Scotch broom (*Cytisus scoparius* (L.) Link) and gorse (*Ulex europaeus* L.) in South Africa: An assessment of invasiveness, management options and feasibility for countrywide eradication

by

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As the candidate's supervisor I have/have not approved this dissertation for submission.

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Abstract

Ulex europaeus L. (gorse) and *Cytisus scoparius* (L.) Link (Scotch broom) are widespread invaders worldwide, and were first recorded in South Africa during the 1930s and 1940s, respectively. This study investigated the current distribution, population size and structure and the reproductive biology of both species in the country. The study further investigated post-harvest seed biology and seed bank characteristics of these species. The response of Scotch broom to wildfire was also investigated, and the seed and seedling responses to elevated temperatures were determined for both species. The weed risk assessments were conducted and the efficacy of possible management actions were investigated. Findings from this study showed that the distribution of gorse and Scotch broom was limited to the eastern part of South Africa possibly due to limited introductory efforts. Fourteen gorse populations with a total of 3950 individual plants were identified covering 16510 m^2. Scotch broom had 46 populations with 121135 individual plants covering a total area of 97260 m^2. There was a huge variation in population size across sites for both species possibly due to different environmental conditions, propagule pressure, residence time and level of disturbances. Both species reproduced sexually and vegetatively by resprouting, and adult plants were prolific seed producers. Moreover, there was a positive relationship between seed set per plant and the growth parameters such as height, stem diameter and crown diameter. Seeds of both species exhibited physical dormancy, which required mechanical scarification or heat plus smoke treatments to break dormancy. Wildfire broke seed dormancy and promoted seedling recruitment in Scotch broom. The presence of gorse and Scotch broom in the country and the accumulated large seed banks show that these species are most likely to thrive in areas with moderate climatic conditions. Regions with elevated temperatures, however, may not be suitable for the establishment of these species because elevated temperatures retard their growth. Due to high invasive potential of gorse and Scotch broom in South Africa, an immediate management action is required. As a result, this study recommends herbicide usage and prescribed burning as these management actions can significantly reduce the above ground biomass and seed banks size, thus making the eradication possible at a later stage.

Preface

The field work described in this dissertation was conducted in three South African provinces (Eastern Cape, KwaZulu-Natal, and Free State) from June 2013 to November 2015. The experimental work was carried out in the School of Life Sciences, University of KwaZulu-Natal, Westville campus, from February 2014 to November 2015. This work was carried out under the supervision of Dr. Syd Ramdhani and the co-supervision of Dr. Sershen Naidoo and Prof. John R. Wilson.

This study represents original work by the author and has not otherwise been submitted in any form for any degree or diploma to any tertiary institution. Where use has been made of the work of others, it is duly acknowledged in the text.

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I, Philani M. Mbatha declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

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Chapter 1: Introduction

1.1. *Background*

Biological invasion refers to the ability of invasive alien species to colonise, spread and outcompete other species in ecosystems where they are introduced (Valéry *et al*., 2008). Human activities such as international air travel, trade, tourism and emigration facilitate the spread of these species across geographic regions (Lodge *et al*., 2006; Nentwig, 2007). In case of plant invasion, some alien plants are introduced intentionally as ornamentals, fodder and wood, or for medicinal purposes (Pyšek *et al*., 2002), whilst others are introduced unintentionally as contaminants (Pyšek *et al*., 2011). The invasion success of these species depends largely on their ability to overcome barriers associated with various stages of invasion, and such stages include introduction, establishment and the species spread (Blackburn *et al*., 2011).

A number of traits such as phenotypic plasticity (Bossdorf *et al*., 2005), polyploidy (te Beest *et al*., 2011) and high competitive ability (Hawkes, 2007) confer the invasion success in introduced plants. Factors such as propagule pressure, residence time, dispersal mechanisms and different forms of disturbances also determine the invasion success of other invasive plants (Hill *et al*., 2005; Richardson and Pyšek, 2006; Dennehy *et al*., 2011). Once established, some can have severe ecological and economic impacts (Pimentel *et al*., 2005; Vilà *et al*., 2011).

Many of the invasive plants are highly competitive and consume more resources such as water, light and nutrients than native plants (Williams and West, 2000). Some also outcompete native plants for pollinators (Williams and West, 2000; Morales and Traveset, 2009) and reduce the pollinator visitation rate, and hence, the reproductive success of native plants (Morales and Traveset, 2009). Others reduce diversity (Hejda *et al*., 2009), fitness and the growth (Vilà *et al*., 2011) of native plants. In other cases, these species reduce the abundance and fitness of animal species (Vilà *et al*., 2011). The high competitive ability of invasive alien plants also leads to soil erosion (Williams and West, 2000), and some have the potential to change soil chemistry (Caldwell, 2006), frequency and the intensity of wildfire (Williams and West, 2000). These plants outcompete economically important crops for resources and are sometimes toxic to cattle (Pimentel *et al*., 2005).

South Africa has a long history of plant invasions dating back to 1600s (Zimmermann *et al*., 2004; Moran *et al*., 2005). Currently, there are approximately 8750 alien plants (Wilson *et al*., 2013) covering about 10 million hectares across the country (Enright, 2000; Richardson and van Wilgen, 2004; Moran *et al*., 2005). Some of these alien plants displace native flora, reduce agricultural productivity and disrupt ecosystem functioning in various parts of the country (Enright, 2000; Le Maitre *et al*., 2000). In order to mitigate these threats, the South African National Biodiversity Institute: Invasive Species Programme (SANBI: ISP) was initiated by the Working for Water (WfW) Programme in 2008 to detect new invaders, perform post-border risk assessments and to develop and implement eradication plans if feasible (Wilson *et al*., 2013). The programme has subsequently developed risk assessments for a number of invasive plant species, and is currently implementing eradication plans for some of those (Wilson *et al*., 2013). This study, which contributes to SANBI: ISP's mandate, was designed to assess the invasiveness of *Ulex europaeus* L. and *Cytisus scoparius* (L.) Link in South Africa, and the feasibility of species management.

1.2. *Study species*

1.2.1. *Ulex europaeus* L. (gorse)

Ulex europaeus, commonly known as gorse, is native to the temperate Atlantic coast of Europe (Hill *et al*., 2001; Hill and Gourlay, 2002) and has invaded many parts of the world including New Zealand, Australia, Chile and Hawaii (Hill and Gourlay, 2002; Hill *et al*., 2008; Ireson *et al*., 2008). The plant was introduced as a garden ornamental or hedge plant (Viljoen and Stoltsz, 2007), and to stabilise highway embankments (Clements *et al*., 2001). In areas where the species is invasive, it normally invades disturbed pastures, roadsides, open sites and commercial forests (Hill *et al*., 2001).

1.2.2. *Cytisus scoparius* (L.) Link (Scotch broom)

Cytisus scoparius, commonly known as Scotch broom, is native to Europe and North Africa (Peterson and Prasad, 1998; Jarvis *et al*., 2006; Herrera-Reddy *et al*., 2012). This species has invaded many countries including Australia, New Zealand, Canada, Chile, India, Iran and Japan (Peterson and Prasad, 1998; Suzuki *et al*., 2000; Herrera-Reddy *et al*., 2012; Srinivasan *et al*., 2012). Scotch broom was introduced into these countries as a garden ornamental, hedge plant and to prevent soil erosion particularly on highway embankments and sand dunes (Peterson and Prasad, 1998; Herrera-Reddy *et al*., 2012; Srinivasan *et al*., 2012). It often invades disturbed pastures, commercial forests, roadsides and natural ecosystems (Bellingham and Coomes, 2003; Harrington, 2009).

1.3. *Rationale, aims, research questions and the significance of the study*

1.3.1. Rationale for the study

Gorse and Scotch broom are among 84 emerging invaders in South Africa (Nel *et al*., 2004), and were first recorded during the 1930s and 1940s, respectively (South African Plant Invaders Atlas [SAPIA] records, 2013). The predictive models for both species suggest that these species are most likely to occupy 23-24% of the South African regions that have moderate climatic conditions (i.e. high rainfall and cool temperature) (Mgidi *et al*., 2007). Empirical data on the physiological behaviour of both species in response to climatic change, however, are scarce. As a result, this study was conducted to determine the current invasive status of gorse and Scotch broom in South Africa, and to assess the species response to elevated temperatures as many regions of the world are predicted experience a rise in temperatures due to an increase in atmospheric CO_2 (Intergovernmental panel on climate change [IPCC], 2013).

1.3.2. Aims and objectives

The broad aim of the study was to assess the invasiveness of gorse and Scotch broom in South Africa (both of which require compulsory control as they are under Category 1a according to National Environmental Management: Biodiversity Act No. 10 of 2004) (Molewa, 2014) and the feasibility of species management. The invasiveness of both species was determined by assessing species distribution, population size and structure, reproductive biology, post-harvest seed biology, seed bank characteristics, impact of wildfires, seed and seedling responses to elevated temperatures and weed risk assessments. The feasibility of species management was assessed by determining the herbicide efficacy in selected populations of both species and the costs associated with the initial clearing.

1.3.3. Research questions

The following questions were conceived in order to determine the invasive status of gorse and Scotch broom in South Africa:

- What is the current distribution and population demography of both species?
- Which land-use types support gorse and Scotch broom?
- How does population the structure of both species compare across populations?
- What is the post-harvest seed physiology of both species?
- What is the reproductive capacity (i.e. reproductive output, germinability and seed bank size) of both species?
- How do seeds and seedlings of both species respond to elevated temperatures?
- How do established Scotch broom plants respond to fire?
- Does each species pose an invasive risk?
- Is chemical control a feasible and realistic management action for both species?

1.3.4. Significance of the study

The data generated from this study will contribute towards SANBI: ISP's mandate to monitor and manage invasive plants as authorised in the South African National Environmental Management: Biodiversity Act No. 10 of 2004 (Molewa, 2014), also see Reyers *et al*. (2007). The data will inform SANBI: ISP of the invasiveness of gorse and Scotch broom, and the costs associated with the initial clearing. This will then enable the programme to report to relevant biodiversity stakeholders on the invasive status of both species in South Africa and implement management actions if necessary.

1.4. *Structure of the thesis*

In chapter 1, the concepts of plant invasion and the associated impacts on natural ecosystems are highlighted. Furthermore, study species are briefly introduced, and then discussed further in Chapter 2. The rationale, aims, objectives, research questions and significance of the study are also presented in Chapter 1.

A literature review on plant invasion, with specific focus on aspects covered in this study (i.e. growth form, reproductive biology and seed bank dynamics of invasive plants in native and the introduced regions) are presented in Chapter 2. The morphology, growth and reproductive characteristics of gorse and Scotch broom in other parts of the world are discussed. The impacts of climate change and fire on invasive alien plants are also discussed in Chapter 2. Additionally, different management options adopted for invasive plants and the need for habitat restoration and species reintroduction following eradication are highlighted.

The materials used and methods adopted in this study are presented in Chapter 3, while the results obtained and the trends observed are presented in Chapter 4. In Chapter 5, the results obtained are discussed by drawing on the broader literature on invasion biology. The overall conclusions and recommendations for future work are provided in Chapter 6.

Chapter 2: Literature review

2.1. *Introduction*

Humans introduce invasive alien plants into new regions intentionally for commercial or agricultural purposes or unintentionally as contaminants (Pyšek *et al*., 2002; Lodge *et al*., 2006; Pyšek *et al*., 2011). Although alien plants generally have the potential to become invasive, there are various barriers (see Fig. 2.1 [Blackburn *et al*., 2011]) to plant invasion that these plants need to overcome first. Fig. 2.1 shows a general unified framework for biological invasions proposed by Blackburn *et al*. (2011). Illustrated in this framework, are different stages in biological invasions and the barriers associated with each of them. It further provides suitable terminologies and management options applicable to invasive plants at each of the invasion stages. Casual plants, as shown in this unified framework, refers to the newly introduced plants that reproduce but fail to sustain their populations over a long period (Richardson *et al*., 2000). Introduced plants that overcome reproductive barrier, survive and have self-perpetuating populations over a long period without human interventions are referred to as naturalised plants (Richardson *et al*., 2000). Naturalised plants that overcome the reproductive and environmental barriers, produce high numbers of seedlings a distance away from parent plants, and have the potential to spread widely, are referred to as the invasive alien plants (Pyšek *et al*., 2002; Lodge *et al*., 2006).

The framework in Fig. 2.1 also shows factors that demote or promote the invasion success. For example, species labelled as A are those not transported across their native geographic range, while B1 species are transported but have containment measures put in place to prevent dispersal. B2 species are transported and cultivated but have limited measures to prevent dispersal. B3 species are those introduced and released to the environment. Some of the species released into the environment have limited survival and are referred to as C0. The ones that survive but cannot reproduce are called C1 species. C2 species reproduce but the populations are not self-sustaining while D1 species are actively reproducing with self-sustaining populations. D2 species are actively reproducing and have self-sustaining populations that are widely dispersed. E species are those that have well established populations (actively reproducing, widely dispersed at multiple sites and have high survival).

