Evaluating success of an integrated control programme of *Hakea sericea* Schrader (Proteaceae) in the Western and Eastern Cape Provinces, South Africa through cartographic analysis

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Declaration

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

Signature:

Name:

Date:

Abstract

One of the most threatening factors to the biodiversity of the Cape Floristic Region is that of invasive alien organisms. A contestant for the most noxious of these fynbos threatening organisms is *Hakea sericea*. When left to grow uncontrolled, this small Australian tree forms impenetrable stands that out compete the natural vegetation. Due to the threat this plant poses, an extensive and integrated control programme was initiated to reduce its numbers to a level where it can no longer compete successfully with the indigenous flora. This control programme consists of a carefully devised slash and burn method, chemical herbicides and four biological control agents. Little literature surrounding the success of this control programme is available. Two data sets, Fugler (1979) and Protea Atlas Project 2001, recording the distribution and density of the plant at the height of its invasion and twenty two years later are compared to one another using Geographical Information System techniques. Success of control measures is reflected by: (1) a reduction of 340 135 ha in total invaded by *H. sericea*, (2) a reduction in density and (3) shifts in patterns of average rainfall, altitude, slope and aspect of the areas associated with different density categories of this species. These data provide reward for all those involved in the control programme by justifying efforts associated with the control of the invader. Furthermore, the findings of this project also highlight the value of the control programme as well as indicate how future research should be concentrated in order to perfect the programme.

Opsomming

Uitheemse indringerplante is een van die enkele belangrikste faktore wat die Kaapse Fynbos biodiversiteit bedreig. In hierdie geval is *Hakea sericea* een van die mees kompeterende spesies. Hierdie klein Australie boompie ontwikkel, indien ongekontroleerd gelaat, tot 'n ondeurdringbare digte woud wat natuurlikke plantegroei verdring. Dit is weens hierdie faktor dat ekstensiewe en geïntegreerde kontroleringsprogramme ontwikkel is om die getalle van bome na die vlakke te verlaag waar dit geen bedreiging vir inheemse flora sal inhou nie. Die kontroleringsprogramme maak onder andere van chemiese onkruiddoders, vier biologiese beheermiddels, ontbossing en beheerde brande gebruik. Min literatuur is beskikbaar oor die sukses wat verkry word met die programme. Twee datastelle elk van Fugler (1979), bevattende data oor digtheid en verspreiding van die plante 22 jaar tevore en die Protea Atlas Projek (2001) word vergelyk met behulp van Geografiese Inligtingstelsel (GIS) tegnieke. Die sukses van die beheer maatreëls word weerspieël in: (1) die totale afname van 531 229 ha to 340 135 ha ingedring deur *H. sericea*, (2) afname in die digtheid en (3) verskuiwing in die algemene reënval-, hoogte-, helling- en liggingspatrone wat geassosieer word met die verskillende digtheidskatogorieë van die spesie. Die resultate bide regverdiging vir die kontroleringsprogramme van indringerplante. Ook beklemtoon die projek die waarde van kontroleringsprogramme en dui aan waarop toekomstige navorsing moet konsentreer om die programme te vervolmaak.

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CHAPTER 1

General Introduction

1.1 Introductory remarks

This thesis is an investigation on the success of an integrated control programme, initiated in 1961 on *Hakea sericea* Schrader in South Africa. Chapter 1 covers the objectives and hypotheses related to the programme and includes an extensive literature review addressing the biology of the invader as well as the attempts for its control within the fynbos. Chapter 2 is a self-contained paper that highlights the findings of a cartographic analysis of the control programme. The main objective of this analysis was to quantify the success associated with the control programme by applying geographical information techniques. Chapter 2 has been written in paper format for submission to *The South African Forestry Journal.* Due to the nature of chapter 2, certain information has been repeated in chapters 1 or 3. Chapter 3 contains concluding key messages and recommendations for future research as well as the possible errors associated with the research. This thesis has been written for a broadly defined audience including conservation biologists, foresters, private landowners and those involved in biological control. The findings of which can be viewed as feedback to all previously involved with the programme and as a directional tip to those associated with future control programmes.

The underlying theme of the thesis is conservation of natural ecosystems. The thesis case studies one of the most threatening impacts on biodiversity - alien invasion, with *Hakea sericea* being the focus. A second discipline, Geographical Information Systems (GIS), is neatly tied into the study. This modern day technique allows for precise analysis of environmental state without tedious paper work previously required. The result is a digital automatically computed answer to conservation and physiographic questions associated with the control programme.

1.1.1 Broader Context

Invasive alien organisms are one of the major threats to global diversity (Pimm et al. 1995). In South Africa, one of the most successful invaders to the sclerophyll vegetation type known as fynbos is *Hakea sericea* Schrader (silky hakea, needlebush, or "naaldeboom"). *Hakea sericea* is a shrub or a small tree 2–5 m in height (Gordon, 1993). The genus *Hakea* belongs to the subfamily Grevilleoideae of the family Proteaceae that are well represented in Australia and South Africa (Fugler, 1983). *Hakea sericea* is native to south-eastern

Australia but has become naturalized in the Western and Eastern Cape Provinces of South Africa since its introduction to Cape Town in 1833 (Fugler, 1983; Neser and Fugler, 1983). The success of *H. sericea* as an invader to the Cape Fynbos ecosystem can be largely attributed to the serotinous nature of the plant that allows for seed release to occur only after the parent plant has died (Morris, 1989; Kluge and Neser, 1991). Approximately 7 500 of these high longevity seeds can be found in $1m^2$ of the ash bed following a fire (Kluge and Richardson, 1983; Gordon, 1993). Thus the plant is pre-adapted to the fire regime that occurs naturally in the fynbos. The introduction of the plant to South Africa without the introduction of its natural enemies has further favoured the proliferation of the plant.

The plant forms dense impenetrable stands in mountain catchment areas and conservation areas of fynbos (Van Wilgen and Richardson, 1985). This high level of infestation causes a significant reduction in indigenous species diversity (Macdonald and Richardson, 1986), surface water resources (Versfeld and Van Wilgen, 1986) and the aesthetic, recreational and scientific value of indigenous plant communities (Kruger, 1981). Furthermore, the added biomass results in an increased fire hazard (Van Wilgen and Richardson, 1985). By 1937, approximately 100 years after its introduction, *H. sericea* had been declared a noxious weed. Contradicting literature sources reveal that at the height of the problem, the plant had invaded between 480 000 ha and 960 000 ha of fynbos (Kluge and Richardson, 1983; Richardson, 1984).

Present control measures include mechanical (including burning), chemical and biological control. Mechanical control consists of felling stands of mature plants, or of felling and burning the subsequent crop of seedlings the following year. This method is effective but costly and difficult on rough mountain terrain (Fenn, 1980). The second attempted method was chemical control. However, this method was not sufficiently successful and it now seems unlikely that any significant reduction of *H. sericea* could be achieved by the use of herbicides (Kluge and Neser, 1991). Biological control is successfully applied as a compliment to mechanical control, or as the only viable method of control on privately owned farmland. This form of control was first introduced in 1962 (Kluge and Neser, 1991) with the use of seed-attacking insects introduced from Australia. These insects were 1) *Erytenna consputa* Pascoe, a weevil which destroys developing fruits of *H. sericea* and 2) *Carposina autologa* Meyrick, a moth which destroys the mature, woody fruits. In 1979 the biological control programme was supplemented with the introduction of 3) *Cydmaea binotata* Lea, an insect targeting vegetative plant parts also introduced from Australia. In addition the bark attacking indigenous fungus, 4) *Colletotrichum gloeosporioides* (Penz.) Sacc. was first identified in 1969 to kill plants, and was subsequently developed as a mycoherbicide to be applied to either mature plants (Morris, 1983) or seedlings (Morris, 1989). The success of the fungus has not been evaluated, though a number of workers have recorded high levels of mortality in stands of *H. sericea* caused by this fungus (Richardson and Manders, 1985; Gordon, 1993).

Although extensive literature surrounding the history, ecology and biology of the plant exists, there are few data on the success of the elaborate control programme that has been implemented. Success refers to both a reduction in the size of the land invaded by *H. sericea* as well as a reduction in the density of the plant. It is generally accepted that where sufficient effort has been applied, the plant is now under control and that there has been an overall reduction in the land covered by the invader. However, this reduction has not been adequately quantified. The main objective of this thesis is to quantify this success not only by determining reduction in land covered or reduction in density, but also by clearly highlighting the shifts in the average physiographic feature values associated with certain density categories. The features considered were average annual rainfall (mm), altitude (m above sea level), slope and aspect. It is important to note that the main objective is not to establish whether or not the distribution or density of the plant is determined by physiographic factors. Richardson (1984) found that geology, rainfall and altitude all influenced the distribution of the plant but that its distribution was independent of aspect. In this thesis, the overlaying of these features is merely to act as alternative qualitative figures whose shift between the years can be used to highlight the success of the control programme. The second objective is to highlight the areas where the control programme has been most successful and direct future research to concentrate on determining the reasons for the varying levels of success. This thesis would thus act as a baseline study for the perfection of the programme.

1.1.2 Data Sources

Three data sources were used for baseline data for this research project. Two of them, Fugler (1979) and data from the Protea Atlas Project were used to create the two temporal comparative distributions and densities of the *H. sericea* while the third source, Richardson (1984) was used to indicate possible factors influencing the control outcomes.

1.1.2 a) Fugler, S.R. 1979.

Fugler (1979) mapped the entire distribution of three hakea species (one of which being *H. sericea*, the other two being *H. gibbosa* (Sm.) Cav. (rock hakea) and *H. suaveolens* R.Br. (sweet hakea) which have both been declared noxious plants but are not as widespread as *H. sericea* and have not been considered in this project) across the then Western, Southern and Eastern Cape. Information on the distribution and densities was obtained from (1) data collected by colleagues and members of the South African Mountain Club (2) a hakea questionnaire to determine the occurrence and infection levels of the pest plant and (3) surveys of the South Western Cape. Fugler (1979) divided his study area into one minute square grid cells and assigned a density category to each cell. Four density categories were defined, i.e. absent (0), scattered individual plants (3), thicket of plants less than 1 hectare (2) and a thicket of plants more than 1 hectare (1). Note the somewhat confusing order of increasing infestation levels: 0<3<2<1. Finally, Fugler (1979) produced a *H. sericea* distribution map as an overlay of the South Africa 1: 500 000 topographical sheets SE 35/17.5 Kaapstad, E 35/24 Port Elizabeth and SE 35/20 Oudtshoorn. This 1979 distribution and density map formed the baseline data to this thesis. This distribution is often referred to as the 'uncontrolled' distribution of the invader in this thesis. Theoretically however, this is not true considering that moderate control had begun as early as 1961 (Annecke and Neser, 1977). However, when compared to the 2001 distribution where control over the entire study area is evident, the 1979 data set seems to resemble an uncontrolled distribution.

1.1.2 b) Protea Atlas Project

In November of 1991, the Protea Atlas Project was launched at the initiative of the Botanical Society of South Africa and supported by the National Botanical Institute. The project was financially sponsored by the Department of Environmental Affairs and Tourism and World Wildlife Fund South Africa. The Protea Atlas Project was formally concluded in 2001 and culminated in the production of a fully comprehensive "Atlas of Proteas" within the Cape Floral Kingdom that was handed over to the National Botanical Institute for posterity (Forshaw, 2003).

