Seeds will be released close to the ground, reducing spread, and some will germinate. The area should then be burnt to kill seedlings before they set seed. The area can then be subjected to a follow-up 2 – 4 years after the fire to remove any seedlings that escaped the fire. The area should then be left for two years before the next fire, when the cycle will repeat itself.
- Treatment of blocks with *Acacia* and *Eucalyptus* species will differ in that more than one follow-up treatment is needed. Wattles produce large numbers of seeds that accumulate in the soil (Richardson and Kluge, 2008), whereas stands of eucalypts changes soil-nutrient properties (Gaertner *et al.*, 2011) that could lead to poor native plant recruitment, or to secondary invasion by other species.

We determined the maintenance cost using the methods outlined in section 4.2.3. We assumed that the alien plant cover in maintenance phase would be less than 2 %. The cost to conduct block burns per hectare was estimated from historical information obtained from the Vergelegen annual costing reports.

4.3 RESULTS

4.3.1 Extent of alien plant invasion

Three genera (*Acacia*, *Eucalyptus,* and *Pinus*) accounted for the bulk of the remaining invasive alien plant cover on Vergelegen (Table 4.2). Eucalypts were the most widespread, with invasive stands covering 476 ha at various densities, with 429 ha and 283 ha supporting *Pinus* and *Acacia* stands with lower levels of cover. Thus, after 11 years of clearing on Vergelegen, about 10 % of the 2200 ha earmarked for clearing was still invaded to some extent by alien trees. The remaining alien tree stands that had not received an initial felling treatment occurred in four MUs, with eucalypts being the most abundant, with wattles and pines present at lower densities.

Table 4.2: Area (ha) occupied by three invasive alien tree genera in six cover classes in the 26 management units in Vergelegen.

Invasive alien plant genus	Cover class						Total
	Closed (>75%)	Dense (51-75%)	Medium (26-50%)	Scattered (6-25%)	Very scattered (1-5%)	Occasional (< 1%)	
Pine					345	84	**429**
Acacia				140	142		**282**
Eucalyptus		142	140	90	104		**476**
Total	**0**	**142**	**140**	**230**	**591**	**84**	**1187**

4.3.2 Projected costs and scenarios for future control

The estimated cost to immediately treat all alien plants at the current extent of invasions (initial clearing and five follow-up treatments; the “base cost”) amounted to R 7.1 million (made up of R 4.3 million for initial clearing and R 2.7 million for follow-up). This is about 17 % of the total clearing cost spent to date.