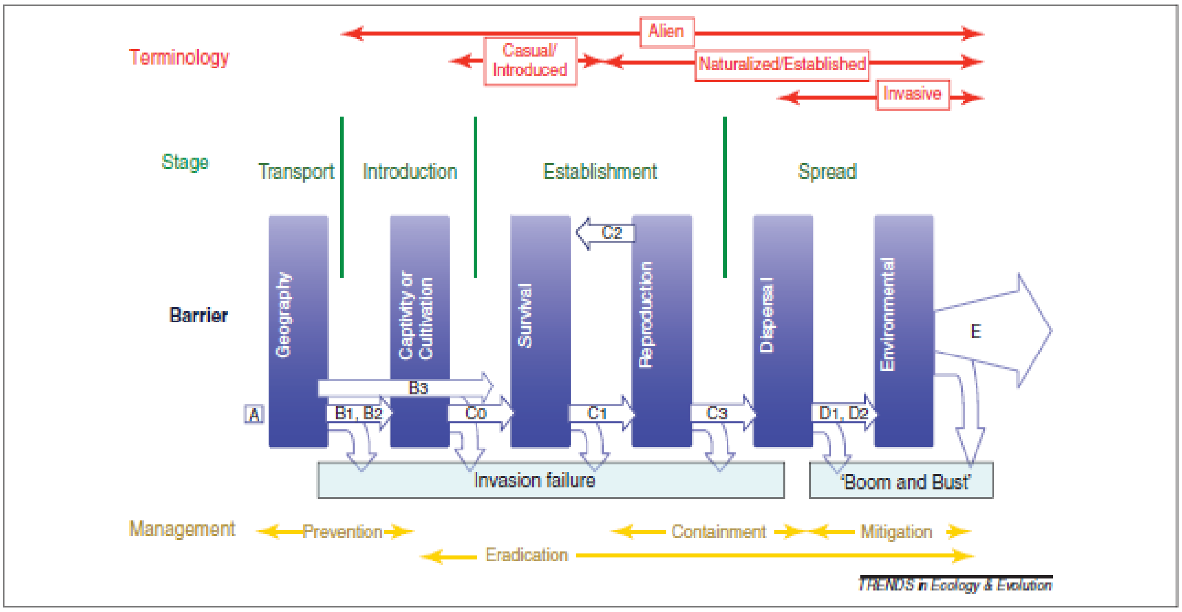

Figure 2.1: A general unified framework showing various barriers to plant invasion that alien plants need to overcome before becoming invasive (taken from Blackburn *et al*., 2011). Alien plants failing to overcome these barriers do not become invasive.

Once established, some of the introduced invasive alien plants can have negative impacts on plant biodiversity and natural ecosystems (Hejda *et al*., 2009; Vilà *et al*., 2011), and the costs associated with their management are very high (Pimentel *et al*., 2005). South Africa is one of the countries suffering from the consequences of plant invasions. Economically, the country loses approximately 6.5 billion every year due to plant invasions (van Wilgen *et al*., 2012). In 1994, the Working for Water (WfW) Programme of the Department of Water Affairs and Forestry was initiated to facilitate the management of these species (Hobbs, 2004; MacDonald, 2004). This programme has spent approximately ZAR 3.2 billion since then in attempts to manage invasive species. Some of these species, however, were not successfully managed (van Wilgen *et al*., 2012). At present, the South African Biodiversity Institute: Invasive Species Programme (SANBI: ISP) is running a range of projects looking at the post-border risk assessments in order to deal with issues of plant invasions (Wilson *et al*., 2013).

An effective management of invasive alien plants, however, requires a more fundamental understanding of the growth, ecophysiology and the reproductive biology of these plants. This can be achieved by developing comparative studies examining growth and reproductive characteristics of invasive plants in native and introduced regions (Hinz and Schwarzlaender, 2004). These studies can then give insight into causes and factors determining the invasion success (van Kleunen *et al*., 2010). As a result, this chapter discusses and compares the growth and reproductive characteristics of invasive alien plants in native and introduced regions, and the possible management options. In light of the main aims of this study, special focus is then given to gorse and Scotch broom.

2.2. *Growth characteristics of invasive plants*

The growth rate of some invasive alien plants is high in the introduced compared with native regions (Ramula *et al*., 2008). In habitats with low plant density, some invasive alien plants grow taller and survive longer (Meekins and McCarthy, 2001; Herrela *et al*., 2011).

Once established, others produce more seedlings (Herrera *et al*., 2011) and form dense stands (Beckmann *et al*., 2009) in the introduced compared with native ranges. The lack of natural enemies such as pathogens, herbivores and parasites in the introduced regions and the availability of resources promote the invasion success of these plant species (Cappuccino and Carpenter, 2005; Blumenthal, 2006). In the absence of natural enemies, natural selection allows for the selection of genotypes with high competitive ability (Blossey and Nötzold, 1995). The selected genotypes result in a shift in resource allocation, with more resources allocated to growth and reproduction than to herbivore defence. This phenomenon is referred to as the "optimum defence theory" (Blossey and Nötzold, 1995). Other studies have, however, found no evidence for rapid growth in some introduced invasive alien plants (e.g. Scotch broom [Paynter *et al*., 2003]), and this may be due to the environmental conditions not suitable for their growth.

2.3. *Reproductive biology of invasive plants*

Invasive alien plants can reproduce sexually (Suzuki, 2003), asexually by apomixis (Amsellem *et al*., 2001) or by vegetative resprouting (Witkowski and Garner, 2008). Depending on the climatic origin of introduced plants, some that reproduce sexually have either short or long flowering phenotypes (Godoy *et al*., 2009), whilst others have both (Tarayre *et al*., 2007; Atlan *et al*., 2010). Once bloomed, some of these plants undergo self-pollination (Colautti *et al*., 2010) while others depend on pollinators for successful reproduction (Stout *et al*., 2002). Several studies reported a positive correlation between self-pollination and plant invasiveness (Burns *et al*., 2011) (i.e. 66% of weed species in Canada were self-compatible) (Richardson *et al*., 2000). In North America, however, 56% of the invasive alien woody species were out-crossers (Richardson *et al*., 2000). This variation in reproductive mechanisms was also reported for 17 invasive plant species in South Africa (Rambuda and Johnson, 2004). Moreover, plants that use cross-pollination mechanism produce high fruit set and high number of seeds per fruit compared with the ones that are self-compatible (Stout *et al*., 2002; Colautti *et al*., 2010) due to high pollinator visitation rate, as many studies (e.g. Bartomeus *et al*., 2008; Vilà *et al*., 2009; Dietzsch *et al*., 2011) have suggested.

Upon fertilisation, some invasive alien plants produce more seeds in the introduced compared with native regions (Blossey and Nötzold, 1995; Rees and Paynter, 1997). Buckley *et al*. (2003) and Daws *et al*. (2007) reported that seeds produced by some invasive alien plants are large in the introduced regions compared with those produced in native ranges. Other studies have found no differences in seed size of invasive plants in native and non-native ranges (Mason *et al*., 2008). Many of these species produce dormant seeds with hard seed coats (Hill *et al*., 2001; Magda *et al*., 2013). In this regard, different scarification methods (including mechanical, chemical or smoke treatments) and stratification methods (including heat and cold stratification treatments) induce germination in seeds with hard seed coats (Williams, 1981; Bossard, 1993; Mandák, 2003; Sixtus *et al*., 2003; Pérez-Fernández and Rodríguez-Echeverría, 2003; Harrington, 2009). The time required to break dormancy in seeds with hard seed coats, however, varies among species (Perglová *et al*., 2009).

2.4. *Seed bank dynamics*

Seed bank densities of invasive alien plants can remain constant in certain sites or change over time at other sites. Lonsdale *et al*. (1988) for example, monitored the seed bank density of *Mimosa pigra* in two regions of northern Australia for two years. In one region, seed bank density was invariant and only increased from 7284 to 9885 seeds/m^2, while in the other region, the seed bank density increased drastically from 1898 to 10950 seeds/m^2 within a two-year period. Moreover, the seed bank density of some invasive plants vary widely across sites (Fumanal *et al*., 2008). According to Buhler *et al*. (2001) and Wang *et al*. (2009), factors that affect such changes in seed bank density within and across sites include disturbance events, plant density and the presence of actively reproducing adult plants. Some of these plants accumulate large seed banks in the introduced compared with native ranges (Rees and Paynter, 1997). In many cases, seeds of invasive alien plants remain viable in seed banks for long periods (Hill *et al*., 2001; van Clef and Stiles, 2001). Those that have high viability are at the upper (i.e. 0-5 cm) soil layers in high densities (Gonzalez *et al*., 2010). Populations with high recruitment rate, however, have low densities of seed banks in the upper soil layers (Fumanal *et al*., 2008).

2.5. *Impacts of elevated temperature on plant growth*

Climate change is associated with an increase in temperature, extended warm seasons and a reduction in annual precipitation (van Jaarsveld and Chown, 2001), and this can have negative impacts on plant biodiversity. In Europe, more than 22% of plant species are threatened, while 2% are estimated to go extinct by 2080 because of climate change (Thuiller *et al*., 2005). According to Hellmann *et al*. (2008), however, climate change may create suitable sites for the establishment of some invasive alien plants. It can also lead to a shift in flowering time, and some of these plants (especially those introduced for horticulture) tend to produce large flowers (Willis *et al*., 2010). Some invasive alien plants are most likely to experience a shift in range or have their climatic envelopes narrowed (Bradley *et al*., 2009).

Several studies have reported plant species (including gorse and Scotch broom) to be sensitive to high temperatures (e.g. Fox and Steinmaus, 2001; Leakey *et al*., 2003; Haldimann and Feller, 2004; Haldimann and Feller, 2005; Potter *et al*., 2009). This retarded growth is often linked to altered photosynthetic processes (Haldimann and Feller, 2005) and can lead to a reduction in reproductive capacity and hence, species persistence (Potter *et al*., 2009. This temperature effect is not permanent and can be reversed at lower temperatures (Haldimann and Feller, 2004). Wang *et al*. (2011), however, reported the germination rate and plant growth of invasive *Ipomoea cairica* to increase at elevated temperatures compared with at ambient temperatures, which suggests that not all plant species are heat sensitive.

2.6. *The role of fire in seedling recruitment and plant growth*

Fire promotes seedling recruitment in some invasive alien plants (e.g. *Fumana* spp. (Lloret, 1998) and Scotch broom (Srinivasan *et al*., 2012)). According to Albrecht and McCarthy (2006), it reduces leaf litter, creates safe sites for species establishment, and even stimulates seed germination. A reduction in leaf litter reduces competition, thus increasing survival (Lloret, 1998) and the biomass accumulation (Tyler, 1995) of newly emerging invasive alien plants. Fire also induces resprouting in some species (Albrecht and McCarthy, 2006) and alters the availability of soil nutrients (Soto *et al*., 1997). High fire frequency for example, retain nutrients to the soil from the burnt plant materials (Romanyà *et al*., 2001) thus promoting the growth of new plants (Huenneke *et al*., 1990). Other invasive alien plants and native plants, however, are sensitive to fire (van Wilgen *et al*., 1990; Lloret, 1998). When fire intensity is high, it increases soil temperatures and kills a significant number of seeds of many fire tolerant and non-fire tolerant species in seed banks, thus reducing the seedling recruitments (van Wilgen *et al*., 1990; Tyler, 1995).

2.7. *Management options and the associated risks*

2.7.1. Mechanical and chemical control

Mechanical and chemical control methods are appropriate for the management of naturalised plants that have not spread widely (Fowler *et al*., 2000). Mechanical control involves the removal of invasive plants by bulldozing, hand pulling, hoeing, harvesting, draining, grubbing, mowing or tilling in order to kill the plants (Masters and Sheley, 2001; Culliney, 2005). According to Flory and Clay (2009), this method can promote the establishment of indigenous plants, but may not be suitable for infestations along steep slopes as it can promote soil erosion (Ding *et al*., 2006). Chemical control involves the use of synthetic herbicides with the capability of inhibiting processes such as photosynthesis, respiration, lipid and amino acid biosynthesis in species of target (Culliney, 2005).

Although the success of these methods is noticeable, associated drawbacks have raised concerns. For instance, these methods are both labour intensive and require repeated applications, thus increasing associated costs (Ding *et al*., 2006). Mechanical removal can also disturb soil thus increasing chances for re-invasion and soil erosion (Flory and Clay, 2009). The problems associated with chemical control methods include the development of herbicide resistance in some invasive alien plant taxa, and some broad range herbicides can attack non-target species (Simberloff, 2001). Other herbicides can pollute the environment and affect the diversity of surrounding native plants (Flory and Clay, 2009). Apart from the above, direct human contact with some herbicides can affect the functioning of the immune system or even cause diseases such as cancer, Parkinsonism, diabetes, retinopathy, heart disease, neuropathy and hypertension (Culliney, 2005).

2.7.2. Fire

Another method proposed in the control of invasive alien plants is the controlled burning. Fire often kills the aboveground biomass of invasive plants (Srinivasan *et al*., 2012). In dense stands, this can allow for secondary control methods to be easily achieved (DiTomaso *et al*., 2006). During the species control using fire, invasive alien plants need to be targeted and burnt before the maturation of their seeds, and while immature seeds are still on parent plants as those fallen off to the ground may not experience lethal temperatures (DiTomaso *et al*., 2006). It is also crucial to burn invasive alien plants during their growing season as carbohydrate reserves (DiTomaso *et al*., 2006) and plant survival are low at this time (Gleason and Ares, 2004). This method may not always be effective though because some invasive alien plants are fire tolerant (Brooks and Pyke, 2001). In such cases, the application of other methods in conjunction with fire is recommended.

Drawbacks associated with fire are that it is a form of a disturbance and can alter soil chemistry and open new niches with conditions suitable for plant invasion (DiTomaso *et al*., 2006). Fire is also capable of scarifying seeds of invasive alien plants thus promoting seedling recruitment (D'Antonio and Meyerson, 2002; DiTomaso *et al*., 2006; Srinivasan *et al*., 2012). It is important to note, however, that seedling recruitment through fire can significantly reduce seed bank size of invasive alien plants (Dennehy *et al*., 2011) if such species are being continuously managed.

2.7.3. Biological control

Biological control is effective in the management of some invasive alien plants that are well established (Culliney, 2005). This method involves the identification, screening and the introduction of host specific exotic natural enemies (i.e. pathogens, predators or parasites) from the alien plants' native ranges (Hobbs and Humphries, 1995; Ding *et al*., 2006). These natural enemies attack target species and destroy vital organs responsible for species survival (Culliney, 2005). This behaviour reduces competitive ability and can even lead to plant death, thus reducing invasive alien plant populations and the associated impacts (Fowler *et al*., 2000; Culliney, 2005). The impacts of biological agents on closely related native plants, and on plants morphologically similar to target species need to be critically assessed before releasing the agents to the environment (Fowler *et al*., 2000).