One of the 1779 species recorded was *H. sericea* (Forshaw, 2003). Atlassers recorded the degree of infestation of or approximate number of individuals in an area with a radius of 500 m. The degree of infestation (density categories) occurred along a similar intensity scale as that of Fuglers' (1979) data: absent (0), dead plants only, 1-10 individuals were recorded as the precise number, 10-100 individuals (Frequent), 100-10 000 individuals (Common) and >10 000 individuals (Abundant). To ensure comparable data sets, areas that contained 1- 10 individuals were clumped into the Frequent class. Additionally areas of dead plants were assigned the 0 category based on the assumption that if that area had been surveyed at a later time, no plants would have been found thus the present yet dead plants are only temporary even without any further anthropogenic or biological intervention.

This project resulted in a database indicating co-ordinates, species, collectors' name and infestation levels. These data were used to create the second time-dated distribution and density overlay of *H. sericea*. Together with that created by using Fuglers' (1979) data, comparisons between the density and distribution of the plant over 22 years was made possible.

1.1.2 c) Richardson, D.M. 1984.

In 1984, Richardson carried out a related project. His objective was to determine which physiographic features influenced the spread of the pest plant. He obtained the spread of *H. sericea* in the then Western Cape based on that completed by the Directorate of Forestry in 1977. According to these data the plant was found to cover a total area of 960 000 ha. A grid was then overlaid on the distribution and the following information was recorded for 10, randomly selected points per quarter degree square: presence/ absence of hakea spp., altitude, aspect, geology and mean annual rainfall.

Results revealed that geology, rainfall and altitude all influenced the distribution of the plant while hakea distribution was independent of aspect. Considering that rainfall, altitude and aspect all fall along a continuum of numerical values, these features were identified as physiographic features relevant to this thesis, which could reflect on the success of the control program. This will be further explained in section 2.2. In addition, slope was identified as a possible feature to reflect control success. A shift in geology cannot be measured in numerical terms and geology was thus not included as a feature.

1.1.3 Objectives and research questions

The project aims to identify changes in the distribution and level of infestation of *H. sericea* across the Western and Eastern Cape Provinces over a 22-year (1979 – 2001) period. In addition, it is hoped that shifts in average values of certain physiographic features can be highlighted to further indicate the scale of these changes.

The project aims to emphasise the successes and failures of the control programme that has been described. Therefore, it is an explanation for what has occurred and not necessarily a forecast of what can occur. It is important to remember that the non-occurrence of a species at a given site does not necessarily mean that the species is unable to exist there (Shaughnessy, 1980). The absence of the plant could be historical rather than ecological as Richardson (1984) showed to be the case in the two natural breaks in the *H. sericea* spread defined by Fugler (1979). Therefore, areas with absent density categories are only relevant for that specific period of time. Furthermore, it is important to realise that the possibility for these areas to have present values in the future still exists. This realisation is vital when considering present / absent physiographic comparisons. The precise value of average physiographic features on areas where *H. sericea* is absent and the difference between this value and the equivalent value of areas where *H. sericea* is present is not important as such. However the difference between these two values between two dates is very indicative of the success of the control measures.

Along with the broader objectives, the following key questions were addressed:

- How much land was covered by *H. sericea* in 1979 and 2001? How much of each density category?
- Has the density of *H. sericea* been reduced, and how much land has been cleared of this species?
- Is there a pattern between the 1979 or 2001 distribution and densities and the rainfall, altitude, slope or aspect?

- Is there a pattern between the success of the control program and the rainfall, altitude, slope or aspect?

This project aims to provide a holistic overview of the current status of *H. sericea* regarding its persistence as an invader to the Cape and the degree of difficulty associated with controlling the pest. It also aims to contribute to the understanding of the management of hakea invasions in Mountain Fynbos vegetation.

1.1.4 Hypotheses

Hakea sericea has been described as a persistent invasive weed (Baker, 1965) with properties enforcing and supporting further invasions by the plant. However, as early as 1863, serious and dedicated attempts at the control of *H. sericea* have been initiated and at times, successfully executed. Based on these two assumptions, the following hypotheses have been formulated, i.e.,

> *H1: The total land infested by* H. sericea *and its overall infestation levels within the Eastern and Western Cape Provinces have been reduced over the past 22 years.*

> *H2:* Hakea sericea *has inhabited new areas outside of its' 1979 distribution.*

It was assumed that control of the plant began with the targeting of areas which experienced the highest infestations, i.e. density category 1. These areas generally occurred in the out-of-reach and out-of-sight areas such as mountain peaks. Mountain peaks have the highest rainfall, altitude and slope. Therefore shifts in the average value of physiographic features such as rainfall, slope, and altitude associated with these areas will be greater than those of light infestations, i.e. density category 3. From this assumption we derive the next hypotheses, i.e.,

> *H3: The average value for physiographic features associated with density category 1 will be lower in 2001 than in 1979.*

> *H4: Highest densities of uncontrolled 1979 distribution occur in highest rainfall, altitude and slope areas.*

> *H5: Highest success will occur in those areas which had the highest infestation levels in 1979.*

It is difficult to predict what has happened to the averages associated with density categories 2 and 3, however, with a reduction of the average value associated with category 1 (the upper extreme) and the average value of category 0 (the lower extreme) expected to remain constant, we can form the following hypothesis:

H6: The physiographic feature range of infestation has decreased over the 22 years.

1.2 Literature Review

1.2.1 Taxonomy

Hakea sericea Schrader, common name needlebush, naaldeboom, speldboom or silky hakea (previously referred to as *H. acicularis* (Vent.) R.Br. and *H. tenuifolia* (Salisb.) Domin.), belongs to the genus *Hakea* which is endemic to Australia and contains about 140 species (Wrigley, 1979). The genus was named after a German patron of botany Baron Christian von Hake (1745-1818) (Neser, 1968; Australian National Botanical Gardens, 2002) while its species name is after the Latin word for silky, 'sericeus' (Fugler, 1979). *Hakea* belongs to the subfamily Grevilleoideae, together with all the other Australian Proteaceae and one South African genus, *Brabejum* (Fugler, 1983). All other South African Proteaceae belong to the subfamily Proteoideae (Kluge and Neser, 1991).

1.2.2 Description

H. sericea is an erect, single-stemmed, woody evergreen shrub or small tree which can grow to a height of 2-5 m (Gordon, 1993). It has needle-like leaves approximately 6 cm in length that are usually leathery and rigid (Fugler, 1979; Australian National Botanical Gardens, 2002). The plant has cream coloured inflorescences which are composed of one to several narrow curved flowers on short stems in the wide angle of the leaves (Australian National Botanical Gardens, 2002) and woody follicles or fruits (20-25 mm in diameter), each of which contains two winged seeds (Neser and Fugler, 1983), and remains on the plant for several years (Fugler, 1979).

1.2.3 Autecology

Regeneration of *H. sericea* growing within South Africa occurs solely from seed. The plant is serotinous and the winged seeds are held in woody follicles until the parent plant dies (Morris, 1989; Kluge and Neser, 1991). Fire is usually responsible for the death of the plant and the release of the accumulated seed store (Kluge and Neser, 1991). The majority of the seeds fall close to the dead parent plant, resulting in the establishment of dense daughter stands. However, on occasion a few seeds (perhaps one seed per million (Richardson, 1994)) are dispersed by wind and thus create satellite foci consisting of isolated shrubs found kilometres away from the nearest dense stand. These satellite foci radiate and ultimately join to form extensive, dense even-aged stands (Dyer and Richardson, 1992). Following seed release, germination occurs rapidly and the first viable seeds are produced after two years. The pollination ecology of *H. sericea* has not been well studied in South Africa. All that is known is that the flowers are frequented by bees and flies that are thus probably the major pollinators (Dyer and Richardson, 1992).

1.2.4 Natural Distribution

H. sericea of Australia is distributed (Figure 1.1) around the Ballarat-Melbourne Dandenong- Geelong area and the coastal regions from Cape Coran east to Mallacata Inlet and then north to Twofold Bay; from Cape Smoky along the coast to Grafton, in detached highlands and coastal dividing ranges. The plant also occurs at a few isolated localities around Goulburn and the Grampians and on Flinders Island in the Bass Strait (Fugler, 1979).

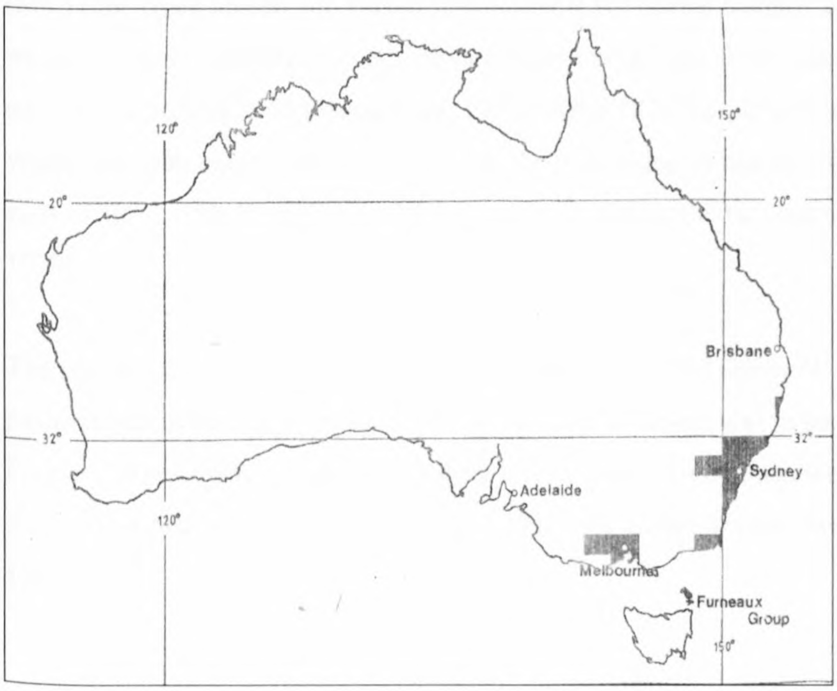

Fig. 1.1. Natural distribution of *Hakea sericea* in Australia , adapted fom Fugler (1979).

The annual rainfall of these areas exceeds those of South Africa and ranges from 600 mm in the south-west to 2 250 mm in the north-east. The vegetation is eastern, sub-tropical and temperate rain forest that contains eucalypt hard woods, tree-ferns, palms and epiphytes (Fullard, 1967). The soils are mainly derived from sandstones and quartzite with low levels of nutrients (Richardson, 1994). The area experiences intense fires approximately every 15 years.

The species *H. sericea* has many forms in Australia (Neser, 1968). It is believed that the type form of the pest plant introduced to South Africa originated from Botany Bay, near Sydney in New South Wales (Annecke and

Neser, 1977; Kluge and Neser, 1991). The environment in the Sydney area is sufficiently similar to the Western Cape Province of South Africa thus enabling *H. sericea* to proliferate when introduced in the absence of its natural enemies (Neser, 1968). Two biotypes occur in South Africa. One of which is widespread while the other occurs in relatively confined areas of the Eastern Cape Province (Kluge and Neser, 1991).

1.2.5 Introduction to South Africa

The earliest record of *H. sericea* growing within South African borders dates back to 1833 and Baron C.T.H. Von Ludwig (Fugler, 1979; Sheather, 2003). Baron Von Ludwig established the Ludwigsburg Gardens in Cape Town in 1831 which consisted of exotics from all over the world. One of these exotics to be introduced two years later was *H. sericea*. Later in 1847, John Montagu planted *Hakea* (including *H. sericea*, *Hakea gibbosa* (Sm.) Cav. (rock hakea) and *Hakea suaveolens* R.Br. (sweet hakea)) along with some other notorious Australian weeds, as dune stabilizers along the new road being built from Cape Town through Bellville that was being covered by drifting sand (Mossop, ca. 1927). After 1875 the plant was planted as hedges to keep animals out of young pine plantations and as firewood in the processing of raisins (Neser and Fugler, 1978). By the 1880's, *H. sericea* along with *H. gibbosa* were being distributed by the two main forestry nurseries in Cape Town (Fugler, 1979).