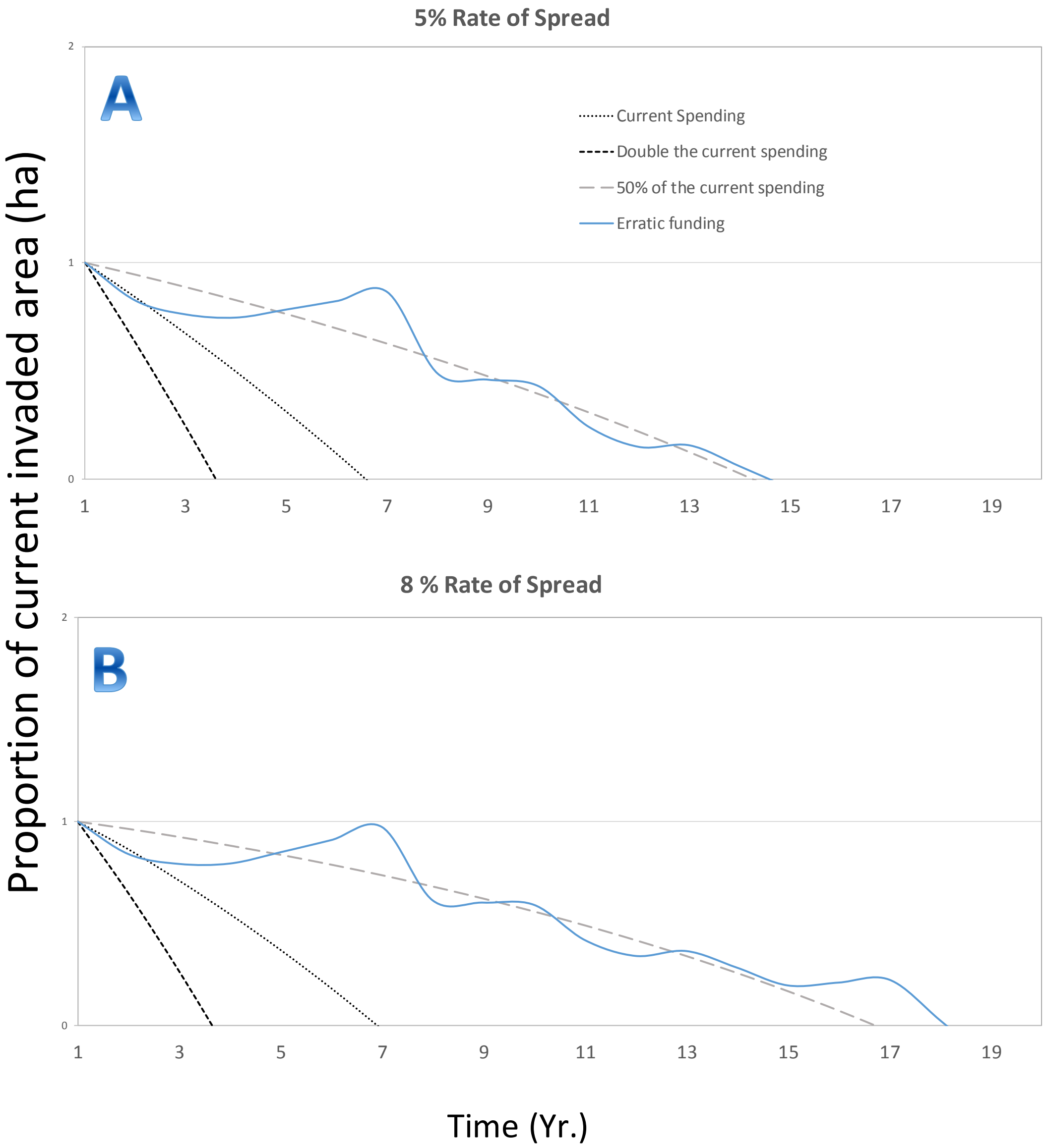

Figure 4.2: Estimated time to reach a maintenance level of invasion on Vergelegen under different funding scenarios. Panels A and B show projections for different scenarios at annual spread rates of 5% and 8% respectively.

The projected future cost of control ranged from R 6 million to R 30 million, depending on the management scenario (Table 4.3). All scenarios that were considered could lead to a reduction to maintenance level in the extent of invasive trees (Figure 4.2). Under current funding level for both 5 and 8 % spread rates, it should take 7 years to reach a manageable level of invasion, the cost being 1.5 times greater than the estimated "base cost". Our estimates suggest that successful control could be achieved with half the current funding, but then only after 15 and 17 years at 5 and 8 % spread rates respectively. Importantly, the 50 % funding scenario would require three times the estimated base cost.

Table 4.3: Scenarios to reduce plant invasion to a manageable level on Vergelegen.

Management Scenario	Total (ZAR x 1 000 000)	Time to reach sustainable "maintenance phase" (years)
Funding at current levels 5 % annual rate of spread	11	7
Double the current funding 5 % annual rate of spread	6	4
50 % of the current funding 5 % rate of spread	24	15
Erratic funding 5 % rate of spread	24	15
Funding at current levels 8 % annual rate of spread	11	7
Double the current funding 8 % annual rate of spread	6	4
50 % of the current funding 8 % rate of spread	27	17
Erratic funding 8 % rate of spread	30	19

The erratic funding scenario (a more realistic scenario given the current economic climate) could achieve a maintenance level of control, but only after 15 and 19 years under 5 and 8 % spread rates respectively, and at four times the estimated base cost. Doubling the current funding could reduce invasions to a maintenance level within 4 years.

We estimated that R5.9 million would be required to maintain the estate at low levels of invasion (2 % cover) over one fire cycle, i.e. over 15 years. The 2200 ha was divided into 6 blocks (Table 4.4), the blocks will first be cleared and then burnt the following year. The vegetation age will range from 10 – 15 years depending on the management block. Once a block is burnt it will receive its first follow-up treatment two years later, the number of follow-up treatments will depend on the dominant alien species present (section 4.2.6).