2.8. *Restoration after eradication, associated challenges and possible solutions*

Native plant restoration after the eradication of invasive alien plants is very important because it reduces chances for re-invasion (Masters and Sheley, 2001; D'Antonio and Meyerson, 2002; Beater *et al*., 2008). Nevertheless, this process is difficult to achieve if invasive alien plants have been in the area for an extended periods (Corbin and D'Antonio, 2004). Many of these plants accumulate large seed banks and alter the soil chemical properties to such an extent that conditions are no longer favourable for native plant recovery (Brooks *et al*., 2004; Corbin and D'Antonio, 2004; Pretorius *et al*., 2008). Depending on the extent of invasion, the probability of native plant re-establishment can be reduced by 40-80% (Higgins *et al*., 1999). As a result, different methods to mitigate problems of altered soil properties are being practiced worldwide. Such methods include the introduction of fast growing non-invasive alien plants that can fix nitrogen in excess (D'Antonio and Meyerson, 2002; Pretorius *et al*., 2008) and controlled multiple burnings (Corbin and D'Antonio, 2004) in order to reduce soil nitrogen as nitrogen volatilises (escapes from the soil as a vapour) at temperatures above 200°C (DiTomaso *et al*., 2006). Fire can also remove nitrogen fixers from the area (e.g. Scotch broom and French broom) thus reducing soil nitrogen by a significant amount (Haubensak *et al*., 2004). In areas with reduced vegetation, introduction of fast growing sterile alien grass species can play a crucial role in the prevention of soil erosion (D'Antonio and Meyerson, 2002).

2.9. *Study species*

2.9.1. Gorse

Gorse is a thorny leguminous perennial shrub that belongs to Fabaceae family (Hill *et al*., 2000) [Fig. 2.2]. It can grow up to 7 m tall with a stem diameter of c. 21.7 cm. Both, height and stem diameter correlate with plant age (Lee *et al*., 1986). The stem of the plant is either smooth or pubescent and armed with conspicuous spines to deter herbivores. Spines are deeply furrowed and can be 10-30 mm long (Clements *et al*., 2001). Gorse produces acicular evergreen leaves that develop to scales or spine-like phyllodes as the plant matures (Viljoen and Stoltsz, 2007). This species normally flowers at any time of the year producing pea-like dark yellow flowers that are about 15-20 mm long (Viljoen and Stoltsz, 2007; Ireson *et al*., 2008). It produces ciliated green pods (c. 10-20 mm) that become dark brown at maturity, with each pod containing 5-9 brown seeds (Clements *et al*., 2001). Gorse plants can live for up to 29 years (Lee *et al*., 1986).

Figure 2.2: (A) gorse population, (B) gorse plant with flowers and stems armed with phyllodes, (C) gorse plant with mature pods and spiny stem (Photos by P.M. Mbatha, 2014 [Estcourt, South Africa]).

Seeds produced by gorse have hard seed coats (Williams, 1981; Hill *et al*., 2001) which prevent germination unless dormancy is broken either by mechanical, chemical or heat scarification methods (Sixtus *et al*., 2003). High proportion of seeds shed are viable (Sixtus *et al*., 2003) and are released by ballistic explosion from seed pods (Hill *et al*., 1996) to form large seed banks (Gonzalez *et al*., 2010). Some of these seeds remain viable in seed banks for more than 10 years (Hill *et al*., 2001). Seeds of this species are dispersed by quails, ants, humans, vehicles, wind, and water or by wild animals to other regions (Hill *et al*., 1996; Clements *et al*., 2001; Hill *et al*., 2001). According to Sixtus *et al*. (2003), the germination capacity of seeds of this species is optimum at 10-15°C.

Disturbance such as fire promotes seedling recruitment and shrub recovery in gorse (Lee *et al*., 1986). The mortality rate of seedlings during species recruitment, however, is very high (Hartely and Thai, 1982). Once established, gorse plants form dense stands, accumulate litter on the ground and reduce species richness (Lee *et al*., 1986; Sullivan *et al*., 2007). Gorse also alters soil chemical properties and nutrient balance (Leary *et al*., 2006). The invaded soil becomes acidic (Leary *et al*., 2006), thus promoting the growth of other invasive plants (e.g. Scotch broom) (Lee *et al*., 1986). This species has high fuel loads that cause fire hazards (Marino *et al*., 2011, Madrigal *et al*., 2012). Gorse is normally eaten by sheep and goats but is not suitable for cattle grazing because it is not easily digestible and it affects animal fitness (Clements *et al*., 2001).

In order to minimise threats posed by gorse, a number of control methods are being practiced. Such methods include prescribed burning, chemical and biological control (Hill *et al*., 2001; Rees and Hill, 2001). Prescribed burning reduces the aboveground biomass and seed bank size significantly (Rolston and Talbot, 1980). Seed bank size also decline due to seed germination induced by fire (Rolston and Talbot, 1980). Individual plants that escape fire as resprouts are being killed by herbicides (Rolston and Talbot, 1980). The most effective herbicides for gorse include picloram 240 g/L, glyphosate 360 g/L and triclopyr ester 480 g/L, applied at 1-4% concentrations. The efficacy of these herbicides in the management of gorse is more than 80% (Viljoen and Stoltsz, 2007). The effectiveness of biological agents such as *Exapion ulicis*, *Tetranychus lintearius* and *Cydia succedana* on gorse management was tested in Australia, New Zealand and Chile (Hill *et al*., 2008). Predators for these agents and the ability of gorse to reproduce at any time of the year in other countries made these agents ineffective (Hill *et al*., 2008). Hence, an effective management of this species requires an integrated weed management approach that can employ more than one control methods to manage the infestations (Herrera-Reddy *et al*., 2012).

2.9.2. Scotch broom

Scotch broom is a perennial leguminous shrub that belongs to Fabaceae family (Kang *et al*., 2007; Oneto *et al*., 2010). It can grow up to 6.7 m tall with a stem diameter of c. 35 cm (Downey and Smith, 2000). The plant height and stem diameter correlate with age (Srinivasan *et al*., 2007). This plant produces green fleshy stems that become woody as the plant matures. It produces alternate trifoliate leaves that become simple above, and leaves senesce during harsh conditions (i.e. dry summer or periods of stress) (Oneto *et al*., 2010). According to Peterson and Prasad (1998), leaflets are obovate in shape with acute or mucronate tips, and are c. 4-8 mm long. Leaves and stems can either be smooth or hairy. This species flowers in spring, autumn or winter producing bright yellow, pea-like flowers that are about 20 mm long. Scotch broom produces c. 20-50 mm long hairy green pods, which become dark brown at maturity (Fig. 2.3). This species can live for up to 20 years (Downey and Smith, 2000).

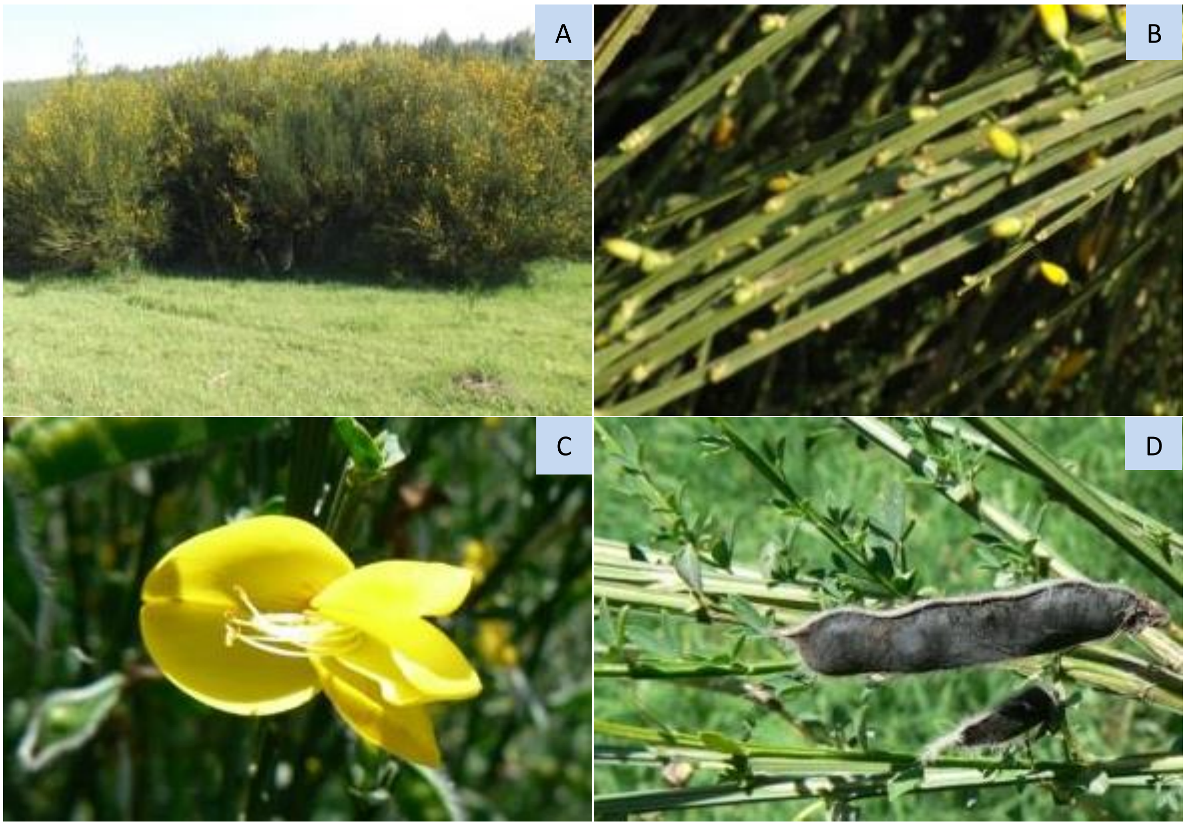

Figure 2.3: (A) Scotch broom population, (B) Scotch broom stem, (C) Scotch broom flower, (D) Scotch broom individual with leaves and mature pods (Photos by S. Ramdhani, 2014 [Kamberg, South Africa]).

Pods produced by this species contain seeds with hard seed coats (Williams, 1981) which prevents them from germinating unless dormancy is broken either by cold stratification (Harrington, 2009), high temperature (Bossard, 1993) or by mechanical scarification (nicking) (Williams, 1981). This species can produce c. 28-14212 seeds/m^2 per year in the introduced regions compared to c. 72-5649 seeds/m^2 produced in the native regions (Rees and Paynter, 1997). Seeds of this species are released by ballistic explosion from the plant pods (Bossard, 1991) into seed banks. Seed bank densities are high in the introduced regions and range from 190 to 27000 seeds/m^2 compared with seed bank densities in native ranges that range from 460 to 10000 seeds/m^2 (Rees and Paynter, 1997). More than 90% of seeds in seed banks are viable (Paynter *et al*., 1998; Sheppard *et al*., 2002) and persist for 4-5 years in seed banks (Magda *et al*., 2009; Magda *et al*., 2013). The seeds of this species are dispersed to other regions by water, wind, wild animals, ants and human or by vehicle tyres (Bossard, 1991; Peterson and Prasad, 1998).

Once introduced to new regions, the disturbance events promote seedling recruitment and the survival of Scotch broom (Bossard, 1991; Paynter *et al*., 1998; Sheppard *et al*., 2002). The mortality rate of seedlings in dense stands, however, is very high due to plant canopy which prevents understory seedlings from receiving light (Bellingham and Coomes, 2003; Prévosto *et al*., 2006; Magda *et al*., 2009). Predation pressure also affects seedling survival (Downey and Smith, 2000).

At the juvenile stage, Scotch broom grows rapidly and starts reproducing after two to three years (Sheppard *et al*., 2002; Magda *et al*., 2009). Upon establishment, populations of this species form dense stands (Slesak *et al*., 2016), thus out-competing other species for resources (Prévosto *et al*., 2006). It also fixes nitrogen and has the potential to alter soil chemical properties (Haubensak and Parker, 2004; Caldwell, 2006; Oneto *et al*., 2010; Slesak *et al*., 2016). Scotch broom reduces pastoral grazing value not only by displacing fodder species, but also by being unpalatable to livestock (Jarvis *et al*., 2006). Leaves of this species contain quinolizidine alkaloids, spartein and isoparteine, which also leads to livestock loss (Peterson and Prasad, 1998).

In order to minimise threats posed by Scotch broom, a number of control methods have been practiced in Australia and New Zealand (Jarvis *et al*., 2006). These methods include mowing (for small populations near properties), herbicides, prescribed burning, and biological control (for massive infestations) (Alexander and D'Antonio, 2003; Odom *et al*., 2003; Holst *et al*., 2004). The herbicides of choice include glyphosate (Roundup Pro®), triclopyr ester (Garlon 4®) and imazapyr (Stalker ®), applied at 1-4% concentrations for foliar spray treatment and 10-20% concentrations for basal bark treatments. Both, prescribed burning (Alexander and D'Antonio, 2003) and herbicide usage (Oneto *et al*., 2010) can reduce plant biomass by more than 90%. Although these methods have the potential to reduce infestations significantly, Herrera-Reddy *et al*. (2012) suggested that the successful control of Scotch broom can be achieved through well-planned long term integrated management option strategies. The fact that fire breaks dormancy in seeds of Scotch broom can be crucial in the reduction of seed bank size (Alexander and D'Antonio, 2003) and hence, chances for re-invasion (Alexander and D'Antonio, 2003). Populations recovering from seed banks, however, have to be controlled using methods such as biological control or herbicides to prevent further seed input (Ketchum and Rose, 2003; Herrera-Reddy *et al*., 2012).

2.10. *Concluding remarks*

Many studies comparing the plant behaviour in native and introduced regions report that invasive alien plants are highly competitive (Hawkes, 2007). Some of these species grow rapidly and produce massive number of seeds, thus out-competing native plants. A number of factors including polyploidy, phenotypic plasticity and enemy release from native ranges confer this competitive ability (Blossey and Nötzold, 1995; Bossdorf *et al*., 2005; te Beest *et al*., 2011). Some of these species are highly invasive in specific regions but not in others. Other factors (i.e. environmental conditions rather than plant traits) may possibly play a major role in such cases. Therefore, studies linking plant behaviour, traits and environmental conditions need to be developed in order to better understand reasons for invasion success of these plants in specific regions. Understanding the plant biology of invading species under different climate change scenarios can also allow scientists to develop more effective and innovative management strategies for invasive alien plants.