The registered history of the plant as a pest began in 1863 when *H. sericea* started to encroach onto valuable pasturelands in Bathurst (Philips, 1938). This encroachment was to such a degree that 63 years later, the Knysna Farmers' Association requested that the plant be claimed a noxious weed (Philips, 1938). This was done in 1937 in terms of proclamations 161/1938 and 171/1940 of the Weeds Act, No 42 of 1937 (Phillips, 1938; Fugler, 1983).

1.2.6 Noxious weed

Dispute surrounding the extreme extent of the invasion is evident in the literature. According to Kluge and Richardson (1983), almost 480 000 ha of mountain fynbos of the then south and south-western Cape were affected by *H. sericea* infestations. Richardson (1984) however elevates this total to 960 000 ha for the entire Western Cape, based on *Hakea* infested areas mapped by the Directorate of Forestry. The general distribution of the pest plant in 1992 is shown in Fig. 1.2. Currently *H. sericea* is found in most of the water catchments areas and many mountainous conservation areas (Fugler, 1982). Small infestations have been monitored in Transkei and Northern Kwa-Zulu Natal (Kluge and Neser, 1991) however they are not considered to be a problem in these areas.

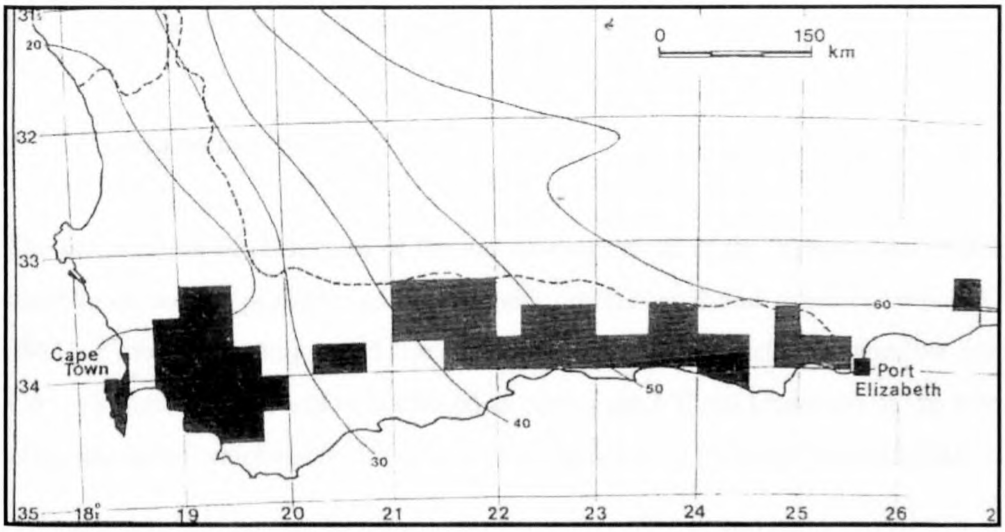

Fig. 1.2. The distribution of *Hakea sericea* in the Western and Eastern Cape Provinces, South Africa (From Dyer and Richardson, 1992). The isolines (20-60) indicate the percentage of annual rain falling in the summer (October to March). The dashed line encloses the fynbos biome.

The success of *H. sericea* as an invader of the Cape (as well as New Zealand and Portugal (Dyer and Richardson, 1992; Australian National Botanical Gardens, 2002)), has been attributed to an array of special adaptations. Some of these include: the plants' ability to produce large numbers of seeds (7,5 million seeds per hectare according to Kluge and Richardson, 1983; Gordon, 1993) in the absence of its natural enemies (Neser, 1968); the seeds are protected by woody follicles and released *en masse* after fire (Fugler, 1983; Kluge and Neser, 1991); the high seed longevity in the canopy (Neser, 1968; Gordon, 1993); efficient dispersal of winged seeds by wind (Hall, 1979; Gordon, 1993); high germinability (Richardson and Van Wilgen, 1984); rapid germination of high proportion of the seeds (Richardson and Van Wilgen, 1984); high nutrient content of the seeds (Mitchell and Allsopp, 1984); and a lack of competition from the low-growing fynbos vegetation (Kluge, 1984).

Baker (1965) describes the plant as a major weed claiming that the species has adaptations to enable individual plants to thrive in a variety of habitats. He suggests that their populations contain plants with 'general-purpose genotypes' that can build populations immediately. Secondly, if major weeds remain in a particular habitat for sufficient lengths of time, they may be selected for closer match with the environment that once again increases their chance of survival within the habitat. As a result, the South African genotypes are now very different to any examined so far in Australia (Dyer and Richardson, 1992; Richardson, 1994). Furthermore, within its natural habitat, *H. sericea* displays fairly different ecotypes, which is an indication that the species is predisposed to rapid genetic adjustment which once again aids invasion (Dyer and Richardson, 1992).

1.2.7 Problems associated with Hakea sericea

1.2.7.1 Conservation problems

The colonization of *H. sericea* of the mountainous areas of the Western and Eastern Cape has brought about a cascade of serious problems to the aesthetic, recreational and scientific value of fynbos vegetation (Kruger, 1981). Fynbos is a unique and threatened sclerophyllous vegetation type that forms a substantial part of the Cape Floristic Region, which is classed as one of the 6 floral kingdoms of the world. It is home to about 8600 plant species of which approximately 70% are endemic to South Africa (Marshall, 2001).

H. sericea forms abundant populations in only a few generations. This tendency to dominate the vegetation results in the elimination of the indigenous communities trying to survive beneath the *hakeas* (Fugler, 1983; Klein, 1999). This results in a drastic reduction in diversity, ranging from genes to ecosystems, of the indigenous plant communities (Macdonald and Richardson, 1986; Higgins *et al,* 1999). It has been found that the invasion of aliens can reduce native plant species richness by 50-86% (Richardson *et al*, 1989) as well as increase the recruitment failure of the dominant functional plant types found in fynbos (Higgins *et al*, 1999) and therefore significantly threaten the plant diversity of fynbos.

1.2.7.2 Effects on catchment water supplies

The conversion from low plant communities such as fynbos to tall communities such as forest results in a decrease in streamflow (Kruger, 1977a). *H. sericea* is only considered to be a small tree. However, because of the dense stands that the woody plant forms, reductions in streamflow are comparable to that experienced by forests (Fugler, 1983; Versfeld and Van Wilgen, 1986). The dense stands formed by the plant also increase evapotranspiration from the catchment areas (Neser and Fugler, 1978).

The Working for Water Programme (WfW) of the Department of Water Affairs and Forestry was launched in 1994 (Klein, 1999) to combat alien invasions. This programme's main aim is to safeguard South Africa's water resources by employing thousands of jobless people to clear the water catchments areas and watercourses of high water-requiring alien invaders such as *H. sericea*.

1.2.7.3 Effect on fire hazard

Since *H. sericea* stands contain a greater proportion of coarse flammable fuels than fynbos species, the potential for blow-up fires is increased in areas where *H. sericea* dominates (Kruger, 1977b; Versfeld and Van Wilgen, 1986). *H. sericea*, together with the invasive pines of the fynbos, increases biomass by up to ten times that of native vegetation thereby substantially increasing the intensity of the fires to a possibly detrimental level for the indigenous communities (Marshall, 2001). The increased intensity of fires kills the indigenous seeds while stimulating germination of *H. sericea* seeds. Hotter fires also alter the chemical properties of the soil, causing a water-repellent layer that contributes to flooding and mudslides (Marshall, 2001).

The Ukuvuka Operation Firestop campaign was created with the key objective to combat the alien plant invasions that have made the Cape's wildfires progressively more dangerous (Marshall, 2001). By doing so, the campaign creates job opportunities. The model program also hopes to unify diverse communities in and around the city and in rural areas, to conserve mountain parkland and to encourage nature sensitive urban planning (Marshall, 2001).

1.2.8 Control Programmes

Approximately 100 years after *H. sericea* was introduced to South Africa, the plant was proclaimed a noxious weed (Phillips, 1938). However, no formal action to control the weed was taken until the 'Hakea Conference' in 1961 when an interdepartmental committee was formed which proposed various procedures for control of all the hakeas (Annecke and Neser, 1977). Since then, three methods of control have been introduced, i.e. mechanical, chemical, and biological control agents, i.e. *Erytenna consputa* (*Hakea* fruit weevil), *Carposina autologa* (*Hakea* seed-moth), *Cydmaea binotata* (*Hakea* leaf weevil) and *Colletotrichum gloeosporiodes* (indigenous pathenogenic fungus).

1.2.8.1 Mechanical control methods

Since the 1940's, various attempts at mechanical controlling of the weed were undertaken (Kluge, 1984). However, many of these attempts failed due to a suite of common mistakes (Fugler, 1983; Kluge, 1984). Some of these errors included cutting down of the plant above the lowest green leaves thus enabling survival; failing to burn the stands before fruit production by seedlings; failure to follow-up, identify and remove survivors after burning; and a lack of continuity and co-ordination between the involved parties (Fugler, 1983).

In 1976 the Department of Forestry began a thoroughly devised mechanical control programme (Fenn, 1980) which was termed the 'fell-and-burn' method (Fenn, 1980; Fugler, 1983; Richardson and Van Wilgen, 1984; Kluge and Neser, 1991) and has since become the conservation policy (Kluge and Richardson, 1983). The programme runs as follows: The mountainous fynbos areas are divided into management units ranging from 100 ha to 1000 ha. These units are referred to as compartments and their sizes are dependant on the terrain and degree of alien infestation (Fugler, 1983). All *H. sericea* plants are cut down before burning by using a combination of slashers, bowsaws, beenhooks, chainsaws and mechanical bush cutters (Le Roux, 1978). The cut plants are left to lie for 12 to 18 months which provides sufficient time for fruit on the dead plants to release their winged seeds. Considering that the cut plants are lying low to the ground, and that the seeds are distributed by wind, the chance of the seeds being transported considerable distances are low. Soon after the seeds have germinated, but before they have fruited, the compartment is burnt and all seedlings are subsequently destroyed. Every two years after the fire, the compartment is searched and all surviving seedlings are carefully pulled out by hand. This task, known as 'follow-up' is considered to be the most arduous of this control method (Le Roux, 1978).

Mechanical control has been considered to be extremely effective and has yielded positive results. Between the years 1976 and 1979, 13 376 ha in the Western Cape Forestry Region had been cleared (Fenn, 1980) and a year later 17 267 ha from the then Southern Cape Forestry Region had been cleared of *H. sericea* (Fugler, 1983). However, along with the benefits are the ecological risks or dangerous issues associated with mechanical control measures such as these. Firstly, with the treatment of government owned lands, adjacent privately owned lands act as a source for recolonisation by *H. sericea* (Fenn, 1980; Kluge and Neser, 1991). Regulations have been imposed requiring property owners with land adjoining conservation areas to clear their land of hazardous vegetation which has protected a portion of this land (Marshall, 2001). Secondly, the costs involved with the programme can be extensive (Kluge and Neser, 1991) and the areas infested with these dense impenetrable *H. sericea* stands are often located in inaccessible locations making eradication difficult and time consuming. A third risk relates to the increased biomass that the cut plants add to the environment. These plants serve as fire fuel and result in intense fires, which could prove to be detrimental to the indigenous fynbos vegetation (Richardson and Van Wilgen, 1986).