Table 4.4: Maintenance phase cycle illustrates the time required to fell, burn and follow-up each block; each block represents 366 ha.

Year	**Blocks**					
	1	**2**	**3**	**4**	**5**	**6**
1	Fell					
2	Burn	Fell				
3		Burn	Fell			
4			Burn	Fell		
5	Follow-up pines Follow-up eucalypts Follow-up wattles			Burn	Fell	
6		Follow-up pines Follow-up eucalypts Follow-up wattles			Burn	Fell
7	Follow-up wattles Follow- up eucalypts		Follow-up pines Follow-up eucalypts Follow-up wattles			Burn
8		Follow-up wattles Follow- up eucalypts		Follow-up pines Follow-up eucalypts Follow-up wattles		
9	Follow-up wattles Follow- up eucalypts		Follow-up wattles Follow- up eucalypts		Follow-up pines Follow-up eucalypts Follow-up wattles	
10		Follow-up wattles Follow- up eucalypts		Follow-up wattles Follow- up eucalypts		Follow-up pines Follow-up eucalypts Follow-up wattles
11			Follow-up wattles Follow- up eucalypts		Follow-up wattles Follow- up eucalypts	

12				Follow-up wattles		
				Follow- up eucalypts		Follow-up wattles
						Follow- up eucalypts
13					Follow-up wattles	
					Follow- up eucalypts	
14						Follow-up wattles
						Follow- up eucalypts

4.4 DISCUSSION

4.4.1 Forecasted control timeframes

This study suggests that all scenarios would eventually lead to a maintenance phase being achieved but at different costs and timelines. The most likely scenario of "erratic funding" at 5 and 8 % spread rates predicted a total cost of four times the estimated "base cost" and could take up to 19 years to reach a maintenance level of invasion. The best scenario based on cost and time is a doubling of the current funding levels (for both 5 and 8 % spread rates); under this scenario 4 years would be needed to reach a maintenance level of invasion. This would not be possible since at least five years would be needed to complete the full cycle of follow-up operations within each MU. The current management action plan requires a minimum of 6 years to reach a maintenance phase, since we assume that initial clearing and biomass removal will take place in year 1, followed by five annual follow-up treatments. Hence a minimum of 6 years would be required after the last initial clearing had been completed to reach a maintenance level over the whole study site. These findings are encouraging. For example, several other studies (Marais *et al.,* 2004; McConnachie *et al.,* 2012; van Wilgen *et al.,* 2016) estimated that control may take several decades, or may never be reached, given the complexities of managing invasive alien plants over large and inaccessible areas with limited resources and often inefficient application of treatments.

The total cost to clear Vergelegen down to a maintenance level would be between R55 and 80 million (R49 million already spent, plus 6 – 30 million depending on the scenario). Maintaining the estate at a maintenance level (R5.9 million per 15-year maintenance cycle) would therefore amount to between 7.3 and 10.7 % of the cost to bring the estate to a maintenance level.

4.4.2 Opportunities to integrate fire and alien control management

The natural ecosystems of the CFR are fire-prone and fire-adapted, and alien plant control operations need to be integrated with the use of fire if they are to be successful. There are two reasons that fire is required. The first is to use fire as an effective means of killing the immature seedlings of pines and hakeas that germinate and establish after the adults are felled. The second is to reduce the amount of dead biomass resulting from the clearing operations. Prescribed burning should ideally be carried in the late summer and early autumn (February to early April), since serotinous shrubs (notably species in the genera *Leucadendron* and *Protea*) are sensitive to fire season, with optimal seedling recruitment occurring after fires in summer and early autumn (Bond *et al.*, 1984; van Wilgen *et al.*, 1985). Prescribed burns can be extremely risky during this period, and obtaining permission to burn at these times is almost impossible, given the reluctance of Fire Protection Associations to accept the risk of runaway fires that could damage infrastructure and threaten human lives. For a prescribed burn to be permitted, it is normally recommended that temperatures should be less than 25°C, wind speed should be moderate (20 km/hr), and some rain should have fallen 2 to 3 days before potential burn days. Unless all these conditions are met, permission is not granted to proceed with prescribed burns. These guidelines reduce the available window to conduct prescribed burns during the ecologically optimal late summer period. The spring months of September and October provide the safest weather for burning (van Wilgen *et al.*, 1990, van Wilgen and Richardson, 1985), but burning in spring is discouraged because of detrimental effects on the vegetation (Bond *et al.*, 1984; van Wilgen and Viviers, 1985). There have been suggestions that burning prescriptions could be relaxed where a failure to burn would mean a failure to complete a vital part of the alien control programme (van Wilgen *et al.*, 2016). By allowing limited burning in September and

October, burning plans could be completed. However, a trade-off would need to be made between the negative impact on native vegetation and the positive impact of reducing the burden of follow-up manual weeding which is needed if fire is not used.