Chapter 3: Materials and Methods

3.1. *Determination of the national-scale distribution*

Records on historical distribution of gorse and Scotch broom in South Africa were extracted from Southern African Plant Invaders Atlas (SAPIA) (accessed in May 2013), South African herbaria and from the existing literature. Additional populations, including those in cultivated sites, were identified through networking and meeting with landowners, land managers, land users and residents in areas where populations of both species were reported. The iSpot website (www.ispot.org.za) which allows for the sharing of knowledge on the country's biodiversity was also used to search for new populations. The flyers and posters describing the morphology of both species, were distributed by P.M. Mbatha and SANBI: ISP staff members to the public and scientific community in order to encourage the reporting of new populations. Flyers were distributed at weed conferences and forums whilst posters were displayed at nature reserves, botanic gardens, Westville and Pietermaritzburg campuses of the University of KwaZulu-Natal (UKZN), and at schools near the invaded areas. Historically recorded populations of both species were visited to verify their existence. Upon receiving locality information from the public, reported populations were visited for taxonomic verification. Global Positioning System (GPS) co-ordinates of all identified populations were recorded and voucher specimens were collected for taxonomic identification and herbarium collections.

3.2. *Population surveys*

In order to determine the population size and density for each of the identified populations, the total number of individual plants at a given site was counted through comprehensive surveys. Parallel walked transects, up to 20 m apart (depending on plant density), were used to locate and count the number of individuals (Zenni *et al*., 2009; Kaplan *et al*., 2012). The search was abandoned if no plants were encountered within a 100 m distance (in all cardinal directions) from the last plant encountered. Surrounding GPS co-ordinates for each of the identified populations were recorded for area determination and the land-use types invaded by populations of both species were recorded. Geographic Information System (GIS) shape files were created using World Geodetic System (WGS) 1984 and the GPS co-ordinates were used to create polygons in ArcMap GIS (Version 9.3). The shape files with created polygons were then used to calculate total area (m^2) covered by each of the identified populations. Plant densities (individual plants per m^2) were determined by dividing the total number of plants per population by the area covered (Cipollini and Bergelson, 2001).

3.3. *Population structure*

In order to determine the population structure, growth parameters such as basal stem diameter, crown diameter and plant height were measured for all individual plants per population (in nine gorse and 12 Scotch broom populations selected randomly). The basal stem diameter of individual plants was measured using a calliper (Prévosto *et al*., 2004) and the crown diameter was measured in two perpendicular directions using a tape measure. Plant height was measured from the ground level to the last leaf of the tallest branch using a tape measure (Prévosto *et al*., 2004). In some populations of both species, few individual plants had multiple stems (see Fig. 4.6 in the Results chapter) making the measurements of basal stem diameter difficult. In such cases, this parameter was not measured. The data on population structure were represented as histograms showing frequency size class distribution of growth parameters for each of the selected populations.

3.4. *Reproductive biology*

3.4.1. Flowering phenology and minimum size at reproduction

In order to determine flowering and fruiting phenology of both species, the flowering and fruiting times of five populations per species were monitored every three months from March 2014 to March 2015. In order to determine minimum size at reproduction, the presence of flowers, flower buds, pods and pod-stalks on individual plants of both species were recorded in five populations per species that were actively reproducing during the time of site visit (Zenni *et al*., 2009). Observations on whether plants had the capacity to resprout or produce suckers were also made in selected populations. This was done by uprooting young plants emerging near the mature plants to see if their stem emerged from seeds (seedlings), above the stem of neighbouring plants (resprouts) or from rhizomes (suckering plants) (Kaplan *et al*., 2012; Srinivasan *et al*., 2012).

3.4.2. Reproductive output

In order to assess the reproductive output for gorse and Scotch broom, the data on seed set per plant were collected from three populations per species. These data were collected from Arminel Hotel (-32.5914°S; 26.9326°E), W16 (-32.5811°S; 26.9579°E) and White Mountain Lodge (-29.1110°S; 29.6121°E) populations for gorse. For Scotch broom, these data were collected from a population along the roadside near Butt Farming (-29.3141°S; 29.7673°E), White Mountain Lodge (-29.1067°S; 29.6131°E) and X19 (-32.5617°S; 26.9149°E). A maximum of forty individual plants of different size classes that had completely seeded were selected randomly from these populations. All pods from selected plants were collected and counted (Sheppard *et al*., 2002). In order to estimate the number of seeds per pod, seeds within each pod were counted from a sample of 100 pods. The average from that was taken as an estimate number of seeds per pod (Sheppard *et al*., 2002; Magda *et al*., 2009). The total number of seeds produced by each parent plant was estimated by multiplying mean number of seeds per pod by the total number of pods per individual plant (Magda *et al*., 2009).

3.5. *Post-harvest seed biology*

3.5.1. Seed characteristics and germination biology

Seeds of gorse were collected from the population at White Mountain Lodge and those of Scotch broom were collected from the population along the roadside near Butt Farming in November 2014. The individual seed mass and size (n = 50) was determined for each species. In order to determine seed water content for both species, the oven method by Taylor *et al*. (1997) was followed. Fresh seeds were weighed and dried in a 72°C oven for 48 h. After drying, the dry seed weights were taken and water content on dry basis was determined using the following equation:

$$WC = (FW - DW)/DW \qquad (3.1)$$

where WC is water content, FW is fresh weight and DW is dry weight. Both species exhibit seed dormancy, which may be physical, physiological or a combination of these (Bossard, 1993; Sixtus *et al*., 2003). In order to characterise type(s) of seed dormancy exhibited by South African populations investigated here, seeds were characterised in terms of their water uptake characteristics and then subjected to different scarification methods (mechanical, chemical, hot water as well as dry heat together with smoke treatments).

Firstly, the water uptake curves were generated for both species. For this, nine batches of ten seeds each were weighed in milligrams and imbibed in distilled water. These seeds were removed from water, blotted dry (on paper towel for three hours) and reweighed at 30 min intervals up until 240 minutes (Baskin *et al*., 2004). The water uptake was determined as an increase in seed weights and was converted into percentages using the following equation:

$$WU = (W_i – W_d)/W_d \times 100 \quad (3.2)$$

where WU is the percentage water uptake, W_i is seed mass after imbibition and W_d is seed mass before imbibition. A similar procedure was performed on another set of seeds (nine batches of ten seeds each) that were mechanically scarified by nicking before imbibition (Baskin *et al*., 2004) to determine the effect of nicking on water uptake.

For dormancy breaking treatments, four batches of ten seeds were subjected to each treatment as well as the control (no scarification and no heat/smoke treatment). Mechanical scarification was performed by making small incisions along the length of seed coats of forty seeds (Baeza and Vallejo, 2006). Chemical scarification involved the imbibition of seeds in 96% sulphuric acid for four different time intervals (10, 20, 30 and 40 minutes) (Baeza and Vallejo, 2006), with four batches of ten seeds per time interval. All seeds were rinsed under the running tap water for 10 minutes to neutralise pH (Sixtus *et al*., 2003). In the heat scarification treatment, seeds were placed in hot water at varying temperatures (40, 60, 80 and 100°C) for five minutes and were then cooled under the running tap water for 10 minutes (Sixtus *et al*., 2003). Four batches of ten seeds were used for each temperature. In the dry heat plus smoke (heat + smoke) treatment, four batches of ten seeds were buried in 2 cm of sand which was then exposed to heat and smoke emanating from a grass and woody leaf litter fuelled fire for 20 minutes. The soil temperature over a 20 minutes exposure period ranged from 36-43°C with a mean temperature of 39.8°C for gorse. The soil temperature of Scotch broom ranged from 28-42°C with a mean temperature of 37.8°C. For control treatment, four batches of ten seeds per species were used and did not receive any treatment.

Following dormancy breaking treatments, all seeds used (including those for the control) were surface sterilised in 1% sodium hypochlorite solution for five minutes and rinsed three times in deionised water (Grotkopp and Rejmânek, 2007). Seeds were then imbibed overnight in sterile water at 25°C to allow for water uptake (Kaplan *et al*., 2012). All seeds were then germinated on Petri-dishes between a double layer of paper towel moistened with distilled water (Baeza and Vallejo, 2006). Petri-dishes were kept in a growth chamber at 24°C, in a 16 h light and 8 h dark cycle for 14 days. Germination, regarded as the production of a radicle ≥ 2 mm (Harrington, 2009), was recorded daily up until day 15 and the paper towels were re-moistened if necessary.

3.5.2. Viability assessment via tetrazolium tests

The viability of seeds (of both species) collected from parent plants *in situ* was determined by tetrazolium (TTZ) tests. One hundred fresh seeds per species collected in September 2014 from populations at White Mountain Lodge were tested for viability. Seeds were mechanically scarified by nicking, surface sterilised in 1% sodium hypochlorite solution for five minutes, rinsed three times in deionised water and imbibed overnight in sterile water at 25°C (Grotkopp and Rejmânek, 2007; Kaplan *et al*., 2012). Twenty-five seeds in lots of fours were then stained in Petri-dishes with 1% 2,3,5-triphenyl tetrazolium chloride solution (pH 6.7) at 25°C for 72 h to test for viability (Kaplan *et al*., 2012). After staining, seed coats were removed and seeds with evenly stained embryos were recorded as viable (Kaplan *et al*., 2012).

3.6. *Seed bank studies*

The seed bank density of gorse and Scotch broom was determined for three populations per species: W17b (-32.5819°S; 26.9583°E), White Mountain Lodge (-29.1110°S; 29.6121°E) and W24b (-32.5875°S; 26.9667°E) for gorse; and White Mountain Lodge (-29.1067°S; 29.6131°E), X19 (-32.5617°S; 26.9149°E) and a population near the Spotted Horse Country Inn (-29.2958°S; 29.7387°E) for Scotch broom. Ten soil samples (0.25 m^2, to a depth of 10 cm) from each of these populations were collected from under the parent plants that had seeded (Sheppard *et al*., 2002; Kaplan *et al*., 2012; Geerts *et al*., 2013). The collected soil samples were spread on the ground and left to dry in a ventilated room for a minimum of two weeks to allow for air-drying. The dried soil was then sieved (1 mm pore size) and total number of seeds obtained from the soil samples was counted to determine the number of seeds per 0.25 m^2 (Zenni *et al*., 2009) which was then converted to a number of seeds per m^2. The mean number of seeds/m^2 per population was then multiplied by the total area covered by that population to estimate the number of seeds per population.

The relationship between seed bank density and a distance from parent plants was also assessed for one gorse population at White Mountain Lodge (-29.1110°S; 29.6121°E) and for one Scotch broom population near the Spotted Horse Country Inn (-29.2958°S; 29.7387°E). Five isolated plants located along the periphery of each of these populations were selected randomly for this investigation. Three soil samples (0.04 m^2, to a depth of 10 cm) were collected from under each of the selected individuals per species. Three similar samples were collected 2 m away from parent plants and a further set of three samples 4 m away from parent plants. All soil samples were then dried and sieved as described above, and the number of seeds per sample was then counted. The germinability of seeds (four batches of 25 seeds per population) from seed banks was assessed by the nicking and germination methods as described in section 3.5.1.

3.7. *Assessment of post-fire regrowth in Scotch broom*

The effects of fire on seedling recruitment and resprouting in Scotch broom was investigated using methods described by Srinivasan *et al*. (2007). This part of the study was conducted in one Scotch broom population at Kamberg (Butt Farming, 1st population). The population was burnt in March 2014 but the cause of fire was not known. The first survey following fire was conducted in June 2014 and the second survey in July 2015. During the first survey, seedling emergence and the number of resprouts were recorded for the entire population. During the second survey in July 2015, the population had fully recovered and the plants were surveyed using a quadrat method. A total of ten 3 m^2 quadrats were randomly laid 100 m apart. Species density, percentage cover and the number of resprouts were recorded for each of the laid quadrats. A similar survey was conducted in July 2015 at a nearby population in Butt Farming (2nd population) which did not receive fire for comparative purposes. The data on species density, percentage cover and number of resprouts were recorded.

3.8. *Seed and seedling responses to elevated temperatures*

Gorse seeds were collected in October 2014 from the population at White Mountain Lodge, Kamberg, KwaZulu-Natal (KZN) (-29.1110°S; 29.6121°E), while Scotch broom seeds were collected in October 2014 from the population along the roadside near Butt Farming, Kamberg, KZN (-29.3141°S; 29.7673°E). Collected seeds were stored at 4°C until germination and growth trials were initiated.

For these experiments, seeds were sown at 'ambient' and 'elevated' temperatures and the seedlings that were subsequently produced were allowed to grow at these temperatures. Seeds/seedlings were placed in a greenhouse at the Westville campus of the University of KwaZulu-Natal, Durban, South Africa for the ambient temperature treatment. In order to expose the seeds/seedlings to elevated temperatures, they were placed in a glasshouse on the same site. Air temperature was recorded within the glass- and greenhouse using the ibutton thermocrons daily (at 12H00 and 22H00) over a four-month growth period. Midday/night temperatures in the greenhouse averaged 23.8/13.8 ± 2°C, while the average midday/night temperatures in the glasshouse were 28.4/18.5 ± 2°C. The selection of the ambient temperature range used was based on the average minimum and maximum temperatures at Kamberg, the location at which seeds of both species were collected, for the period during which the growth trial was conducted. For November-February, the maximum temperatures are 22.5 ± 0.6 while minimum temperatures are 11.2 ± 1.1 at Kamberg (http://en.climate-data.org/location/14889/). The ± 5°C increase used for the elevated temperature treatment is based on the fact that global temperatures are predicted to increase by 2-4°C if the current atmospheric CO_2 levels can be increased by double (IPCC, 2013). Like other tropical regions of Africa, South Africa is predicted to experience an increase in temperature between this range (van Jaarsveld and Chown, 2001; Engelbrecht *et al*., 2011).