1.2.8.2 Chemical control methods

It seems unlikely that any significant reduction in the proliferation of *H. sericea* can or will be due to herbicides. The dense impenetrable stands of *H. sericea* mostly occur in the mountain catchment areas. Generally streamflow from the mountains is used for agriculture and as drinking water and introducing chemicals to these areas could prove to be hazardous and should therefore be avoided whenever possible

(Fugler, 1983). The application of these chemicals to the awkward terrain in which *H. sericea* occurs makes the spraying of chemicals from both the ground and the air difficult (Kluge and Richardson, 1983; Kluge and Neser, 1991). Other than that, the development of herbicides is both costly and time-consuming (Kluge and Neser, 1991). Stricter regulations regarding herbicide properties have also placed financial risk on companies that develop herbicides. As a result, fewer herbicides are produced and they tend to have a broad-spectrum effect rather than being specific (Kluge and Neser, 1991). Nevertheless, attempts have been made at producing an effective herbicide. Fugler, 1983 has reported that Roundup (Glyphosate) trials were unsuccessful but Garlon (triclopyr) achieved satisfactory results on plants 1-2 m tall. Both these herbicides are broad spectrum and expensive and have ecological impacts and as a result, neither are widely applied. Currently tebuthiuron remains the only product registered against the weed (Kluge and Neser, 1991).

1.2.8.3 Biological control methods

In 1960, F.J. Simmonds of the Commonwealth Institute for Biological Control proposed that biological control may be affective against *H. sericea* in South Africa (Annecke and Neser, 1977). This proposal was further supported by the 'Hakea Conference' held in Stellenbosch during February 1961 (Kluge and Neser, 1991). The initial aim of the biological control programme was to use insects (seed-attacking) to slow the spread of the *H. sericea* and to reduce its aggressiveness to a level where indigenous plants would be able to compete with it (Kluge and Neser, 1991).

To support the mechanical control of *H. sericea* or ultimately eventually replace the 'fell-and-burn' method of control, the biological control programme was initiated. This was the first biological control programme in South Africa whose inception was not influenced by other countries (Kluge and Neser, 1991). The programme was initiated by the Department of Agricultural Technical Services in the early 1960's when Webb left for Australia in search of a controlling agent (Annecke and Neser, 1977; Kluge, 1984; Kluge and Neser, 1991). Neser (1968) contributed to the work and found that in areas where seed attacking insects were absent, *H. sericea* produced large amounts of seed. The destruction of large numbers of seed in perennial plants is usually of little value as a biological control (Fugler, 1983). However, *H. sericea* reproductive system is similar to that of annual or biennial weeds because the fruits are retained on the parent plant and released *en masse* only once the plant has died. Furthermore, the *H. sericea* does not reproduce vegetatively and has no persistent seed bank (Kluge and Neser, 1991) therefore, the destruction of large amounts of seed could be considered as a useful control method (Neser, 1968) and the focus was placed on finding an agent responsible for doing just that. This was a world first in which a perennial weed was targeted for control by using a seed-attacking biological control agent (Kluge and Neser, 1991).

Considering that seed-attacking insects show a high degree of specialization (Neser, 1968) and that none of the South African Proteaceae has fruits similar to the *H. sericea*, the release of seed-attacking insects was considered safer than the release of vegetative consuming agents (Fugler, 1983). After thorough testing to ensure their safety and specificity to *H. sericea* only, three biological control agents have been released (Kluge, 1984; Kluge and Richardson, 1983).

1.2.8.3 a) Erytenna consputa Pascoe (Curculionidae: Erirhininae)

In 1972, the first biological control agent to successfully establish against *H. sericea* in South Africa was released (Gordon, 1993). This seed-feeding insect was employed to reduce the number of seed released from the plant after fire. The weevil, *Erytenna consputa* Pascoe (Curculionidae: Erirhininae) destroys the immature fruits of *H. sericea* by tunnelling into the succulent, developing fruit. In the course of its development a larva can destroy three young fruits (Kluge, 1984). The adults, which are a mottled, reddish-brown colour and measuring 4-5 mm in length (Kluge and Neser, 1991), further damage the plant by feeding on succulent leaves, flower buds, young fruit and the flowers themselves (Neser and Annecke, 1973; Kluge, 1984; Kluge and Neser, 1991).

The success of the *E. consputa* as a biological control agent is enhanced by the behaviour adaptation of the females egg-laying synchronized with the brief period each year (August to October) when the developing fruits are suitable for larval development (Kluge, 1984). A second adaptation is development of the ovaries which is initiated by a chemical substance, peculiar to *H. sericea*, which is taken up by the females during feeding. No amount of feeding on other plant species will induce egg development (Kluge, 1984). This is the mechanism of specificity of the insect. *E. consputa* weevils are also well-adapted to cope with fire and can live for up to three years which is rather unusual for weevils (Kluge and Neser, 1991). This is necessary to ensure the survival of these weevil populations between fires since *H. sericea* can take 18 months after post-fire germination to once again produce fruit (Kluge, 1984).

E. consputa is responsible for causing a significant reduction in seed production which in turn should reduce the need for follow-up work. It also prevents the build-up of seed on isolated plants, or on plants in inaccessible places which reduces the aggressiveness of the weed (Fugler, 1983).

In a study on a mountain slope at Goudini in the Western Cape, where 20 adults were released in 1975, fruit loss increased from 39% to 81% between 1979 and 1981, 86% of which was attributed to *E. consputa* (Kluge and Siebert, 1985; Kluge and Neser, 1991; Richardson, 1994). Natural abortion was considered to be responsible for the remaining mortality factor (Kluge and Neser, 1991). At another site where fruit set of hakea was monitored over three years, fruit production had reduced by 82%, mainly as a result of *E. consputa* attack (Kluge, 1984).

Reduced success levels of the insect could very well be attributed to one of two factors. Firstly, climatic maladaptation: This occurs when insects are transfered from a natural/ favourable climate to an unnatural/ unfavourable climate and the functioning of the insects is negatively impacted on and thus declines. Secondly host plant incompatability which refers to the applications of incorrect strains of the insect to incorrect strains of the pest plant (Kluge and Neser, 1991).

However, considering that there is debate on the minimum percentage seed loss required in order for the biological control agents to lower the seed bank to a suitable level and that in some cases this level has been determined to be as high as 99.9%, a second biological control agent was introduced in 1972, i.e. *Carposina autologa.*

1.2.8.3 b) Carposina autologa Meyrick (Lepidoptera: Carposinidae)

Neser (1968) found the Hakea seed-moth *Carposina autologa* Meyrick (Lepidoptera: Carposinidae) on naturally growing *H. sericea* plants in Australia. This insect was employed in 1970 to supplement *E. consputa* by destroying the mature, woody fruits of the *H. sericea* (Gordon, 1993; Kluge and Neser, 1991). Although resultant seed destruction is not severe, it nevertheless contributes to the control of the invader (Gordon, 1993). Its biology has been described by Neser (1968). In autumn, the adults emerge, mate and lay eggs on the surface of the mature fruit. Several weeks later, during winter, the eggs hatch and the neonates explore the suture on the adaxial surface of the fruit, after which they tunnel through the surface into the seed cavity. Although more than one egg per fruit may be laid, the larvae are cannibalistic and the result is only one developed egg per fruit. Both seeds are required for larval development. During the forth and fifth instars, the larva prepares an exit tunnel which the prepupa uses to escape from the fruit before pupating in a cocoon in the soil.

The success of *C. autologa* is further enhanced by a few special adaptations. Larval development in the fruits of the *H. sericea* is completed by mid-summer, so that the pupae are buried in the soil during late summer when the fires are most common. As a result, the phenology of the insect ensures that it is adapted to surviving fires. Furthermore, the egg-laying habits and larval penetration behaviour provide evidence for the specificity of the insect to *H sericea* (Kluge and Neser, 1991). The moth is also able to disperse by making use of the wind (Gordon, 1993).

Attempts to establish *C. autologa* colonies began with the releasing of moths onto caged plants and by placing neonates onto fruits in the field (Kluge and Neser, 1991). It was soon realised, as was in Australia, that the neonates' mortality was high and thus their application as such, futile (Neser, 1968; Kluge and Neser, 1991). Neonates needed to be placed within the fruits in order to be effective. Currently, the most effective method is to insert larvae into holes drilled in the fruits (Gordon, 1993).

Experiments were undertaken at two sites near Stellenbosch in the Western Cape; Paradyskloof and Knorhoek. By counting the number of emergent holes on the fruits found in these plots, Gordon (1993) was able to determine the level of activity and success of the *C. autologa* as a control agent. It was found in 1990 that the average number of fruit attacked for Paradyskloof and Knorhoek had increased to 51.7% and 36.8% respectively, nine years after the release of the insect. The total mean seed destruction for the two sites was 64.2% for Paradyskloof and 50.6% for Knorhoek. The mean number of fruits attacked per tree increased over the study period, while the mean number of healthy fruits per tree decreased (Gordon, 1993).

1.2.8.3 c) Cydmaea binotata Lea (Curculionidae: Erirhininae)

More recently a safe yet less conservative approach was taken on 30 November 1979 by introducing vegetatively attacking insects (Kluge and Neser, 1991). The first of these was a leaf-boring weevil, *Cydmaea binotata* Lea., which was released first at Devon Valley near Stellenbosch in the Western Cape Province (Kluge and Neser, 1991). The use of *C. binotata* was primarily aimed at the destruction of seedlings of *H. sericea* and to cause damage to the plant by enhancing the infection rates of fungal pathogens (Neser, 1968; Kluge and Neser, 1991).

Small adults (2-3mm) mostly occur on the growing parts of the plant where they feed on the succulent leaves stems and buds. Throughout the year, the eggs are laid in excavations in the leaves or sprouting buds. The larvae tunnel down the leaves or distal sections of soft stems. This stage can prove to be the most damaging stage. Pupation occurs in a flimsy cocoon just below the surface of the soil. Adults can cause slight damage by feeding on leaves and buds (Kluge and Neser, 1991).

Although *C. binotata* is not specific only to *H. sericea*, it is non-the-less considered adequately specific with adult feeding, egg laying and larval development being restricted to some species in the genus *Hakea* (Kluge and Neser, 1991).

Laboratory studies have shown that the insect can significantly suppress seedling growth by reducing leaf production and root development (Kluge and Neser, 1991). The feeding damage also makes the plant more susceptible to attack by pathogens. However, the success of the insect in the field seems to be somewhat dismal and the reasons for the low establishment rates need to be investigated. *C. binotata* has made no obvious reductions in the density of *H. sericea* seedlings (Kluge and Neser, 1991).

1.2.8.3 d) Colletotrichum gloeosporioides (Penz.) Sacc.

Several plant pathogens have proved useful as biological control agents of weeds (Morris, 1991). An endemic fungus identified as *Colletotrichum gloeosporioides* which attacks the vegetative parts of *H. sericea* was initially identified by Taylor (1969). A more intensive study on the fungus was started in 1980. Common symptoms on affected plants include stem and branch lesions, from which copious amounts of gum exude, and a progressive die-back of shoot tips. On stems and branches, the bark around a lesion may be killed but the wood does not seem to be harmed. Plants may die if lesions occur in lower regions of main stems and the fungus girdles the stems (Morris, 1991). Even when the plant is not killed, growth and fruiting are limited.

The disease occurs widely and is common in areas infested with *H. sericea*. Areas with more than 90% of the hakea naturally infected or dead due to *C. gloeosporioides* have been found in the Western Cape Province (Fugler, 1983). The Eastern Cape biotype of the *H. sericea*, has been found to be less vulnerable to *C. gloeosporioides* than the widespread biotype of the plant which dominates the Western regions of the Cape (Morris, 1991).