The Vergelegen project also generated a large amount of dead biomass since its inception, and burning is required to reduce this biomass. Both block and stack burns were conducted, and these have mostly been done in winter (May to August) to reduce the risk of runaway fires. Most were successful, but some were unsuccessful or patchy, and this impeded the follow-up process and resulted in secondary invasion of the same species (Zavaleta *et al.*, 2001; Loo *et al.*, 2009). Once the biomass was removed, follow-up treatments were easily executed. Based on experience, late summer burns were preferable and allowed for clean burns, although the risk of run-away fires is significantly increased. To reduce the risk, Vergelegen used the services of WoF (Working on Fire) and the FPA (Fire Protection Association), as both organisations could provide trained and experienced crews.

4.4.3 Management recommendations

The historical success of the Vergelegen project has been mostly due to the consistent management of clearing contractors, with regular measurements of progress and monthly costings being reported to Vergelegen senior management. The process of reporting on a regular basis ensured that the annual plan of operations (APO) was adhered to and that any changes to the plan were reported. Independent audits ensured that information captured by project managers was accurate. These procedures ensured that work was of a high standard and that any problems that could influence the APO and/or future budget changes were detected, leading to acceptance of the project by the funders. This contrasts with many other CFR projected areas where the problem is running away from managers (van Wilgen *et al.*,

2016) who have to work in an increasingly bureaucratic and rule-bound environment that focuses on job creation, training and empowerment initiatives at the expense of ecological outcomes. These additional requirements create confusion about how to prioritise projects, and often result in projects not being selected optimally (Kraaij *et al.*, 2016). Private land-owners however are not constrained by these additional goals and can insist on high-quality work and optimal prioritisation of areas that will provide the greatest results.

Obtaining sustained funding for managing plant invasions on private land can be difficult, since private landowners often have a limited understanding of what the long term financial commitments and implications are. Therefore, before any clearing is considered funders require detailed costing, timelines and operating procedure. This provides additional challenges in an environment that often demands flexibility and adaptive management (van Wilgen and Wannenburgh, 2016).

Due to the above factors, careful planning is required to increase the effectiveness of alien control programmes. The following are recommended:

- *Set clear objectives in the form of outcomes*: An outcomes-based approach is needed with clear defined goals (i.e. to reach “maintenance phase”; to prevent loss of biodiversity or to reduce the loss of ecosystem services). This will allow the control actions to be tailored to ensure that control will lead to the desired outcomes (Downey, 2010b).
- *Define project area:* Using a standardized set of metrics to describe the extent of the invasion by (1) determining the status of the invasion by identifying the species, densities as a measure of abundance (i.e. area occupied; net infestation), age structure and delineating the area into easily defined management units by using natural and/or man-made boundaries (i.e. roads and rivers); (2) qualitative observations of current

and potential impact, understanding the associated site specific impacts will help with funding motivation and prioritisation; (3) estimate the potential range that could be occupied by predicting future population growth and spread.

- *Prioritise areas for alien plant clearing*. On private land, land-owners often have limited funds available for clearing operations. To reduce the impact of widespread invasion on biodiversity, control programs need to be prioritised (Forsyth et al. 2012), and work needs to focus on areas where control is both achievable and likely to have the greatest benefit to native biodiversity (Downey *et al.*, 2010b). Such a site-led approach will ensure maximum benefit from the limited resources available for management of widespread plant invasion (Williams *et al.*, 2009).
- *Institute a process of independent monitoring:* Regular monitoring by independent auditors should assess progress towards outlined goals, and it should be acceptable to adapt goals or time frames if necessary. Research has revealed that such monitoring can be carried out at a relatively low cost (van Wilgen *et al.*, 2012). Monitoring will ensure effective management and that best practice techniques are implemented.