In order to determine seed germinability in both species, the germination trials were conducted on nicked seeds as described above. Four batches of ten seeds per species were then incubated at ambient and elevated temperatures for 15 days, and the data on percentage germination were collected on a daily basis.

In order to determine the effect of elevated temperature on seedling emergence and growth, 300 seeds per species were nicked, surface sterilised in 1% sodium hypochlorite solution for five minutes (Grotkopp and Rejmânek, 2007) and rinsed in deionised water before being sown at a depth of 1 cm in polystyrene seedling trays filled with a 1:1 mixture of river sand and pine bark (Loveys *et al*., 2002; Grotkopp and Rejmânek, 2007; Magda *et al*., 2009). The soil was watered to field capacity before sowing 30 seeds in each of ten seedling trays. Five of these seedling trays (per species) were incubated at ambient temperature and the other five were incubated at elevated temperature. The seedling trays were watered twice a week with nutrients (Dr Fisher's Multifeed Classic, Plaaskem (Pty) Ltd, SA; 19:8:16 N: P: K ratio) being added to water on one of the irrigation events each week. Seedling emergence (i.e. the protruding of the seedlings under the soil mixture) was monitored on a daily basis for three weeks.

After three weeks of growth, seedlings of both species produced at ambient and elevated temperatures were transplanted to 5 L pots filled with the same growth medium used in seedling trays (n = 21 for gorse and n = 12 for Scotch broom per treatment). Pots with transplanted seedlings were maintained (for 120 days) at temperatures under which they were produced. Seedlings were irrigated twice every week to field capacity with nutrients added during one of the weekly irrigation events as described above. Seedling height, stem and crown diameters were measured on weekly basis. On the last day of the growth trial, ten seedlings per species per treatment were randomly harvested for biomass, leaf area and leaf area ratio determination.

Harvested seedlings were separated into phyllodes (for gorse), leaves (for Scotch broom), stems and roots (Loveys *et al*., 2002). Roots of harvested seedlings were washed to free them of soil before being dried using paper towel (Liu and Stützel, 2004). Phyllodes or leaves were forced flat and placed into a leaf area meter (CL-202 Leaf Area Meter, CID Inc., USA) to measure the leaf area (Loveys *et al*., 2002). Roots, shoots and phyllodes or leaves were then dried in an oven at 70°C for 48 h for dry mass determination (Liu and Stützel, 2004; Grotkopp and Rejmânek, 2007). The phyllode or leaf area ratio showing the ratio of phyllodes or leaves to total dry biomass was determined.

3.9. *Weed risk assessment*

The Australian weed risk assessment protocol developed by Pheloung *et al*. (1999) was used to determine if both species require a post-border assessment in South Africa. This protocol was developed to assess risks of species introduced into Australia and New Zealand, but also works for species introduced into countries outside Australia (Gordon *et al*., 2010). The protocol has 49 questions based on biogeographical, biological, ecological and the invasive traits of species being investigated (Pheloung *et al*., 1999). In this study, these questions were answered based on data collected and observations made *in situ*, experimentation and from the existing literature. Guidelines developed by Gordon *et al*. (2010) were applied in answering these questions.

3.10. *Management options and estimation of initial clearing costs*

One gorse population (W14b; -32.5819°S; 26.9583°E) and one Scotch broom population (X19; -32.5617°S; 26.9149°E) both located within the Amathole Forest (Hogsback, Eastern Cape [EC]) were selected for herbicide treatments in August 2014. Gorse population was divided into two plots of 260 m^2 each while the Scotch broom population was divided into three plots of 510 m^2 each. All adult plants within each plot were counted and cut down to ground level. Immediately after cutting, individual plants were treated with different concentrations of Garlon (triclopyr butoxy ethyl ester 480 g/L, Dow AgroSciences SA (Pty) Ltd). In plot one and two for both species, the remaining stumps were treated with 1% and 2% herbicide, respectively. In the third plot for Scotch broom, cut stumps were treated with a 4% herbicide. In all plots, seedlings were treated via foliar spray.

Herbicide concentrations were prepared as follows: 1% was prepared by mixing 50 ml herbicide in 5 L of water, 2% by mixing 100 ml herbicide in 5 L of water and 4% by mixing 200 ml herbicide in 5 L of water. In all concentrations made, 50 ml Eco-guard dye was added in order to mark and easily identify the treated individuals. The herbicide triclopyr was selected because it is known to reduce populations of both species significantly (Viljoen and Stoltsz, 2007; Oneto *et al*., 2010). The effectiveness of triclopyr was then monitored at four-month intervals for one year by recording the number of resprouts from treated plants. In two other populations, one for gorse (W24b [200 m^2 plot]; -32.5875°S; 26.9667°E) and one for Scotch broom (Mahlinza [174 m^2 plot]; -32.5704°S; 26.9200°E) both within the Amathole Forest (Hogsback, EC), individual plants were counted, cut down to ground level, but were not treated with the herbicide to serve as the control. The number of resprouts was recorded every four months in treated and non-treated (control) populations.

The amount of effort and costs required for the clearing of all known/identified gorse and Scotch broom populations were estimated based on costs and time taken to clear one population per species. Guidelines by the WfW programme were used for the estimation of clearing costs. The following equations were used to estimate costs associated with the initial clearing of gorse and Scotch broom:

$$CC_m\ (R) = CC_p/P_a \tag{3.3}$$

$$CC_{ap}\ (R) = CC_m \times TA_{ap} \tag{3.4}$$

$$LC_m\ (R) = [T_{1p} \times \text{no. of people} \times \text{rate/h/person}]/P_a \tag{3.5}$$

$$LC_{ap}\ (R) = LC_m \times TA_{ap} \tag{3.6}$$

$$TC_{ap}\ (R) = CC_{ap} + LC_{ap} \tag{3.7}$$

where CC_m is chemical costs per m^2, CC_p is chemical costs per population, P_a is population area, CC_{ap} is chemical costs for all populations, TA_{ap} is total area covered by all populations, LC_m is labour cost per m^2, T_{1p} is time to clear one population (which was recorded during the population clearing), LC_{ap} is labour costs to clear all populations, TC_{ap} is total costs to clear all populations.

3.11. *Data analysis*

The distribution maps and area calculations were done in ArcGIS (Version 9.3) (Booth and Mitchell, 2001) while graphs showing minimum size at reproduction were constructed in R statistical package using the codes taken from Geerts *et al*. (2013). Frequency size class distributions of individual plants per species were presented in the form of histograms. The statistical analysis was performed in SPSS statistical software (Version 21) (Meyers *et al*., 2013). Parametric tests were performed in all data sets meeting the assumptions for parametric tests. The data that did not satisfy the assumptions were log transformed, and if normalised, parametric tests were then performed on the transformed data. In cases where data could not be normalised, non-parametric tests were performed. All percentage data were arcsine transformed before performing statistical tests.

Multiple linear regression analysis was used to develop predictive models for reproductive output using growth parameters such as plant height, stem diameter and crown diameter as predictor variables and seed set per plant as the responding variable. An independent sample t-test was used to compare seed water uptake in nicked and unnicked seeds. A simple linear regression model was developed to predict the rate at which seed bank size drop with an increase in distance from parent plants. The population density and percentage cover in burnt and unburnt plots fifteen months after the burning and the seed and seedling responses to elevated temperatures were compared using an independent sample t-test.

Chapter 4: Results

4.1. *Introduction*

The results on species distribution, population size and structure, reproductive biology, post-harvest seed biology, seed bank characteristics, post-fire survey on Scotch broom, seed and seedling responses to elevated temperatures, weed risk assessments and management options and their associated costs for gorse and Scotch broom are presented in this chapter. Whilst species distribution and population sizes are given for all populations, a number of parameters were only measured for selected populations and these are identified in each case.

4.2. *Determination of the national-scale distribution*

Among various methods (poster and pamphlet distributions, internet, and networking with landowners, public and weed specialists) used to determine countrywide distribution of both species in South Africa, the engagement with public and landowners returned the most results. The engagement with weed specialists which occurred once a year over a three-year period at national conferences lead to the confirmation of only three populations per species. Poster and pamphlet distributions and the species search through internet did not result in the identification or confirmation of any populations of either species.

The engagement with public, landowners and weed specialists collectively led to the identification of 14 gorse and 46 Scotch broom populations in the eastern part of South Africa, specifically in cool mountainous areas. These populations were within the same quarter degree as those historically reported in SAPIA records. It was difficult, however, to determine whether some of these populations were new or had been recorded previously, given the fact that many historical records provided localities on quarter degree scales rather than specifying the GPS coordinates.

Populations identified in this study were found in different vegetation types of the grassland biome (Appendix i), mostly in commercial forests, private and public properties (Appendix ii and iii). Gorse populations occurred in the Eastern Cape (EC) (Hogsback) and KwaZulu-Natal (KZN) (Estcourt, Kamberg, and Underberg) (Fig. 4.1A). Some historically reported gorse populations in Woodbush Forest (2330CC, Limpopo); Giant Castle Game Reserve (2929AB, KZN) and Lowerstoff Farm (3226BD, EC) were not located during the course of this study despite intensive searches in these areas.

Scotch broom populations occurred in EC (Hogsback), KZN (Bulwer, Estcourt, Himville, Kamberg and Underberg) and Free State (FS) (Van Reenen) (Fig. 4.1B). One Scotch broom population historically reported to be in FS (Warden: -27.8443°S; 28.9588°E) was taxonomically confirmed by P.M. Mbatha to be *Spartium junceum* L. from the Fabaceae family.

Although this study aimed at locating all South African populations of both species, it is possible that not all were found. Many other populations may still do exist as silent populations. Additionally, the searching effort for new populations in this study was biased because the physical search conducted by the researcher focused more in areas with historical records of species existence. The species search in areas with no historical records of existence relied on responses from the public, landowners and weed specialists, and none of the new populations were identified at those areas.

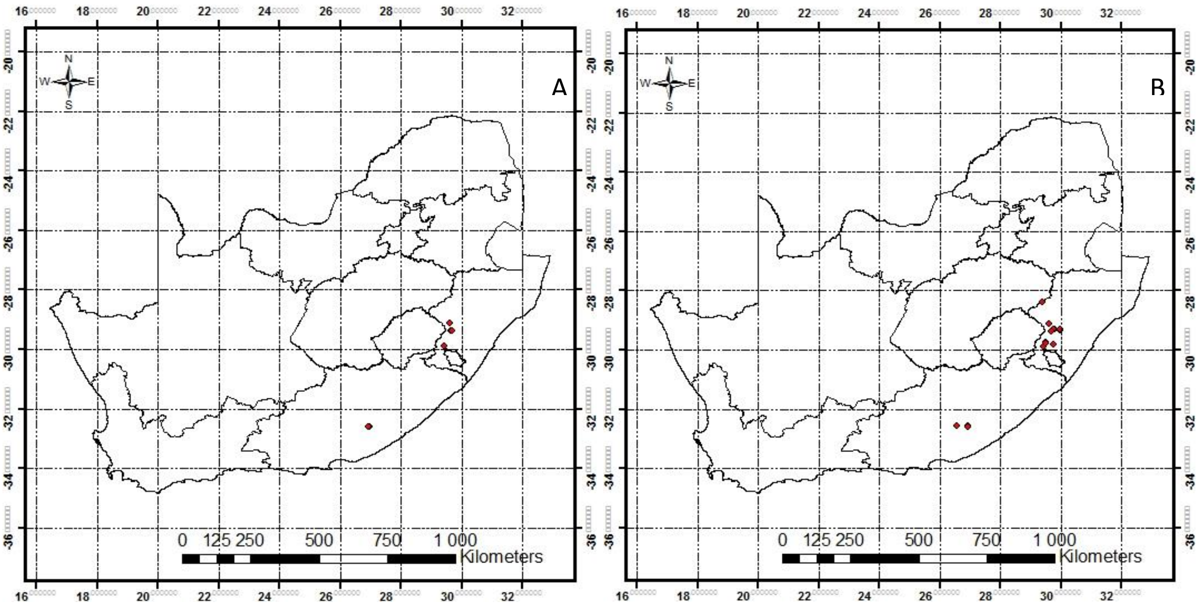

Figure 4.1: Confirmed distribution of (A) gorse and (B) Scotch broom in South Africa.

4.3. *Population survey*

4.3.1. Gorse

Gorse populations occurred in different land-use types (Fig. 4.2) such as open sites (i.e. areas freely accessible), private properties, commercial forests and nature reserves. None of these populations appeared to have been cultivated. Nine of the 14 identified populations were casual while five were naturalised. Four naturalised populations were in commercial forests and one was in an open site. Three casual populations occurred in commercial forests while three were in private properties. The Kamberg Nature Reserve had two casual populations while one was in an open site.

The individual plants per population ranged from 1 to 1878, and the population with highest number of individuals (plant abundance) (1878) was at White Mountain, while the site with least number of plant abundance (1) was at Ekhubeni (2^{nd} population). The plant abundance in commercial forests and open sites was higher than in nature reserves and private properties (Fig. 4.2). These populations, collectively, had 3951 individual plants covering 16510 m^2 (Appendix ii). The area and density of each of these populations varied widely across sites. The area ranged from 3 m^2 (population opposite to W14b) to 7266 m^2 (population at White Mountain Lodge). The population density ranged from 0.09 plants/m^2 (W24a) to 8 plants/m^2 (population opposite to W14b) (Appendix ii).