Various methods of inoculating plants have been attempted. These include: wound inoculation, the use of spore-coated leaf pellets fired from a shotgun, and spraying a spore suspension from a helicopter-mounted spray apparatus or a knapsack-sprayer (Morris, 1983). All methods have been considered successful although results varied somewhat, however, not all are feasible or cost-effective on a large scale (Morris, 1989). The method of application which appears to be most promising is the application of a dried preparation of fungal-colonized wheat bran pieces. When this dried formulation was applied over two seasons at a rate of 10 kg ha^{-1} in the Western Cape Province, a mortality ranging between 30% and 98% was calculated after 4 months (Morris, 1989; Morris, 1991). Inoculation in May or June resulted in a mortality of 93-98% while inoculations made later in the rainy season resulted in a much lower mortality (30-36%). Disease development down the seedling stems appeared to end as warmer, drier summer conditions occurred and healthy side branches often became dominant. This indicates that earlier inoculation with longer wet periods following germination would leave sufficient time for disease to completely cover the seedlings and the result would be higher mortality rates (Morris, 1989). It has been suggested that run-off is responsible for the carrying of spores into protected parts of the plant (e.g. shoot tips) as well as dispersing of the spores (Morris, 1989). One can therefore presume that this method of controlling young seedlings by spore suspension would be best applied during rainy weather which can be applied in the Cape where frequent periods of rain correspond with the germination and early/ sensitive development of seedlings (Morris, 1991).

Several other factors favour the application of this form of the fungus: (a) the bran inoculum retains its viability for up to 16 days when exposed to direct sunlight, it is unlikely that no rain will fall to bring about sporulation and infection for such an extended period of time in these mountains of the winter rainfall areas, (b) the fungus colonizes the bran pieces rapidly, sporulates abundantly on moistened pieces and conidia are dispersed sufficiently high from sporulating bran inoculum to infect seedling stem tips, (c) dried bran formula can be stored for four weeks at room temperature before it loses viability (Morris, 1989).

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CHAPTER 2

Evaluating success of the integrated control program of *Hakea sericea* Schrader (Proteaceae) in the Western and Eastern Cape Provinces, South Africa through cartographic analysis.

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2.1 Abstract

One of the most threatening factors to the biodiversity of the Cape Floristic Region is that of invasive alien organisms. A contestant for the most noxious of these fynbos threatening organisms is *Hakea sericea*. When left to grow uncontrolled, this small Australian tree forms impenetrable stands that out compete the natural vegetation. Due to the threat this plant poses, an extensive and integrated control programme was initiated to reduce its numbers to a level where it can no longer compete successfully with the indigenous flora. This control programme consists of a carefully devised slash and burn method, chemical herbicides and four biological control agents. Little literature surrounding the success of this control program is available. Two data sets, Fugler (1979) and Protea Atlas Project 2001, recording the distribution and density of the plant at the height of its invasion and twenty two years after control are compared using geographic information systems techniques. Success of control measures is reflected by: (1) a reduction from 191 094 ha to 340 135 ha in total invaded by *H. sericea*, (2) a reduction in density and (3) shifts in patterns of average rainfall, altitude, slope and aspect of the areas associated with different density categories of this species. These data provide reward for all those involved in the control programme by justifying efforts associated with the control of the invader. Furthermore, the findings of this project also highlight the value of the control programme as well as indicate how future research should be concentrated in order to perfect the programme.

Keywords: aliens, control programme, Geographic Information Systems, *Hakea sericea*, needlebush, silky hakea

2.2 Introduction

Invasive alien organisms are one of the major threats to global diversity (Pimm *et al*. 1995). In South Africa, one of the most successful invaders to the sclerophyll vegetation type known as fynbos is *Hakea sericea* Schrader (silky hakea, needlebush, or "naaldeboom"). *Hakea sericea* is a shrub or a small tree 2–5 m in height (Gordon, 1993). The genus *Hakea* belongs to the subfamily Grevilleoideae of the family Proteaceae that are well represented in Australia and South Africa (Fugler, 1983). *Hakea sericea* is native to south-eastern Australia but has become naturalized in the Western and Eastern Cape Provinces of South Africa since its introduction to Cape Town in 1833 (Fugler, 1983; Neser and Fugler, 1983). The success of *H. sericea* as an invader to the Cape Fynbos ecosystem can be largely attributed to the serotinous nature of the plant that allows for seed release to occur only after the parent plant has died (Morris, 1989; Kluge and Neser, 1991). Approximately 7 500 of these high longevity seeds can be found in $1m^2$ of the ash bed following a fire (Kluge and Richardson, 1983; Gordon, 1993). Thus the plant is pre-adapted to the fire regime that occurs naturally in the fynbos. The introduction of the plant to South Africa without the introduction of its natural enemies has further favoured the proliferation of the plant.

The plant forms dense impenetrable stands in mountain catchment areas and conservation areas of fynbos (Van Wilgen and Richardson, 1985). This high level of infestation causes a significant reduction in indigenous species diversity (Macdonald and Richardson, 1986), surface water resources (Versfeld and Van Wilgen, 1986) and the aesthetic, recreational and scientific value of indigenous plant communities (Kruger, 1981). Furthermore, the added biomass results in an increased fire hazard (Van Wilgen and Richardson, 1985). By 1937, approximately 100 years after its introduction, *H. sericea* had been declared a noxious weed. Contradicting literature sources reveal that at the height of the problem, the plant had invaded between 480 000 ha and 960 000 ha of fynbos (Kluge and Richardson, 1983; Richardson, 1984).

Present control measures include mechanical (including burning), chemical and biological control. Mechanical control consists of felling stands of mature plants, or of felling and burning the subsequent crop of seedlings the following year. This method is effective but costly and difficult on rough mountain terrain (Fenn, 1980). The second attempted method was chemical control. However, this method was not sufficiently successful and it now seems unlikely that any significant reduction of *H. sericea* could be achieved by the use of herbicides (Kluge and Neser, 1991). Biological control is successfully applied as a compliment to mechanical control, or as the only viable method of control on privately owned farmland. This form of control was first introduced in 1962 (Kluge and Neser, 1991) with the use of seed-attacking insects introduced from Australia. These insects were 1) *Erytenna consputa* Pascoe, a weevil which destroys developing fruits of *H. sericea* and 2) *Carposina autologa* Meyrick, a moth which destroys the mature, woody fruits. In 1979 the biological control programme was supplemented with the introduction of 3) *Cydmaea binotata* Lea, an insect targeting vegetative plant parts also introduced from Australia. In addition, the bark attacking indigenous fungus, 4) *Colletotrichum gloeosporioides* (Penz.) Sacc. was first identified in 1969 to kill plants, and was subsequently developed as a mycoherbicide to be applied to either mature plants (Morris, 1983) or seedlings (Morris, 1989). The success of the fungus has not been evaluated, though a number of workers have recorded high levels of mortality in stands of *H. sericea* caused by this fungus (Richardson and Manders, 1985; Gordon, 1993).

Although extensive literature surrounding the history, ecology and biology of the plant exists, there are few data on the success of the elaborate control programme that has been implemented. Success refers to both a reduction in the size of the land invaded by *H. sericea* as well as a reduction in the density of the plant. It is generally accepted that where sufficient effort has been applied, the plant is now under control and that there has been an overall reduction in the land covered by the invader. However, this reduction has not been adequately quantified. This paper's main objective is to quantify this success not only by determining reduction in land covered or reduction in density, but also by clearly highlighting the shifts in the average physiographic feature values associated with certain density categories. The features considered were average annual rainfall (mm), altitude (m above sea level), slope and aspect. It is important to note that the main objective is not to establish whether or not the distribution or density of the plant is determined by physiographic factors. Richardson (1984) found that geology, rainfall and altitude all influenced the distribution of the plant but that its distribution was independent of aspect. In this paper, the overlaying of these features is merely to act as alternative qualitative figures whose shift between the years can be used to highlight the success of the control programme. The second objective is to highlight the areas where the control programme has been most successful and direct future research to concentrate on determining the reasons for the varying levels of success. This paper would thus act as a baseline study for the perfection of the programme.

In addition to the main objectives, the following key questions were addressed:

- How much land was covered by *H. sericea* in 1979 and 2001? How much of each density category?
- Has the density of *H. sericea* been reduced, and how much land has been cleared of this species?
- Is there a pattern between the 1979 or 2001 distribution or densities and the rainfall, altitude, slope or aspect?
- Is there a pattern between the success of the control program and the rainfall, altitude, slope or aspect?

2.3 Methods

The spatial pattern of infestation at two dates (1979 and 2001) with their densities of *H. sericea* were compared. The 1979 data was derived from Fugler's (1979) *H. sericea* distribution map which was produced as an overlay on the South Africa 1: 500 000 topographical sheets SE 35/17.5 Kaapstad, E 35/24 Port Elizabeth and SE 35/20 Oudtshoorn. Fugler (1979) mapped the complete distribution and density of three hakea species (one of which being *H. sericea*, the other two being *H. gibbosa* (Sm.) Cav. (rock hakea) and *H. suaveolens* R.Br. (sweet hakea)) across what he demarcated as the Western, Southern and Eastern Cape. He divided his study area into one minute square grid cells and assigned a density category to each cell. Four density categories existed, i.e. absent (0), scattered individual plants (3), a thicket of plants covering less than 1 hectare (2) and a thicket of plants covering more than 1 hectare (1). Note the somewhat illogical order of increasing infestation level values: 0<3<2<1. A digital map indicating the distribution of *H. sericea* as well as the densities of the infestation according to Fugler (1979) was generated by placing a grid over the maps produced by Fugler (1979) and transporting from the map the latitude and longitude grid readings of the cells. These grid references and their corresponding densities were then entered into an MS-Excel© spreadsheet which were in turn transformed and imported into a GIS database of the ArcView 3.2© programme. Fugler's (1979) six adjoining analogue maps were transformed into one seamless digital version. The spatial data were recorded in vector format and saved as a so-called shapefile.

The second data set that represents the distribution and density of the plant in 2001 was obtained from the Protea Atlas Project. In November of 1991, the Protea Atlas Project was launched at the initiative of the Botanical Society of South Africa and supported by the National Botanical Institute (Forshaw, 2003). The Protea Atlas Project was formally concluded in 2001 and culminated in the production of a fully comprehensive "Atlas of Proteas" within the Cape Floral Kingdom (Forshaw, 2003). One of the 1779 species recorded was *H. sericea* (Forshaw, 2003). Data was received in an MS-Excel© spreadsheet format and included both the GPS reading of a randomly selected central point representing a circular area with radius of 500m as well as an assigned density category (the degree of infestation of *H. sericea* or approximate number of individuals). The degree of infestation was divided into six density categories, i.e. absent (0); dead plants only; 1–10 individuals recorded as the precise number; 10–100 individuals (Frequent); 100–10 000 individuals (Common) and >10 000 individuals (Abundant). In order to compare this data set to that of Fugler's (1979), areas that contained 1–10 individuals were lumped into the frequent class. Additionally, areas of dead plants were assigned to the 0 category based on the assumption that if that area had been surveyed at a later time, no plants would have been found as dead plants are only temporary even without any further anthropogenic or biological intervention. These data were imported and expressed into ArcView 3.2©. Considering that the Protea Atlas Project had many atlassers over a period of ten years, many of these points overlapped and assigned density categories did not always correspond. In such cases, the highest recorded densities were considered conservatively as the true values, as advised by Rebelo, (2003, pers. comm.). These data were also recorded as point-vector data and saved as a so-called shapefile.