In summary, our assessment suggests that achieving the goal of reaching a maintenance level is achievable, but that consistently spending more sooner would reduce overall costs. These findings support those by Holmes et al. (2000) and Gaertner et al. (2012) who found that efforts required to restore native vegetation are proportional to the time that the area had been invaded, leading to a recommendation that invaded areas should be cleared as soon as possible. However, some privately-owned land might already be heavily invaded and rapid response might no longer be an option. Apart from the financial considerations, the feasibility of clearing invaded land will depend on the location of the area (Gaertner *et al.*, 2012). If the area under consideration is in a region of high conservation priority, clearing should at least be attempted in lightly-invaded areas, the remaining heavily-invaded areas could be left until alternative funding can be found (e.g. land-user incentive). If the area is located in transformed habitat (e.g. agricultural lands) removing invasive plants to focusing on biodiversity may not be feasible or justifiable, in such cases, motivating funding for clearing operations should be aimed at restoring ecosystem processes and functions (Gaertner *et al.*, 2012). Considering this land-owner should apply an outcome based approach and focus resources on areas that will yield the best return on investment. Joint projects between land-owners and government ('land-user incentives') is crucial to ensure that the spread of IAPs in the CFR is reduced.

CHAPTER 5: CONCLUSIONS

There is poor understanding of the factors and historical events that have driven invasions of alien trees and shrubs in the Cape Floristic Region (CFR). Furthermore, few studies have conducted or monitored treatments over temporal and spatial scales relevant to operational contexts on privately owned land. Regarding long-term historical cost and challenges faced by private land-owners when managing invasive plants, most cost calculations are based on estimates from experimental trials and not measurements of costs in operational contexts. Limited information is available on future costing scenarios for large-scale privately funded clearing operations in the CFR, and recommendations on ways of improving management efficiency are urgently needed.

To fill these gaps, this investigation used the alien-plant control programme at Vergelegen Wine Estate as a case study to: (1) reconstruct the spread of invasive alien plants on private land in the CFR; (2) assess the challenges of managing IAPs on private land in the CFR; and (3) investigate how to optimize alien plant management on private land by investigating possible costing scenarios and by providing practical recommendations for future control.

In this chapter I briefly summarize the key findings for each of the objectives and examine how successful I was in filling the gaps identified in the Chapter 1. I also discuss the priorities for future research.

Objective 1: *Reconstruct the spread of invasive alien plants on private land in the Cape Floristic Region: the case of Vergelegen*

Chapter 2 investigated the major factors that contributed to invasions of woody alien plants on a privately-owned farm in the CFR. The objectives of the chapter were to: (1) determine which land-use processes influenced the spread of alien species; and (2) document the invasion patterns and spread rates.

The study examined historically significant events that contributed to land-use change. I also analysed a time series of historical imagery dating back to 1938 (images from 1938, 1966, 1977, 1989, 2004 and 2013) to map changes in the extent of five land-use categories: agricultural land, commercial plantations, invaded land, natural vegetation and urban areas. Changes in land use at the Vergelegen study area over 75 years involved the transformation of 80 % of the area's natural habitat by agriculture, plantations, urbanisation and alien plants by 2002. During this period, based on my analyses using a transition matrix, the extent of change over time between the different land-use categories was investigated to help clarify and identify the underlying drivers that contributed to plant invasion in the study area. It was evident that commercial agriculture and plantations had the most significant impact on the establishment and spread of IAPs, as seen elsewhere in the CFR (Rouget *et al*., 2003; Le Maitre *et al*., 2004; van Wilgen and Richardson, 2012). Significant events that influenced IAP spread were the construction of farm infrastructure such as roads and dams, the abandonment of old agricultural lands, planting of commercial pine plantations and the occurrence of several large wildfires (Richardson and Brown, 1986; Rouget *et al*., 2001). The results of this study suggest that invasions of woody alien planted in the CFR proceed in a predictable fashion in tandem with human-mediated land-use changes that provide and alter seed sources and disturbances that are crucial drivers and dispersal mechanisms of invasions of alien trees. Understanding the factors that contribute to the establishment and proliferation of IAPs is important for planning long-term management strategies.