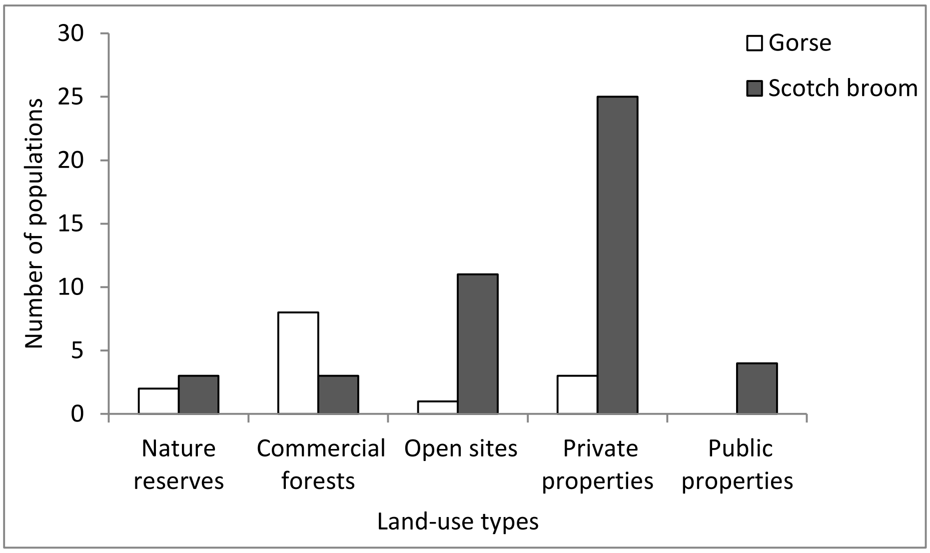

Figure 4.2: The number of populations of gorse and Scotch broom across different land-use types.

4.3.2. Scotch broom

Scotch broom populations occurred in different land-use types (Fig. 4.2) such as open sites, private properties (of which one population appeared to have been cultivated and properly managed), public properties (i.e. schools and police stations and were cultivated and properly managed), commercial forests and nature reserves. Populations in open sites, commercial forests, nature reserves and some in private properties did not appear to have been cultivated, and were not managed. Thirty-six of 46 identified populations were naturalised while ten were casual. Twenty-two naturalised populations and three casual populations were in private properties. In open sites, there were three casual and eight naturalised populations. Commercial forests had three naturalised populations. Public property had one naturalised population and three casual populations while Kamberg Nature Reserve had one casual and two naturalised populations. Private properties had the highest plant abundance.

The individual plants per population ranged from 2 to 81022, and the population with the highest plant abundance (81022) was the one near Spotted Horse Country Inn, while the site with least plant abundance (2) was at Van Reenen (1st population) (Appendix iii). The private property was the land-use type with the highest plant abundance than commercial forests, open sites, public properties and private properties. Populations of Scotch broom, collectively, had 121135 individual plants covering 97260 m^2 (Appendix iii). The area and density of each of these populations varied widely across sites. The area ranged from 25 m^2 (Ekhubeni, 3rd population) to 28520 m^2 (in population near the Spotted Horse Country Inn). The population density ranged from 0.06 plants/m^2 (Ekhubeni, 1st population) to 9.5 plants/m^2 (Fairy Fax, 1st population) (Appendix iii).

4.4. *Population structure*

Gorse plants were up to 4.6 m tall with a maximum stem diameter of 9.8 cm and crown diameter of 4.2 m (Fig. 4.3). The mean height across populations ranged from 0.28 to 1.68 m. The maximum height, stem diameter and crown diameter across gorse populations ranged between 0.86-4.6 m, 2.8-9.8 cm and 1.14-4.15 m, respectively.

Scotch broom plants were up to 5.6 m tall with a maximum stem diameter of 15.7 cm and crown diameter of 5.9 m (Fig. 4.4). The mean height across populations ranged from 0.4 to 2.8 m. The maximum height, stem diameter and crown diameter across Scotch broom populations ranged between 1.1-5.6 m, 1.9-15.7 cm and 0.66-5.9 m, respectively.

Many populations of both species were dominated by young plants, which showed that these species are actively reproducing (Fig 4.3; Fig. 4.4; Appendix iv; Appendix v). Qualitative observations across sites suggest that seedling recruitment was high in canopy gaps and along the population boundaries than in dense stands.

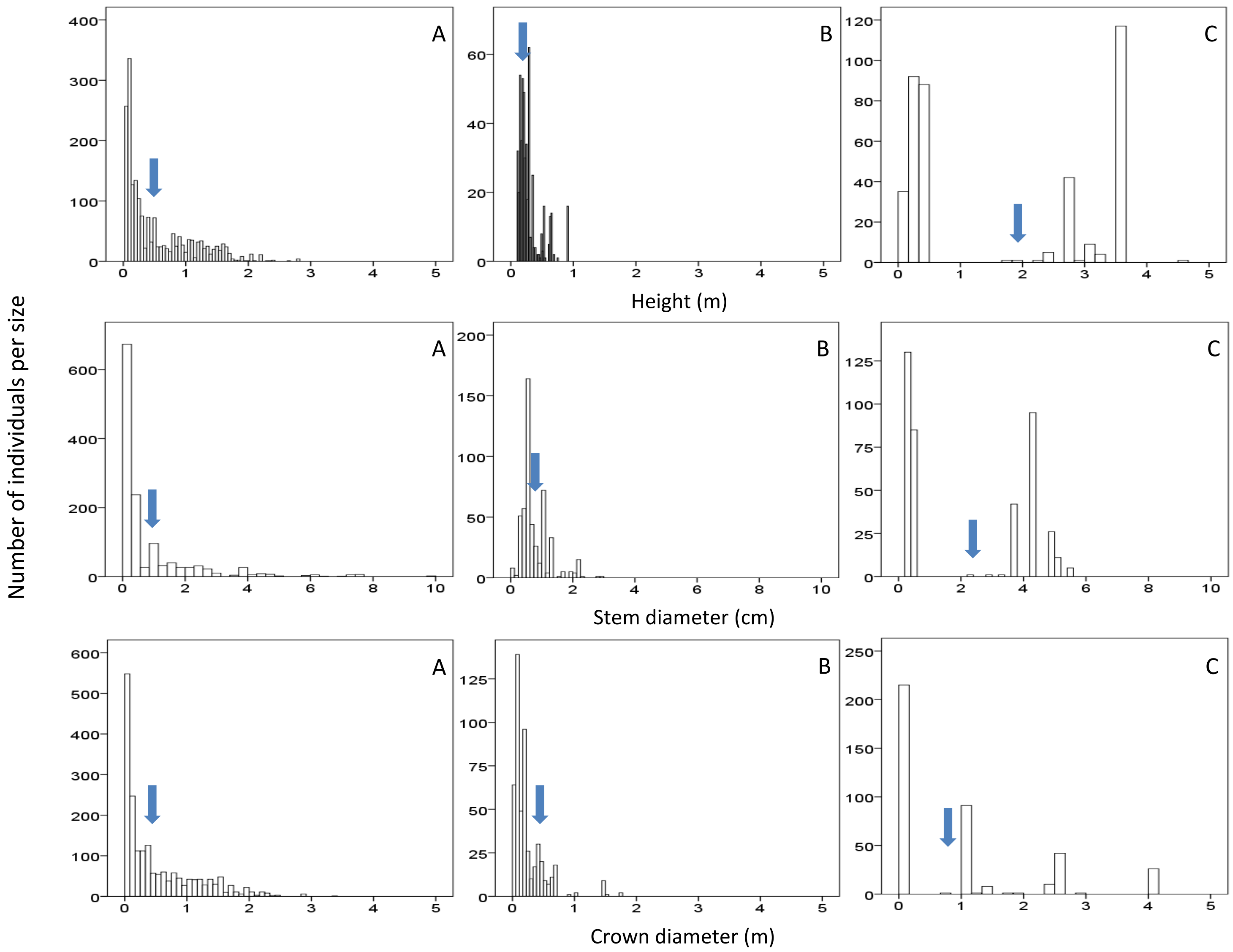

Figure 4.3: Frequency size class distribution for selected gorse populations: (A) White Mountain Lodge, (B) W17b (2nd population), (C) W14b. Mean values for each parameter (height, stem diameter and crown diameter) are represented by arrows above the bars.

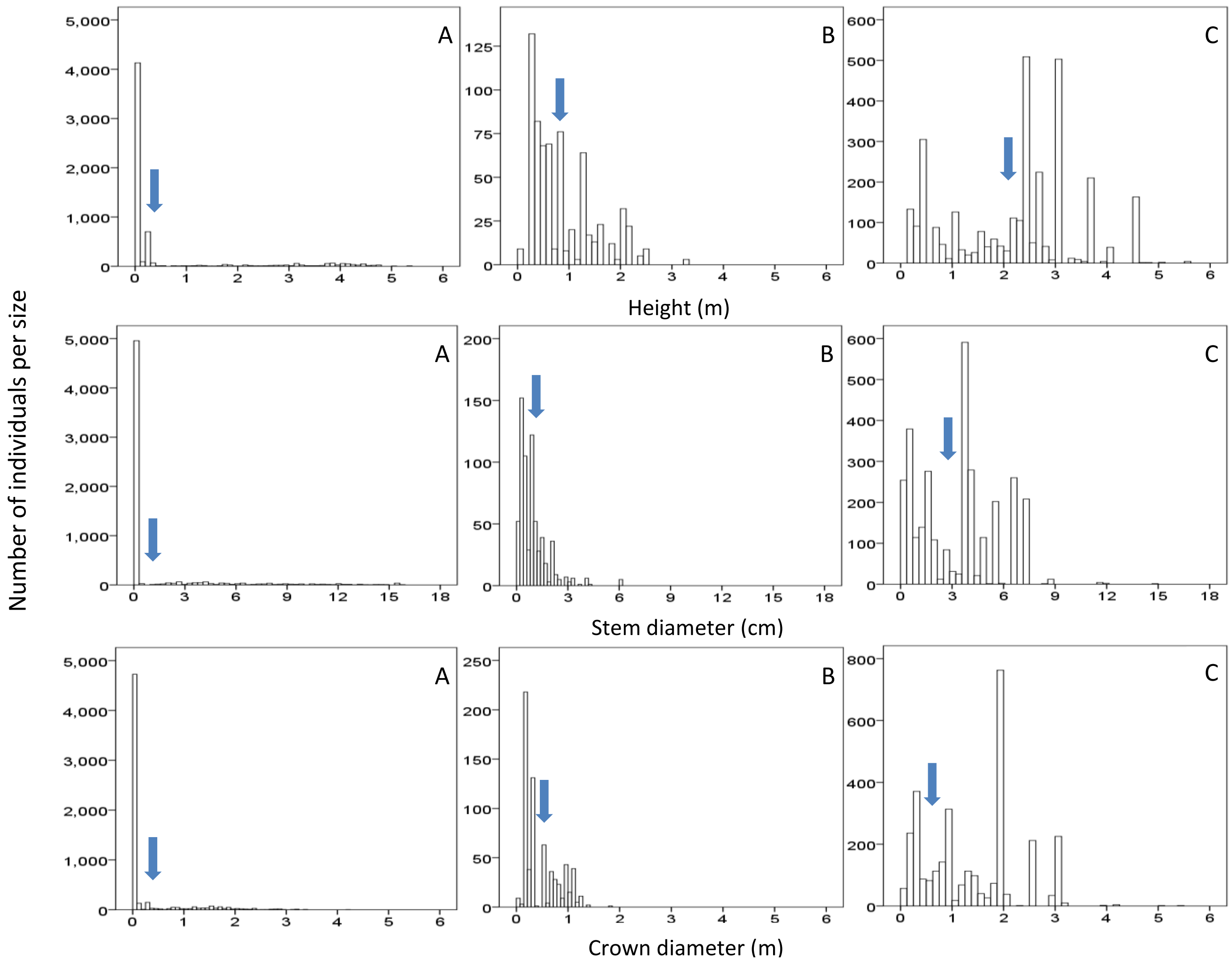

Figure 4.4: Frequency size class distribution for selected Scotch broom populations: (A) Butt farming (2nd population), (B) Gaika Road, (C) Tayler's Farm. Mean values for each parameter (height, stem diameter and crown diameter) are represented by arrows above the bars

4.5. *Reproductive biology*

4.5.1. Flowering phenology and minimum size at reproduction

Gorse and Scotch broom reproduced sexually over an extended period. The flowering onset and pod production in gorse were observed between April and early December, with a peak in winter (June-August), whereas in Scotch broom these stages were observed between June and February with a peak in November-December. During the reproductive seasons, individual plants of gorse and Scotch broom produced buds, flowers and pods synchronously, suggesting the presence of effective pollinators throughout.

These species showed signs of sexual reproduction at an early stage of growth in terms of size. Some of these plants, however, were resprouts from previously cut or eaten individuals. The individuals of gorse started flowering at a minimum height of 0.16 m, stem diameter of 0.4 cm and a crown diameter of 0.09 m (Fig. 4.5A) whereas those of Scotch broom started flowering at a minimum height of 0.17 m, stem diameter of 0.5 cm and a crown diameter of 0.1 m (Fig. 4.5B). All 14 gorse plants in Kamberg Rock Art Centre were resprouts from previously burnt plants (Fig. 4.6) and 32% (283 of 873) of Scotch broom plants in Van Reenen Cemetery were resprouts from cut stumps (Fig. 4.6).