A third digital overlay relating to the success of the control programme was created in the GIS. This shapefile consisted of irregular shaped polygons which were each assigned a number representing the relevant level of success of the polygon. The numbers ranged from –3 to 3 and were obtained by subtracting the 2001 density value from the 1979 density value. For this to be made possible, comparable density values were assigned to the two existing data sets (Table 2.1). This comparison was based on the general observation of Wood, (2003, pers. comm.) that a dense *H. sericea* stand consisted of individual plants growing approximately 1 m apart. Therefore in a plot of 1 hectare (10 000 m^2), one can expect approximately 10 000 individuals. Plots where *H. sericea* were absent were assigned the density value of 0. Thus an area which was reduced from Fugler's (1979) classification of 1 in 1979 to not present in 2001 would have a success value of 3. Areas of no change would have success values of 0 and areas that have experienced further infestations would be represented by negative success values.

Table 2.1. Comparisons between Fugler's (1979) density classification system and Protea Atlas' (2001) density classification system for *Hakea sericea*. The assigned density value refers to the value the density categories were assigned when determining the level of success (1979's density value – 2001's density value).

Fugler's (1979) Density Categories	Protea Atlas's (2001) Density Categories	Assigned Density Value
1- stands greater than 1 hectare	Abundant - > 10 000 individuals	3
2- stands less than 1 hectare	Common - between 100 and 10 000 individuals	2
3- scattered individuals	Frequent - less than 100	1
0 - absent	0- absent	0

Four environmental shapefiles representing rainfall, altitude, slope and aspect were then separately overlaid on to the three previously described shapefiles in order to address the research questions. General rainfall patterns indicated the average annual rainfall for the entire country over a period of 50 years. Altitude, aspect and slope were all deduced from a Digital Elevation Model (DEM) for Western Cape Province with points taken at 80 m apart.

Considering that both data sets claim to have plotted the entire distribution of *H. sericea* in the Western and Eastern Cape Provinces, all areas where no densities are recorded were regarded as free of the plant and assigned a density category and value of 0. To obtain sample areas that could be used to compare with those where the plant was present, a sample area was randomly selected. This area was the smallest possible rectangle encompassing the recorded distribution of the invader falling within the extent of the DEM. The DEM shapefile stretched as far East as Cape St. Francis and thus includes all except for one infestation in the extreme eastern parts of the Eastern Cape. In addition, the rectangle lay entirely within the borders of the Western and Eastern Cape Provinces and excluded as much of the Karoo as possible. This resulted in the limiting of the northern dimension of the sample area and the exclusion of one small infestation NW of Ceres. Alternative study areas could be defined by vegetation or geology or rain patterns, however, to select these study areas would mean that one would assume that the spread of *H. sericea* is influenced by these criteria.

Statistical analysis was not considered necessary for two reasons (Kidd, 2003, pers.comm.). Firstly, theoretically the entire distribution area was sampled and considering the huge number of samples, any statistical test would indicate statistical significance no matter how slight the differences. Secondly, considering that the samples are not independent of one another and that one grid cell's density, rainfall, altitude, slope or aspect is likely to be influenced by it's bordering neighbours density, rainfall, altitude, slope or aspect, statistical analysis would not be appropriate on the entire data set.

2.4 Results

2.4.1 Distribution and density

See Appendices A and B for distribution and density maps of *H. sericea* in 1979 and 2001 respectively. Assuming that Fugler's (1979) distribution maps were correct and that the GIS techniques are reliable, the height of the infestation occurred in 1979 when *H. sericea* covered 531 229 ha of mountain fynbos. This value lies between the previously reported 480 000 ha and 960 000 ha calculated by Kluge and Richardson (1983) and Richardson (1984) respectively. This total area decreased to almost one third by the end of 2001 (Table 2.2).

Table 2.2. Total area (ha) of fynbos infested by *Hakea sericea* in 1979 and 2001 respectively as well as the total area covered by different density categories. Fugler's (1979) categories 1, 2 and 3 are comparable to Protea Atlas' density categories of Abundant, Common and Frequent respectively. Differences in total and the sum of individual density totals can be attributed to projection noises encountered in ArcView 3.2©.

Density Category	1979	2001
3 / Frequent	254 789	140 521
2 / Common	154 419	43 291
1 / Abundant	121 736	4500
Total	531 229	191 094

See Appendix C for success map. In total, 392 114 hectares of land experienced a reduction in density of *H. sericea* while 107 192 hectares of land experienced further infestation of the plant (Table 2.3). A small amount of land (31 929 ha) showed no change.

Table 2.3. Total area (ha) experiencing varying degrees of success of the control programme against *Hakea sericea*. Values 1 to 3 represent success of control measures and a reduction of *H. sericea* density for the area with 3 being the maximum success, i.e. from 1/ abundant in 1979 to absent in 2001. Negative values represent further infestation with –3 being the maximum level of further infestation/ negative success, i.e. from absent in 1979 to 1/ abundant in 2001. Areas that experienced no change are assigned the 0 level of success.

Level of Success	Description	Areas in hectares
3	Positive: decrease by 3 density categories	98 067
2	Positive: decrease by 2 density categories	131 983
1	Positive: decrease by 1 density category	262 063
0	No Change	31 929
-1	Negative: increase by 1 density category	84 839
-2	Negative: increase by 2 density categories	19 912
-3	Negative: increase by 3 density categories	2 441

2.4.2 Physiographic Features

2.4.2.1 Rainfall

A substantial difference (230 mm) occurs between the annual rainfall of those areas where *H. sericea* were recorded in 1979 and those areas where the invader was considered absent in 1979 (Table 2.4). This difference decreases slightly in 2001 as the average annual rainfall of areas where *H. sericea* is present decreased by approximately 28 mm per year.

Table 2.4. The average experienced rainfall (mm) per annum over the last 50 years for those areas covered by the different densities of *Hakea sericea*. Average present refers to the average annual rainfall in mm for all areas where *H. sericea* was present, i.e. 3/ frequent, 2/ common and 1/ abundant.

Density Category	1979	2001
Absent	860	885
3/ Frequent	1051	1018
2/ Common	1164	1126
1/ Abundant	1066	1073
Average Present	1090	1061

Although the mean rainfall of all areas that had infestations of any density was higher than that of the areas where *H. sericea* was absent, the expected pattern of an increase in density occurs with an increase in rainfall was not apparent in either data sets. Instead a pattern was mirrored in both the 1979 and 2001 data sets whereby average rainfall of density category 2/ Common > density category 1/ Abundant > 3/ Frequent > areas absent of *H. sericea*.

When describing patterns observed with the success data set, the data can either be used as a continuous data set indicating varying degrees of success ranging from negative through to positive success, or as a discrete data set indicating areas of success (positive success), further infestation (negative success) and no change. When looking at the continuous data (Figure 2.1), a slight upward curve can be seen indicating that areas experiencing greatest success have higher average annual rainfalls. More convincing would be to analyse the discrete data which reveals that positive success areas experience higher average annual rainfall (1 112 mm $year^{-1}$) than negative success areas (1 021mm $year^{-1}$), whilst those areas where no change in density was experienced having the highest average annual rainfall of 1 133 mm $year^{-1}$.

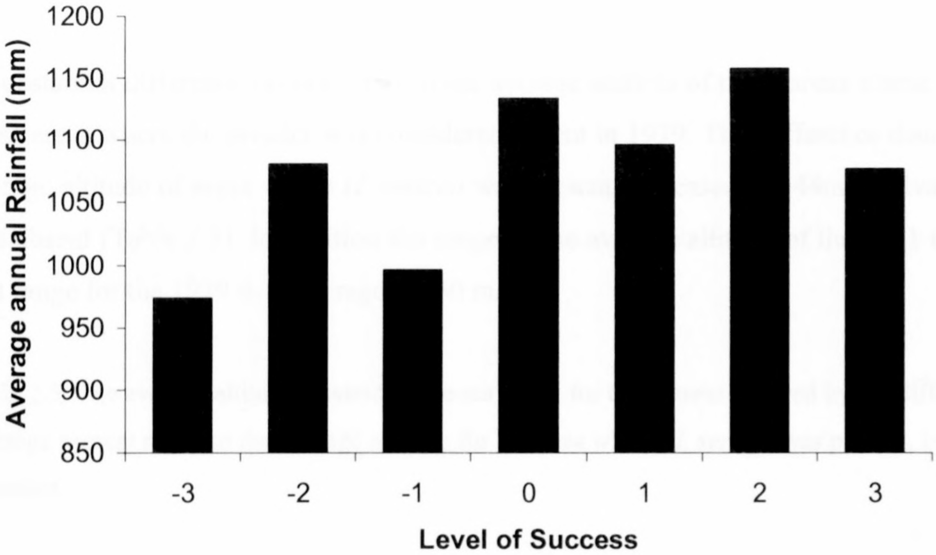


Fig 2.1. Average annual rainfall (mm) of areas that experienced varying levels of control success. Values 1 to 3 represent successful control measures and a reduction of *Hakea sericea* density with 3 being the maximum success, i.e. from a 1/ abundant in 1979 to absent in 2001. Negative values represent further infestation with –3 being the maximum level of further infestation/ negative success, i.e. from absent in 1979 to 1/ abundant in 2001. Areas which experienced no change in density are assigned the 0 level of success.

2.4.2.2 Altitude

A substantial difference occurs between the average altitude of those areas where *H. sericea* were recorded and those areas where the invader was considered absent in 1979. This difference disappears entirely in 2001 as the average altitude of areas where *H. sericea* was present decreased to 544m, equivalent to that where the species was absent (Table 2.5). In addition the range of the average altitude of the 2001 data set is only 21 m whereas that range for the 1979 data average is 160 m.

Table 2.5. The average altitude (meters above sea level) for those areas covered by the different densities of *Hakea sericea*. Average present refers to the average altitude for all areas where *H. sericea* was present, i.e. 3/ frequent, 2/ common and 1/ abundant.

Density Category	1979	2001
Absent	536	544
3/ Frequent	696	549
2/ Common	669	528
1/ Abundant	652	534
Average Present	678	544

A definite pattern is revealed when overlaying both continuous and discrete success data sets with average altitude. The continuous data set indicates that the level of success of the control measures increases as the average altitude increases (Fig. 2.2). The discrete data set reveals that further infestation occurs on average at 465 m above sea level (masl), positive success occurs at 681 masl and areas of no change occur in between these two values at 659 masl, an altitude virtually equal to that of areas which experienced positive success.

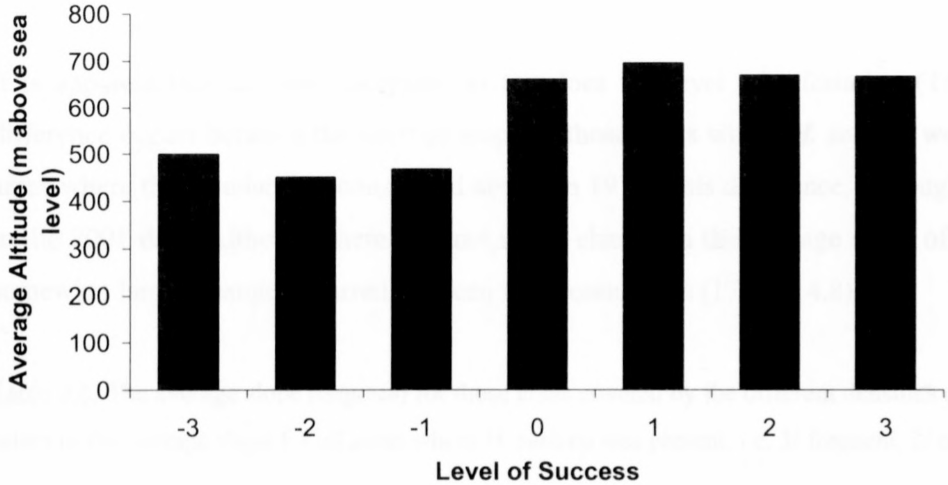


Fig 2.2. Average altitude (m above sea level) of areas that experienced varying levels of control success. Values 1 to 3 represent success of control measures and a reduction of *Hakea sericea* density for the area with 3 being the maximum success, i.e. from a 1/ abundant in 1979 to absent in 2001. Negative values represent further infestation with –3 being the maximum level of further infestation/ negative success, i.e. from absent in 1979 to 1/ abundant in 2001. Areas which experienced no change in density are assigned the 0 level of success.