A limitation of my study was the size and boundaries of the study area. The study area was too small to allow for a comprehensive assessment of the full range of factors that influenced invasions, as factors outside the limits of the study site were probably also important drivers. Assessment over a large spatial scale (e.g. a full quaternary catchment) would have provided a clearer picture of the full range of natural and anthropogenic drivers implicated in the establishment of dense stands of IAPs on Vergelegen. For example, the areas surrounding the study area were predominantly used for commercial forestry purposes and could possibly have been more of a contributing factor to plant invasion. Nonetheless, the assessment covered only Vergelegen revealed interesting and useful insights.

Objective 2: *Elucidate the challenges of managing invasive alien plants on private land in the Cape Floristic Region by drawing insights from Vergelegen Wine Estate (2004-2015).*

Little information is available on the success of privately funded initiatives to management IAPs in the CFR. This study investigated the effectiveness of a large privately funded project in reducing alien plant cover, explored the challenges faced, and detailed the costs associated with long-term clearing operations on privately owned land in the CFR. This is the first such assessment for a substantial privately-funded initiative in South Africa.

Attempts to reduce the extent of plant invasion on Vergelegen Estate between 2004 and 2015 have achieved substantial success. Dense invasions have been reduced from 73 to 8 % of the area, but the cost was much greater than what was originally envisaged (R 49 vs. 12 million), and populations of IAPs remain, albeit at lower densities than at the start of operations. The experience at Vergelegen has clearly demonstrated the complex nature of the social-ecological environment in which IAP control projects take place, a feature that characterises most similar projects elsewhere (Roura-Pascual *et al.*, 2009; Woodford *et al.*, 2016). The problems that confront private landowners are not substantially different from those faced by projects implemented by Working for Water (WfW) on public land in the CFR. Key problems include the lack of foundational knowledge on which to base estimates of the cost of achieving long-term goals; the lack of effective methods to control IAPs; the fluctuating nature of funding due to competing demands for scarce resources; the occurrence of unplanned events, especially wildfires; and unforeseen complications, such as the generation of large amounts of woody biomass. The goal of achieving sustainable control may require a focus on priority areas, leaving others unmanaged (van Wilgen *et al.*, 2016). One feature of the Vergelegen case that distinguishes it from similar operations in the region was the existence of a formal management plan, and a commitment to auditing the plan, that has been absent from state-funded control operations in the CFR to date (van Wilgen *et al.*, 2012b). The sustained financial support from the land-owner made it possible to reduce the level of invasion on Vergelegen. Most landowners in the CFR do not have the resources that were allocated to the project at Vergelegen. This begs the question of whether most private landowners will ever be able to gain control of IAPs at a landscape scale in the CFR - as they are expected to do, and are legally obliged to do in terms of regulations under the National Environmental Management: Biodiversity Act (Act 10 of 2004). Additional sources of reliable funding are urgently needed to address these problems on private land in the CFR. One solution is to implement a system of payment for ecosystem services (PES) whereby off-site users of resources and services (e.g. water) are charged a levy which could be used to support control projects in areas that generate the services (Blignaut *et al.*, 2007). If the goal of achieving control of IAPs on privately-owned land is to be achieved it is imperative to agree on, and to implement, such PES programmes.

Objective 3: *Propose guidelines for optimizing alien plant management on private land in the Cape Floristic Region based on insights from experiences at Vergelegen Wine Estate*

Chapter 4 set out to investigate the magnitude of the current invasion on Vergelegen, and to estimate the resources required to reduce the problem to a maintainable level. I looked at different scenarios based on current funding levels to help determine the best course of action.

Results show alien trees and shrubs in the genera *Acacia*, *Eucalyptus* and *Pinus* were estimated to cover 10 % of the estate at various densities in 2016. Controlling plant invasions at the scale of the operation at Vergelegen is possible, but at a significant cost to landowners (between R 6 and R 30 million). The most likely scenario of “erratic funding” at 5 and 8% spread rates predicted a total cost of four times the estimated “base cost” and could take up to 19 years to reach a maintenance level of invasion. The best scenario based on cost and time is a doubling of the current funding levels (for both 5 and 8% spread rates); under this scenario it would take 4 years to reach a maintenance level of invasion. This would not be possible since at least five years are needed to complete the full cycle of follow-up operations within each Management Unit. The current management action plan requires a minimum of 6 years to reach a maintenance phase, since we assume that initial clearing and biomass removal will take place in year 1, followed by five annual follow-up treatments. This means that at least 6 years would be required after the last initial clearing had been completed to reach a maintenance level over the whole study site. However, the cost involved with maintaining the cleared areas cannot be ignored and will need to be considered during the planning phase. The results show that maintenance phase would cost an estimated 10 % of the total clearing cost necessary to reach maintenance phase. However, the cost to maintain cleared areas may vary depending on the dominant alien species and time under invasion.