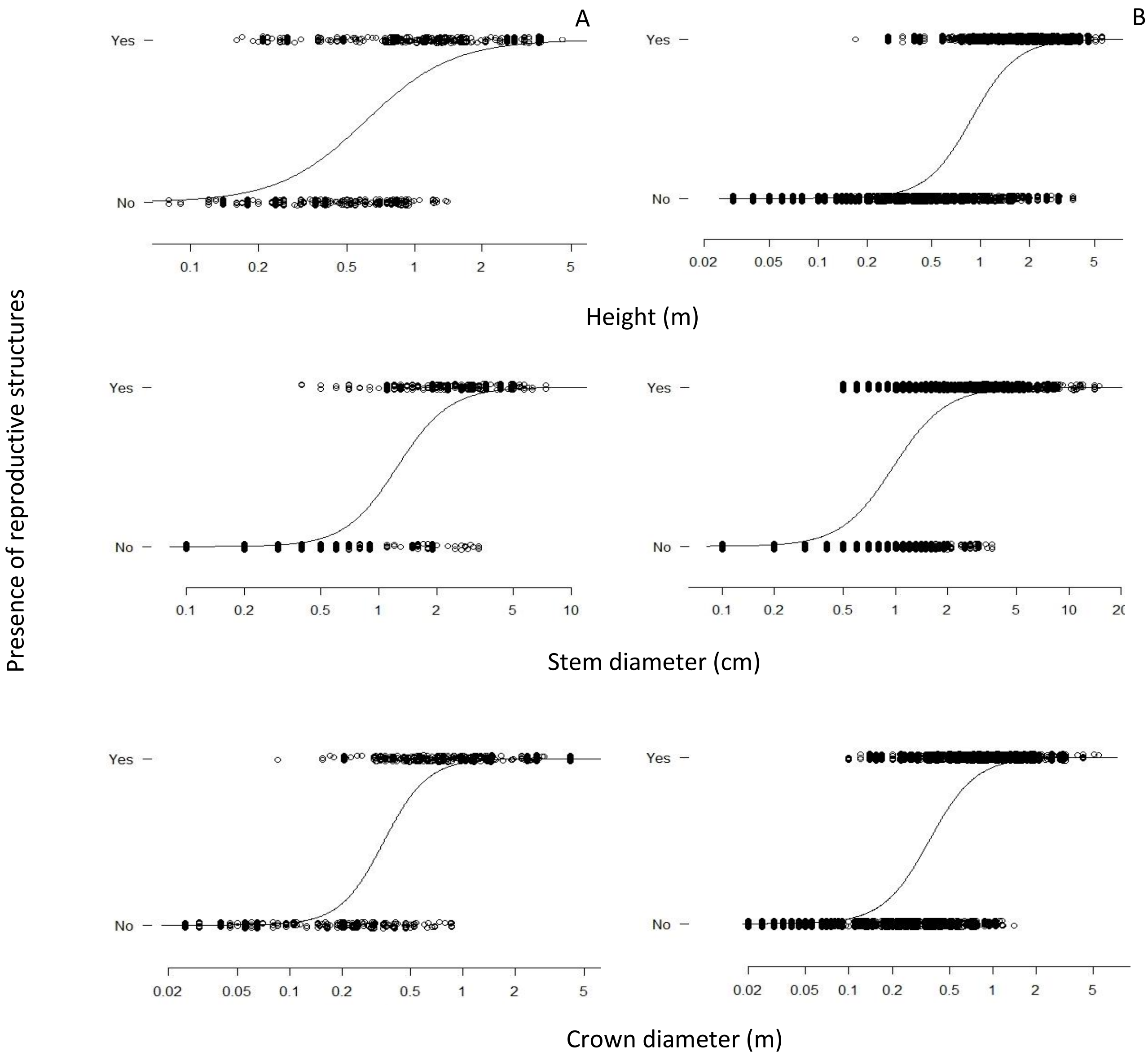

Figure 4.5: The relationship between plant growth parameters (height, stem diameter and crown diameter) and reproductive maturity in (A) gorse and (B) Scotch broom. The presence of flower buds, flowers, or seedpods was taken as an indication of reproductive maturity. The line shown is from a fitted generalised linear model with binomial errors. The log (plant height, stem diameter and crown diameters) were used as explanatory variables. The codes used to develop the model were taken from Geerts *et al*. (2013).

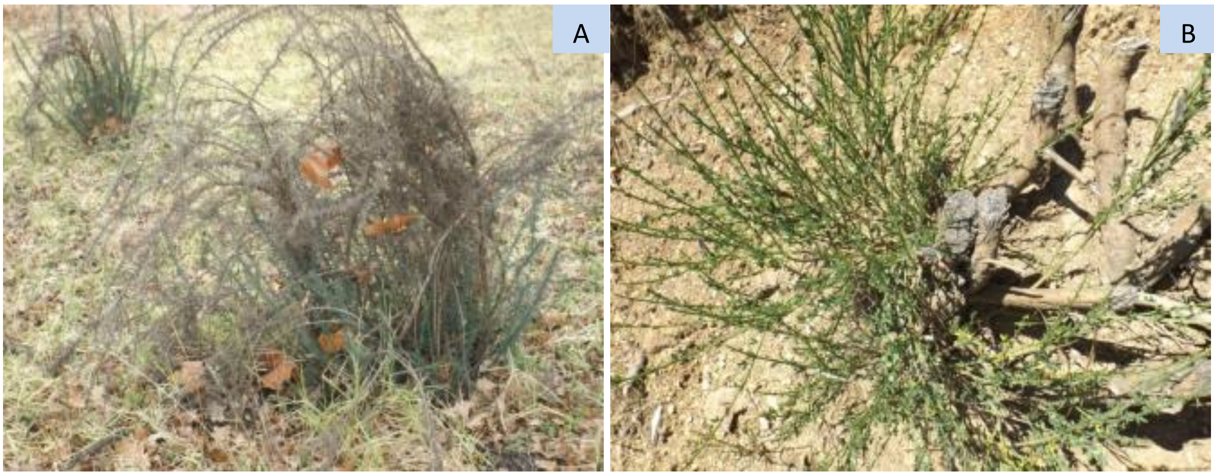

Figure 4.6: Resprouting individuals of (A) gorse from a previously burnt individual (at Kamberg Rock Art Centre) and (B) Scotch broom from a cut individual (at Van Reenen Cemetery) (photos by P.M. Mbatha, 2015).

4.5.2. Reproductive output

There was a huge variation in seed set per plant for both species. Seed set per plant ranged from 100 to 30245 in gorse. The highest seed set of 30245 seeds per plant was observed in the W16 population at Amathole Forestry. In Scotch broom populations, seed set per plant ranged from 476 to 38500. The highest seed set of 38500 seeds per plant was observed in the population near the Spotted Horse Country Inn and there were no signs of seed predation observed in either species.

The growth parameters such as height, stem diameter and crown diameter were good predictors of seed output per plant. For gorse, there was a positive linear relationship when these variables were related to seed set per plant in combination ($r^2 = 0.34$, $p < 0.0005$, Table 4.1), with crown diameter being the most influential variable (see values for partial correlation, Table 4.1). For Scotch broom, there was a positive linear relationship between growth parameters and seed set per plant when they were tested in combination ($r^2 = 0.41$, $p < 0.0005$, Table 4.1) and all these variables contributed significantly within the model ($p < 0.05$ in all cases).

Table 4.1: Statistical values for multiple linear regression models predicting gorse and Scotch broom seed output using growth parameters as the predictor variables.

Species name	Growth parameters	r^2	β	t	p	Partial correlation
Gorse	Constant	0.34	2.341	11.544	0.0005	
	Height (m)		0.181	1.092	0.279	0.117
	Stem diameter (cm)		0.035	1.169	0.247	0.125
	Crown diameter (m)		0.314	1.823	0.074	0.195
Scotch broom	Constant	0.41	3.310	40.664	0.0005	
	Height (m)		0.074	2.490	0.014	0.188
	Stem diameter (cm)		0.025	2.645	0.009	0.200
	Crown diameter (m)		0.174	2.735	0.007	0.207

4.6. *Seed characteristics, viability and germination*

Seeds produced by gorse had a length 2.9 mm, width of 2.1 mm and a height of 1 mm. The seed mass ranged from 2.99 to 8.98 mg. The length, width and height for Scotch broom seeds were 3.4 mm, 2.3 mm and 1 mm, respectively, with seed mass ranging from 4.28 to 12.44 mg. Seeds of gorse and Scotch broom were shed relatively dry with the average seed water content of 0.1 ± 0.09 g H_2O/g dry mass and 0.3 ± 0.11 g H_2O/g dry mass, respectively.

The seed germinability in both species was < 10% when incubated in Petri-dishes (between moistened paper towels) immediately after collection. Tetrazolium (TTZ) tests on seeds of both species, however, confirmed that they were viable (100% positive staining with TTZ) (Fig. 4.7).

Figure 4.7: TTZ stained embryos from seeds of (A1) gorse and (B2) Scotch broom showing 100% viability, and unstained embryos from seeds of (A2) gorse and (B2) Scotch broom.

Following results of the TTZ tests, water uptake studies were conducted on nicked and unnicked seeds. In gorse, the percentage water uptake was equivalent to 24% in nicked as opposed to 12% in unnicked seeds after 240 min imbibition period. In Scotch broom, the water uptake was equivalent to 24% in nicked as opposed to 9% in unnicked seeds.

When germination following mechanical scarification through nicking was compared with other forms of scarification, it was evident that nicking resulted in higher (100%) germinability than acid (which resulted in fungal contamination) and hot water treatments in which average germination was always ≤ 15%. A combination of dry heat and smoke treatment was the second best following nicking and resulted in 62% germinability (Table 4.2). Additionally, 15% of seeds exposed to heat and smoke treatment had signs of few cracks on the seed coats.

Table 4.2: Final percentage germination in gorse and Scotch broom seeds after 15 days incubation following different scarification methods. Values represent mean ± SD (n = 10) for each of four replicates; data are shown for treatment that resulted in maximum germination.

Species	**Control (%)**	**Nicking (%)**	**Heat + smoke (%)**	**Sulphuric acid (%)**		**Hot water (%)**
				10 minutes	40 minutes	100°C
Gorse	8±10	100	62±4	-	13±9.6	8±5
Scotch broom	5±5	100	62±4	5±5.8	-	15±23.8

4.7. *Seed bank studies*

Results from seed bank studies conducted in three populations per species showed that gorse and Scotch broom have accumulated large seed banks. For gorse, seed bank density ranged from 736-54624 seeds/m^2 within populations and the means ranged from 3563-29082 (Table 4.3). Seed bank density of Scotch broom ranged from 1856-79248 seed/m^2 within populations and the means ranged from 5536-41397 seed/m^2 (Table 4.3). Estimated seed bank size per population was extremely high (> 8 million in all cases).

Table 4.3: Estimated seed bank size of gorse and Scotch broom in three selected populations per species in South Africa.

Species and population names		**Area covered (m^2)**	**Seeds/m^2**	**Estimated seed bank size per population**
Gorse	W17b	1466	29082±15798	42634212
	W24a	6018	4754±2243	28609572
	White Mountain Lodge	7266	3563±1680	25888758
Scotch broom	X19 (1st population)	1551	5536±4093	8586336
	Roadside to Lower Loteni	2440	11130±3207	27157200
	near the Spotted Horse Country Inn	28529	41397±19810	1181015013

The seed bank density of both species was higher under the adult plants than from under the young individuals. As with seeds collected from parent plants, there were no signs of seed predation in both species. The germinability of gorse and Scotch broom seeds extracted from seed banks was 98% and 97%, respectively (Fig. 4.8). However, as with seeds collected from parent plants, seeds from the seed banks had to be nicked in order to germinate. The germination rate of fresh seeds and those from seed banks was comparable.

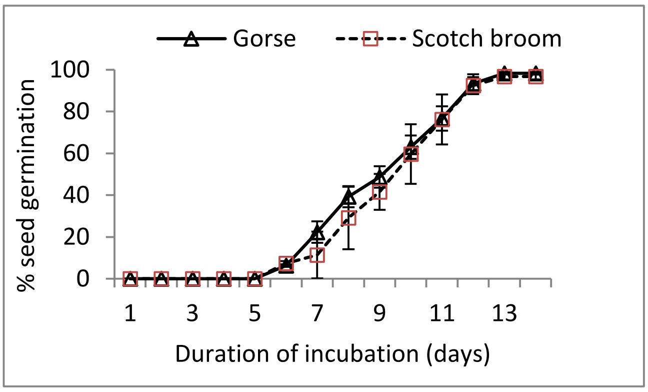

Figure 4.8: The germinability of nicked (Δ) gorse and (□) Scotch broom seeds from seeds banks. Values represent mean ± SD, n = 25 for each of four trials.

There was a strong negative linear relationship between seed bank size and a distance from parent plants in both species ($r^2 = 0.67$, $p < 0.0005$ for gorse; $r^2 = 0.84$, $p < 0.0005$ for Scotch broom). Sixty-seven and 84% variability in seed bank density of gorse and Scotch broom, respectively, was explained by a change in distance from the parent plants. Gorse seed banks decreased to 20% and 10% at a two and four-meter distance, respectively, from the parent plants. Scotch broom seed banks decreased to 4% and 2% at a two and four-meter distance, respectively, from the parent plants.

4.8. *Assessment of post-fire regrowth in Scotch broom*

During the initial survey conducted three months following the fire event, there were no seedlings or resprouts from the burnt population (Fig. 4.9A & B). At the time of the second survey conducted one year later, however, the density of grown up plants (from germinated seeds) was significantly higher in burnt compared with unburnt plots (Fig. 4.9C & D; Fig. 4.10A), and the abundance of small seedlings was very low in both plots. The percentage cover was not significantly different across treatments (Fig. 4.10B) and all parent plants in burnt plots showed no signs of resprouting (Fig. 4.9B).