2.4.2.3 Slope

It is apparent that as slope increases so too does the level of infestation (Table 2.6). Once again, a clear difference occurs between the average slope of those areas where *H. sericea* were recorded in 1979 and those areas where the invader was considered absent in 1979. This difference, although reduced, is represented again in the 2001 data. Although there was not much change in the average slope of the absent plots (7.7 – 8.2), a somewhat larger change occurred between the present plots (17.9 – 14.8).

Table 2.6. The average slope (degrees) for those areas covered by the different densities of *Hakea sericea*. Average present refers to the average slope for all areas where *H. sericea* was present, i.e. 3/ frequent, 2/ common and 1/ abundant.

Density Category	1979	2001
Absent	7.7	8.2
3/ Frequent	17.5	14.8
2/ Common	18.5	14.8
1/ Abundant	18.1	14.4
Average Present	17.9	14.8

A definite pattern is revealed when comparing both continuous and discrete success data sets with average slope. The continuous data set indicates that the level of success of the control measures increases as the average slope increases (Fig. 2.3). The discrete data set reveals that further infestation occurs on average on a slope of 12.5°, positive success occurs on a slope of 18.0° and areas of no change occur in between these two values on slopes of 17.7°, a slope virtually equal to that of those areas which experienced positive success.

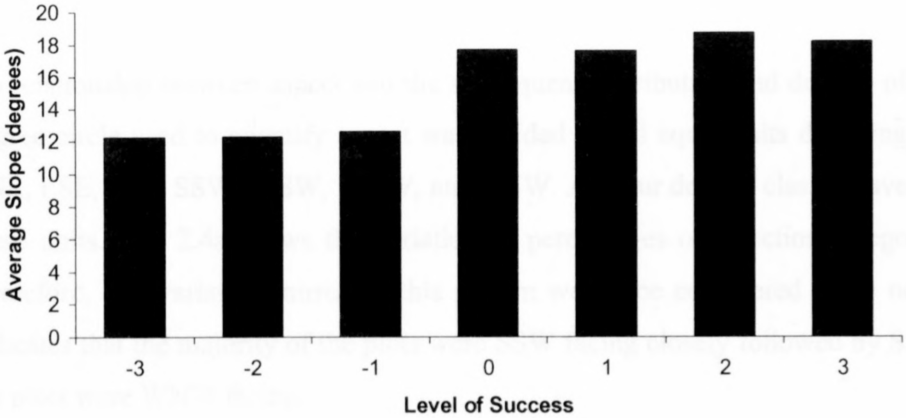
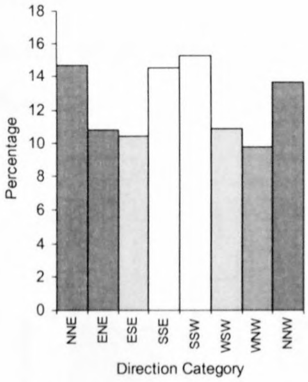


Fig. 2.3. Average slope (degrees) of areas that experienced varying levels of control success. Values 1 to 3 represent success of control measures and a reduction of *Hakea sericea* density for the area with 3 being the maximum success, i.e. from a 1/ abundant in 1979 to absent in 2001. Negative values represent further infestation with –3 being the maximum level of further infestation/ negative success, i.e. from absent in 1979 to 1/ abundant in 2001. Areas which experienced no change in density are assigned the 0 level of success.

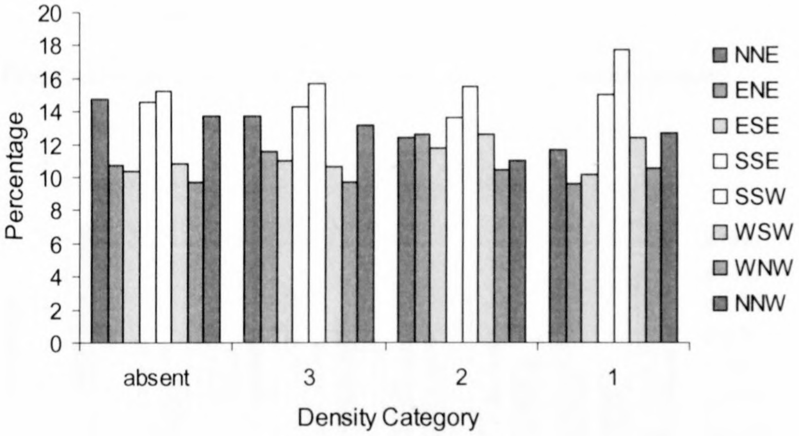
2.4.2.4 Aspect

No relationship between aspect and the subsequent distribution and density of *H. sericea* was found. The 360 degree circle used to quantify aspect was divided into 8 equal units depicting the following directions: NNE, ENE, ESE, SSE, SSW, WSW, WNW, and NNW. All four density classes have ranges extending across all 8 of these units. Fig. 2.4a shows the variation in percentages of direction categories for the entire sample area. Therefore, any variation mirroring this pattern would be considered to be normally distributed. The pattern indicates that the majority of the plots were SSW facing closely followed by SSE facing plots. The minority of the plots were WNW facing.

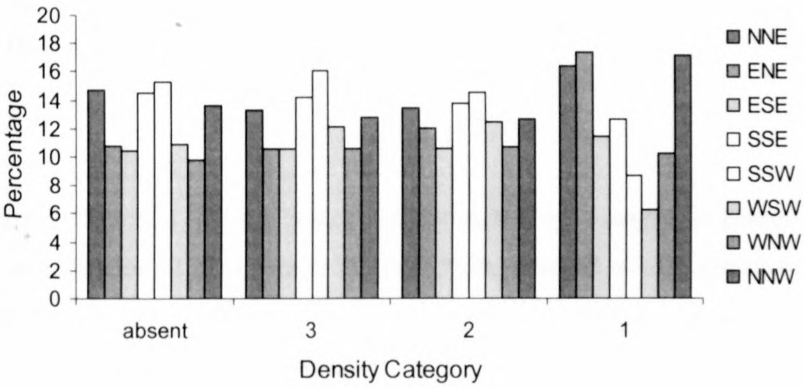
Plots in 1979 (Fig 2.4b) absent of the plant or experiencing density classes 2 or 3 all have their majority of records in the SSW direction and their minority in the WNW direction. However plots of density class 1 have their majority in the SSW direction with their minority in the ENE direction. This general pattern is somewhat altered when viewing the 2001 (Fig 2.4c) results where SSW remains the dominant direction for plots absent of the plant or experiencing density classes 2 or 3 but drops to be the second least for plots experiencing density category 1. In addition, the overall change in the variation of direction category percentages for each density category between dates, increases with an increase in the density of the plant with the most change occurring on plots with density category 1. All variation curves except for that of density category 1 in 2001 can be likened to that of the entire sample plot.



a) Distribution of sample plots with regard to their direction category.



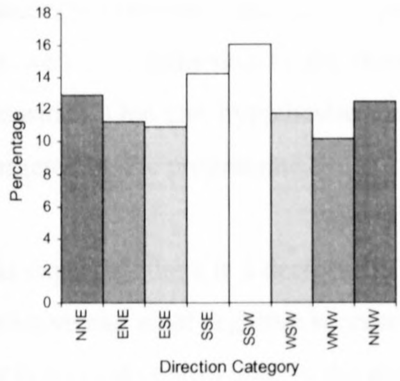
b) Direction categories per density category- 1979



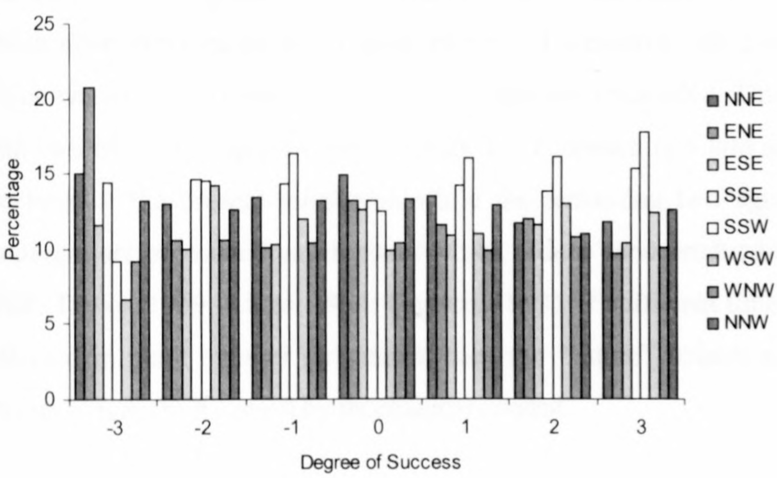
c) Direction categories per density category- 2001

Fig 2. 4. Percentage of density categories of *Hakea sericea* in each direction category for (a) entire sample area, (b) 1979 and (c) 2001. The shade intensity of the colours act as an indication of the intensity of the light experienced at each direction category with the darkest colour representing exposure to most light and the lightest colour exposure to the least.

Direction category percentages for each degree of success can be seen in Fig. 2.5. Areas of success are mostly facing SSW and SSE direction while areas of the highest further infestation (-3) are mainly facing ENE direction.



a) Distribution of success plots with regard to their direction category.



b) Direction categories for each degree of success.

Fig 2. 5. Direction category percentages for each of the 7 degrees of control success. The shade intensity of the colours act as an indication of the intensity of the light experienced at each direction category with the darkest colour representing exposure to most light and the lightest colour exposure to the least. Any pattern in 2.5b resembling that of 2.5a, experiences a normal distribution.

2.5 Discussion

2.5.1 Distribution and density

Success of the integrated control programme is evident in both the reduction of total land invaded by *H. sericea* as well as a reduction in the densities of the invasion, with the greatest reduction occurring in the highest densities. One can hypothesise that it was these heavily infested areas which were first and most efficiently targeted by the programme.

As expected, there is a decrease in total land as one radiates from areas of no change towards areas of the most positive and most negative success. This variation in success could be attributed to either ownership of the land or type(s) of control used in the area. It is likely that areas which experienced negative success or no change are privately owned lands which never initiated the control programme but instead became a refuge for hakeas eradicated from neighbouring government owned and controlled lands. We can further hypothesise that areas which have experienced the cocktail of control measures will have higher levels of success than those areas which were only mechanically or only biologically controlled. This is because the mechanical control together with two of the biological control agents, i.e. *Cydmaea binotata* and *Colletotrichum gloeosporioides* removes the bulk of the present infestation while the remaining two agents, i.e. *Erytenna consputa* and *Carposina autologa*, are reproduction inhibitors which reduce seed production and thus future infestation levels (Neser, 1968; Taylor, 1969; Kluge, 1984; Gordon, 1993). If sufficient time has passed and the seed reduction has been reflected in plant number reductions, then the "future" reduction caused by biological controls adds to the "present" reduction caused by mechanical control.