I made the following recommendations that could help to streamline IAP management and to help ensure that scarce funds are effectively applied:

- *Set clear objectives in the form of outcomes*: An outcomes-based approach with clearly defined goals is needed (i.e. to reach “maintenance phase”; to prevent loss of biodiversity or to reduce the loss of ecosystem services). This will allow control actions to be tailored to ensure that control will lead to the desired outcomes (Downey, 2010b).
- *Define the project area:* Using a standardized set of metrics to describe the extent of the invasion by (1) determining the status of the invasion by identifying the species, densities as a measure of abundance (i.e. area occupied; net infestation), age structure and delineating the area into easily defined management units by using natural and/or man-made boundaries (i.e. roads and rivers); (2) qualitative observations of current and potential impact, understanding the associated site specific impacts will help with funding motivation and prioritisation; (3) estimate the potential range that could be occupied by predicting future population growth and spread.
- *Prioritise areas for alien plant clearing (Forsyth et al., 2012)*. Private landowners often have limited funds available for clearing operations. To reduce the impact of widespread invasion on biodiversity, control programs need to be prioritised, and work needs to focus on areas where control is both achievable and likely to have the greatest benefit to native biodiversity (Downey *et al.*, 2010b). Such a site-led approach will ensure maximum benefit from the limited resources available for management of widespread plant invasion (Williams *et al.*, 2009).

- *Institute a process of independent monitoring:* Regular monitoring by independent auditors should assess progress towards outlined goals, and it should be acceptable to adapt goals or time frames if necessary. Research has revealed that such monitoring can be carried out at a relatively low cost (van Wilgen *et al.*, 2012). Monitoring will ensure effective management and that best practice techniques are implemented.

In summary, the thesis highlights the complexities of managing alien plants on privately owned land. Chapter 2 showed how agricultural development and the planting of plantations and woodlots aided in the introduction of IAPs and how natural and anthropogenic events contributed to the spread and proliferation of alien plants on Vergelegen estate. Chapter 3 then provided insight on the significant cost and management effort required to curve the impacts associated with dense stands of alien plant. It was evident from the historical study that project managers need to implement an adaptive management strategy that should be reviewed annually to allow for possible budget changes and/or a shift in prioritisation. Along with this it is clear that once clearing operations are initiated that effective biomass removal and follow-up treatments are crucial to prevent possible re-invasion. The assessment for future control in Chapter 4 suggests that achieving the goal of reaching a maintenance level would be achievable, but also that spending more sooner would reduce costs in the long run. These findings support the results made by Holmes et al. (2000) and Gaertner et al. (2012) who found that the effort required to restore native vegetation is proportional to the time that the area had been invaded, leading to a recommendation that invaded areas should be cleared as soon as possible. However, some privately-owned land might already be heavily invaded and rapid response might no longer be an option. Apart from the financial considerations, the feasibility of clearing invaded land will depend on the location of the area (Gaertner *et al.*, 2012). If the area under consideration is in a region of high conservation priority, clearing should at least be attempted in lightly-invaded areas. Heavily-invaded areas could be left until alternative funding can be found (e.g. land-user incentive). If the area is surrounded by transformed habitat (e.g. agricultural lands), then removing invasive plants to restore biodiversity may not be feasible or justifiable. In such cases, motivating for funding for clearing operations should emphasize the restoration of ecosystem processes and functions (Gaertner *et al.*, 2012). Landowners should therefore apply an outcome-based approach and focus resources on areas that will yield the best return on investment. Joint projects between land-owners and government ('land-user incentives') are crucial to ensure that the current extent and potential for further spread of IAPs in the CFR is reduced.

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