2.5.2 Physiographic features

The non-occurrence of a species at a given site does not necessarily mean that the species is unable to exist there (Shaughnessy, 1980). The absence of the plant could be historical rather than ecological as Richardson (1984) showed to be the case in the two natural breaks in the *H. sericea* spread defined by Fugler (1979). Therefore, areas with absent density categories are only relevant for that specific period of time and the possibility for these areas to have present values in the future still exists. This realisation is vital when considering present / absent physiographic comparisons. The precise value of average physiographic features on areas where *H. sericea* is absent and the difference between this value and the equivalent value of areas where *H. sericea* is present is not important as such. It is the relative size of the difference between these two values between two dates that is indicative of the success of the control measures. Nevertheless, although *H. sericea* is able to grow across the full spectrum of rainfall, altitude, slope and aspect, the infestation levels did increase with rainfall, altitude and slope. This difference in absent / present values for both 1979 and 2001 values could be explained by the fact that *H. sericea* tends to grow in the mountainous areas (high rainfall, altitude and slope) which are generally unsuited for cultivation or urbanisation. These infestations thus go relatively unnoticed. If these infestations had to encroach on economically potential land, it is likely that they would receive even more urgent attention (Richardson, 1984).

2.5.2.1 Rainfall

The slight difference between the average associated rainfall of plots absent of *H. sericea* in 1979 and 2001 can perhaps be attributed to the fact that Fugler (1979) tended to focus more on the mountain conservation areas (MCA) (i.e. the wetter areas). However, this is minor in comparison to the overall picture of hakea growing in wet areas and is not believed to have a large enough effect on the patterns experienced.

The difference between the average rainfall of absent and present plots decreased substantially in 2001 implying that the range for presence is decreasing. However, due to the heavy infestations attracting the most attention, it was hypothesised that this decrease would be reflected by a decrease in the value associated with density category 1/ Abundant, which was not the case in this scenario. Rather, the slight increase observed could be the result of the elimination of many heavy infestations occurring in wet areas and the persistence of a few heavy infestations remaining in even wetter, more inaccessible areas such as valleys. This would explain the increased average rainfall for all density category 1/ Abundant infestations.

The trend between success and rainfall indicates that the highest infestations, which occurred in areas of highest rainfall in 1979, were the first and most efficiently targeted infestations and thus reveal the highest level of success. A more definitive analysis would require an overlay on type(s) of control used. Dispersal of the indigenous fungus, *C. gloeosporioides* is by means of the medium water (Morris, 1989). Thus it can be hypothesised that the more moist compartments experienced a better dispersal of the fungus and thus higher levels of biological control success than the drier compartments. This could be the stronger explanation for the higher level of success in higher rainfall areas.

2.5.2.2 Altitude

The uncontrolled spread of *H. sericea* (i.e. 1979 distribution) displayed heavy infestations associated with higher altitudes where they could grow unnoticed. This lead to the targeting of these areas and as a result of anthropogenic control at these higher altitudes, the infestations have descended and this is reflected by the reduction in overall altitude associated with the infestations. The reduction in the range and the 118 m drop of average altitude value for density category 1/Abundant over the 22 years further support these findings. However, the pattern created by evaluating the differences of values over the 22 years shows a decreasing difference as density increases. The hypothesised pattern would show the most difference in the density category 1/ Abundant. This deviation between the hypothesised and observed patterns can be attributed to the fact that as altitude increases, the percentage of unattainable land due to extreme steep slopes and thus uncontrollable infestations increases. This percentage acts as a penalty in lowering the full potential of success for these areas.

Success rates in the higher altitudes exceed the success rates in the lower altitudes. An overlay on land ownership might prove to be the more correct explanation for this experienced pattern. Considering that the majority of mountain ranges are government owned, and that government owned lands are expected to be more efficiently controlled, we could expect the success rates of these areas to be higher.

2.5.2.3 Slope

Slope is autocorrelated with altitude, therefore similar patterns are expected when analysing slope and distribution and density of the plant or the success of the control programme as we did when analysing that of altitude. Average slope values of infestation decreased over the 22 years. Slope reveals the ideal results with a reduction in the extreme upper limit and an increase in the extreme lower limit indicating concentration of control measures across the complete range of terrain slope.

The success pattern closely resembles that formed by altitude and success. The fact that areas of no change generally occurred in areas of high altitudes and steep slopes where the highest level of success was also recorded, supports the notion that inaccessible and thus persistent infestations occur in these areas. Once again, an overlay on type of control could be informative. It is likely that these inaccessible/ no change areas require biological control agents in order for their success rates to improve.

2.5.2.4 Aspect

Considering that all variation curves except for that of density category 1 in 2001 can be likened to that of the entire sample plot, we can deduce that (1) distribution and density of *H. sericea* is not dependent on aspect and (2) concentrated effort was applied to those heavy infestations which were previously facing SSW, SSE and

WSW in 1979. The control and subsequent elimination of these infestations have resulted in this deviating pattern of the variation curve of density category 1 in 2001.

Success in these three aspect direction categories further supports the above idea. Explanations other than simply more intense control application could lie in the type of control implicated. It is possible that biological control agents function better/worse and thus enhance/ retard success in certain light intensities. Once again, this could be determined by a control type overlay.

2.6 Conclusion

Quantitative measures of success of the integrated control program are evident in the reduction of total land invaded by *H. sericea* and the densities of the invasion. A secondary measure of the success is the shift in the average physiographic feature values associated with these densities over the 22 years. Valuable shifts and changing patterns indicating success of the control programme were experienced when viewing all four physiographic features, i.e. rainfall, altitude, slope and aspect.

These results do not imply that certain physiographic features lead to enhanced success but rather that variables associated with these physiographic features determine the extent of success prevalent. The first possible explanation could be that the heaviest infestations attract most attention and are thus controlled first and most efficiently. A second possible explanation is land ownership. The state-owned mountain catchment areas are vital to the water supply of South Africa, therefore it is hypothesised that greater effort was made to maintain these areas, as opposed to clearing efforts on privately owned farm-land. Thus ownership could be the fundamental reason as to why higher altitudes and rainfall have experienced higher levels of success. A third possible explanation lies in the type of control measure used. It is likely that the use of biological control in conjunction with mechanical control is the fundamental reason for higher levels of success. Although theoretically the success experienced across the Western and Eastern Cape provinces is due to a cocktail of control measures, in practice it is likely that mechanical control has carried the most weight of this success. Although success of biological control has been highlighted by the literature (Kluge, 1984; Kluge and Siebert, 1985; Morris, 1989; Gordon, 1993) the time required for this form of control to produce equal success levels as mechanical control is far longer. Therefore, it is likely that in future, the role of biological control will increase drastically as they become responsible for preventing the reinvasion of cleared land and reducing the effort required for control as well as the only form of control practised on many privately owned farms.

Although the patterns of success are clearly laid out, the underlying reasons for these observed patterns are undefined and need to be explored. Nonetheless, this project has provided evidence of a successful programme. It also highlights that further creeping of the weed onto virgin lands has occurred and that without careful control, the *H. sericea* can once again reach devastating levels.

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CHAPTER 3

Concluding Remarks

3.1 Key message

All project objectives and research questions have been answered by this thesis. It has become apparent that the integrated control programme initiated in 1961 (Annecke and Neser, 1977) to reduce the numbers of *Hakea sericea* invading the fynbos to a level at which the indigenous vegetation can compete, has been successful. Four decades of tedious effort has resulted in a less *H. sericea* infested natural landscape. This visible reduction is evident when comparing the GIS maps relating to the 1979 and 2001 invasions (Appendixes A and B respectively) which clearly highlight the reduction in both total land covered by the plant as well as the reduction in infestation levels over the 22 years. In addition to this obvious proof of success, the shifts in the average physiographic features associated with the infestations over the two time periods further support the reduction of land area to indicate success.

The control programme works by attacking highest infestations first and most effectively and then, if the resources are available, moving on to the lower densities. Thus highest success will always be prevalent in those areas where infestations were the highest and not necessarily in those areas where physiographic features equal current highest levels of success. Eg. Currently the highest success was experienced at an altitude of 664 masl (fig. 2.2), a reasonable representative of the average altitude of heavier infestations in 1979 (table 2.5). If a study is carried out with the 2001 data as baseline data and a second data set 22 years later, we can expect to find that the highest success will be experienced at an altitude somewhere in the region of 530 masl (average altitude of heavier infestations in 2001) and not 664 masl (table 2.5).

Simply by considering the dates of the relevant literature one can deduce that the importance of the plant as a pest has subsided over the last decade with the majority of attention occurring in the eighties. The literature lagged slightly behind the pathway of the invader, mirroring the increase in invasion and dissipating after the peak was reached. As stated earlier, little literature regarding the success of the program exists. However, the fact that literature regarding the plant as a pest has subsided, is also evidence that the relevance of the infestation has decreased. In this case, no news is good news.

This positive appraisal does not however imply that the invasion of the plant in South Africa is under control. It seems likely that due to the persistent nature of the plant that full control across the whole country will never prevail and that the plant will always raise awareness. The complete eradication of *H. sericea* from the fynbos biome is an unrealistic aim. Instead, the integrated control programme aims for a reduction of population levels to below a nuisance level and the reduction of the aggressiveness of the weed so that the indigenous plants are not out competed by the pest plant.

3.2 Possible sources of error

The first possible source of error in the research would be the human induced error regarding the creation of the 1979 digital distribution and density data set. As previously stated, this digital data set was produced by simply reading off of Fugler's (1979) hard copy maps. The problem might lie in the allocation of the density to the correct grid cell. Considering these maps are 23 years old it is possible that a grid cell (approximately 1.3 mm in length on the original map) could be misread by one grid cell. It is however unlikely that this slight shift of an infestation would affect the results as the overall pattern remains constant.

Secondly, it could be debated that the defined study area from which absent values were extracted does not represent the true possible distribution of the plant. Considering that no better suited alternative was available, the justification for the defined area was explained in section 2.3. Once again, however, it is not the true value which is indicative but rather the patterns experienced. It is important to keep in mind this thesis was not addressing the question: Which physiographic features influence distribution and density of *Hakea sericea*, but rather which features can be used to indicate success?

Thirdly, the validity of the data sources has not been investigated. Considering that both data sets have been through strict reviews and are available through scientific media, they, for the sake of this project, have been considered to be correct and valid. Possible problems associated with the data are: (1) it seems unlikely that the entire area was surveyed and that all infestations were recorded and (2) the different level of knowledge of different groups associated with the data collection could reflect on the data, i.e. estimating density levels for each collector will not constantly yield the same answers.

3.3 Recommendations for future research

Firstly, an overlay regarding land ownership is required to fully understand the success of the control programme carried out by the state. Presently, the possibility exists for the statistics of uncontrolled privately owned lands to dilute the overall experienced success resulting in a lower measure of success. The ownership will have to be date specific. This could pose a problem where lands have changed from government owned to privately owned or vice-versa over the past 22 years.

Secondly, it would be useful if success of the individual control measures, i.e. mechanical, chemical and biological, could be ascertained. These data will probably have to be limited to a few catchments which have retained their data regarding control on *H. sericea*. This would provide insight on which control measures prove most feasible (ecologically, economically and quantitatively). With this data, one could produce time-scale graphs indicating what would happen to an infestation over x years with y control measure. This predictive tool could prove to be very useful in future control programmes.

Finally, with the overlay of physiographic features and type of control, a user friendly guide regarding which control should be applied to which areas could be created for foresters and private land owners or conservationists. This would result in maximum benefits with minimum resource allocation.

3.4 References

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Appendix A

Appendix B