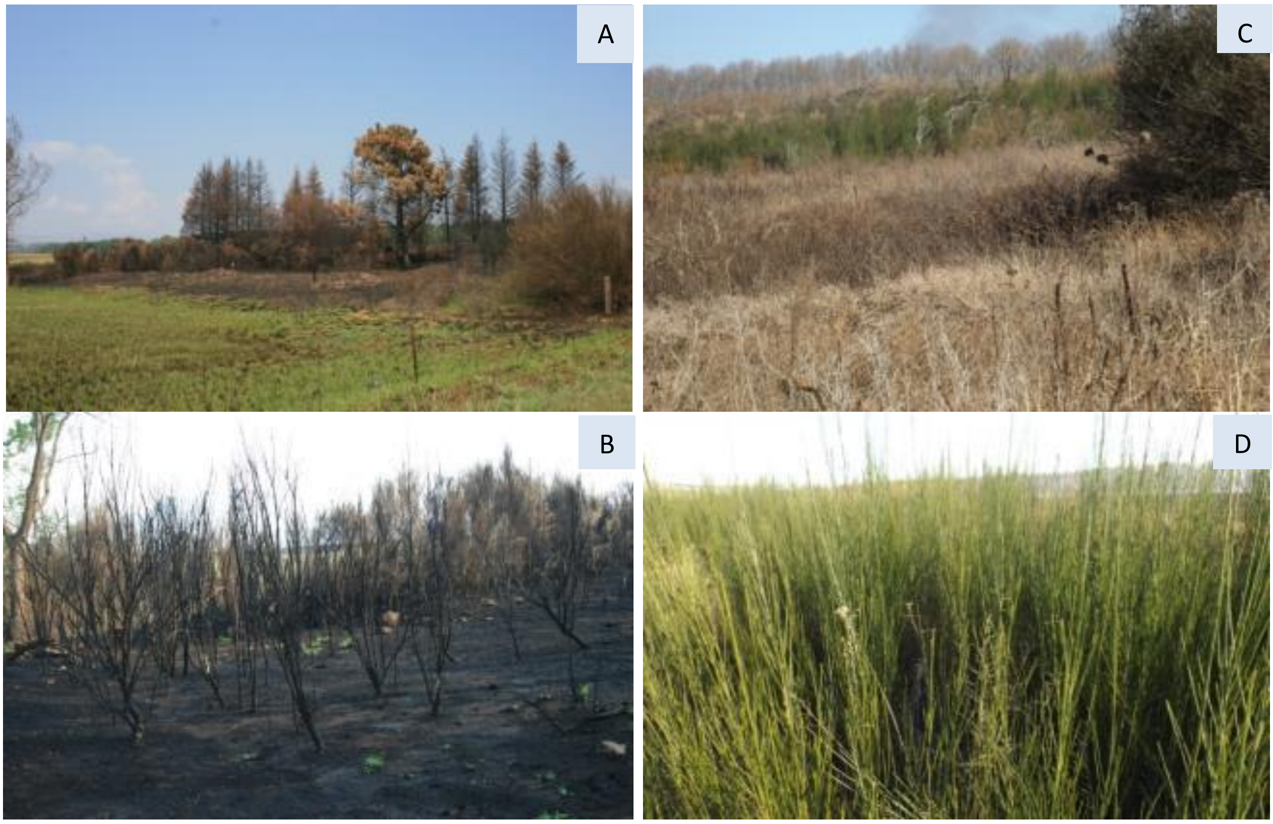

Figure 4.9: The Scotch broom population that experienced fire in 2014 at Kamberg (KZN); (A-B) show site condition three months following fire event (June 2014); (C-D) show site condition 15 months after fire event (July 2015). A & C show landscape views of the site while B & D show close up views.

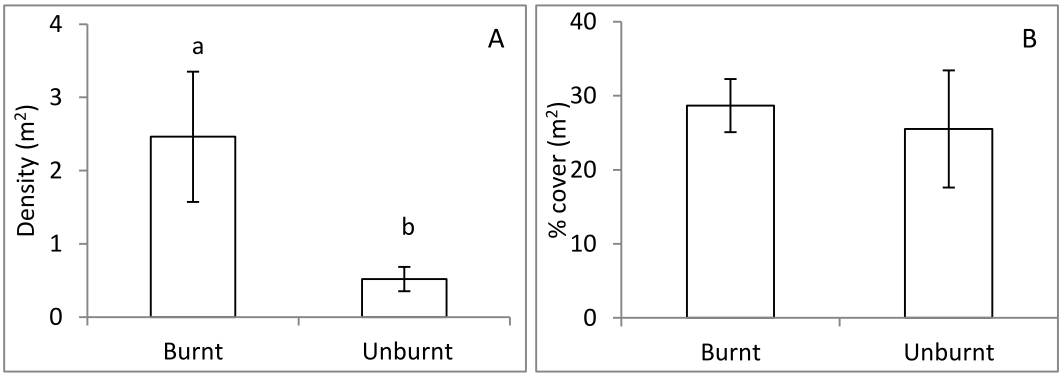

Figure 4.10: The Density (A) and percentage cover (B) of Scotch broom in burnt and unburnt plots at Kamberg, (KZN) 15 months after the fire event. Values represent mean ± SD, n = 10 and are significantly different when labelled with different letters ($p < 0.0005$, Independent sample t-test for plant density and $p = 0.481$, Mann-Whitney U test for percentage cover).

4.9. *Seed and seedling responses to elevated temperatures*

The germination success in seeds of both species did not differ significantly between ambient temperatures (midday/night average: 23.8/13.8 ± 2°C) and elevated temperatures (midday/night average: 28.4/18.5 ± 2°C), and ranged between 60 and 63% in all cases (Fig. 4.11A & B). The germination rate was also not significantly different across treatments (t =

0.0001, df = 6, p = 1, n = 10 for each of four trials, Independent sample t-test for gorse; and t = -0.522, df = 6, p = 0.620, n = 10 for each of four trials, Independent sample t-test for Scotch broom).

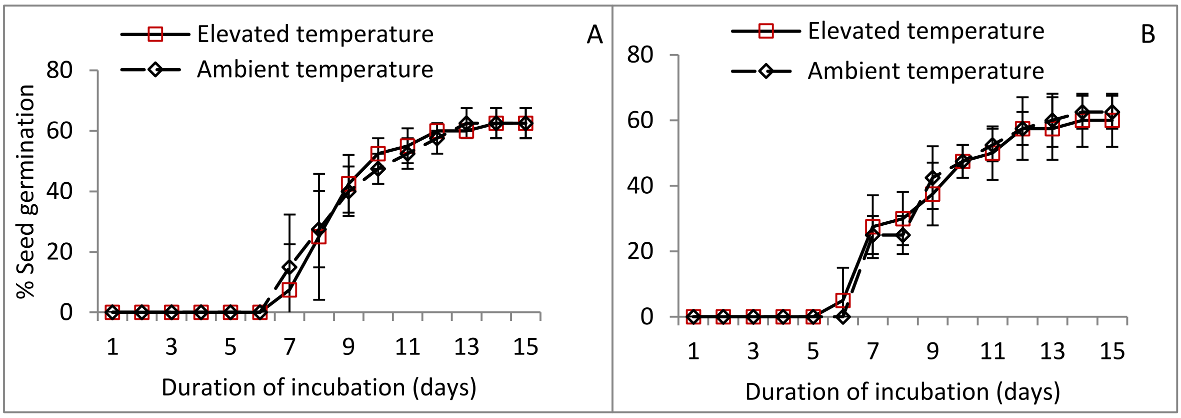

Figure 4.11: Percentage germination of (A) gorse and (B) Scotch broom seeds at (◊) ambient and (□) elevated temperatures. Values represent mean ± SD, n = 10 for each of four trials (t = 0.0001, df = 6, p = 1, Independent sample t-test for gorse; and t = -0.491, df = 6, p = 0.641, Independent sample t-test for Scotch broom).

The percentage seedling emergence in both species was also not significantly different between ambient and elevated temperatures and surprisingly very low (< 30%) (Fig. 4.12) compared to 60% and 63% seed germinability observed in both species.

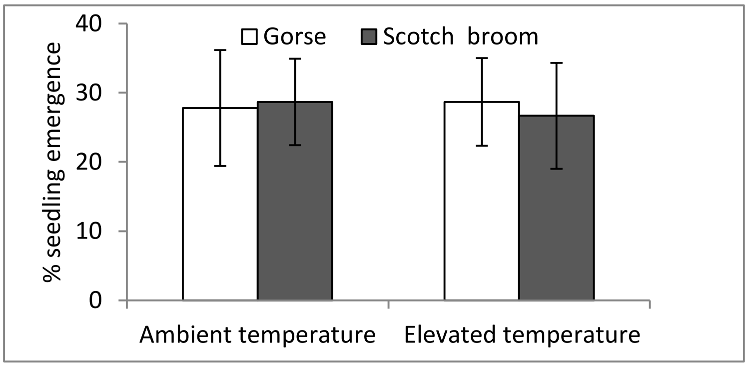

Figure 4.12: Average gorse and Scotch broom seedling emergence at ambient and elevated temperatures. Values represent mean ± SD, n = 30 for each of four trials (t = -0.195, df = 6, p = 0.852, Independent sample t-test for gorse; and t = 0.020, df = 6, p = 0.985, Independent sample t-test for Scotch broom).

The seedling growth of gorse was significantly better at ambient temperatures in terms of height (t = 7.865), stem diameter (t = 8.560), crown diameter (t = 6.213) and dry biomass (t = 9.085) (df = 18, p < 0.0005 in all cases, Fig. 4.13). Similarly, Scotch broom seedlings grew better at ambient temperatures in terms of height (Z = -3.781, p < 0.0005, Mann-Witney U test), biomass (t = 6.299), crown diameter (t = 5.112) and stem diameter (t = 4.958) (df = 18, p < 0.0005, Independent sample t-test) (Fig. 4.13).

After 120 days of plant growth, gorse grew up to 18 cm tall with a stem diameter of 0.6 cm and a crown diameter of 35 cm at ambient temperatures as compared to the height of

15 cm, stem diameter of 0.25 cm and a crown diameter of 20 cm at elevated temperatures (Fig. 4.13A-C). The differences in height and crown diameter between treatments manifested after eight to nine weeks of seedling growth (Fig. 4.13A & C), whereas these differences in terms of stem diameter were apparent after three to four weeks of seedling growth (Fig. 4.13B). Gorse started to show signs of phyllode emergence beneath leaves after three to four weeks of growth, suggesting an early constitutive defence strategy

After 120 days of plant growth, Scotch broom grew up to 60 cm tall with a stem diameter of 0.55 cm and a crown diameter of 60 cm at ambient temperatures as compared to the height of 25 cm, stem diameter of 0.2 cm and a crown diameter of 30 cm at elevated temperatures (Fig. 4.13D-F). The differences in height and crown diameter between treatments manifested after eight to nine weeks of seedling growth (Fig. 4.13D & F), whereas these differences in terms of stem diameter were apparent after three to four weeks of seedling growth (Fig. 4.13E).

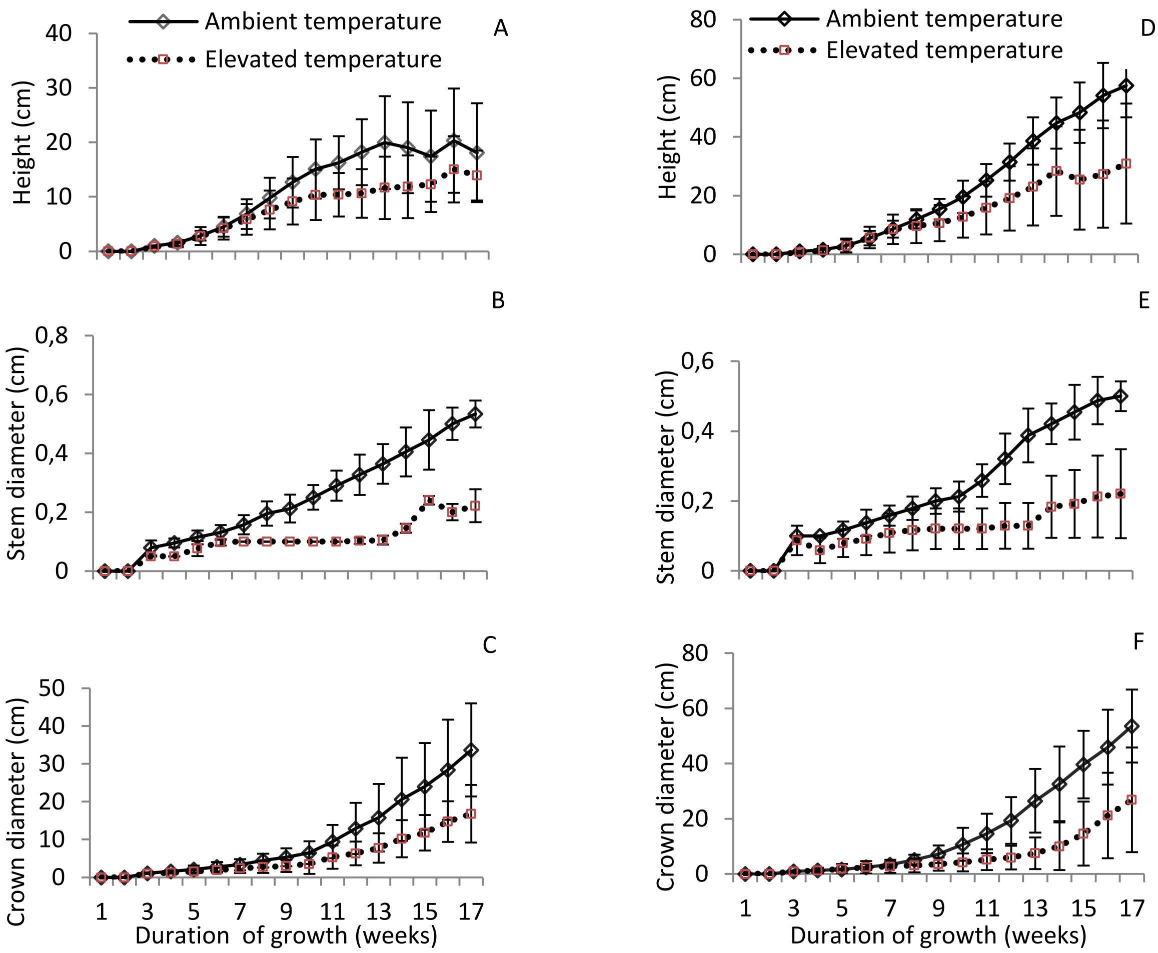

Figure 4.13: Seedling growth of (A-C) gorse and (D-F) Scotch broom at (◊) ambient and (□) elevated temperatures measured on weekly basis. Values represent mean ± SD (n = 21 for gorse and n = 12 for Scotch broom). For both species, $p < 0.05$ when final values were compared between treatments (Independent samples t-test/Mann-Whitney U test).

The cumulative growth in dry biomass and leaf area for gorse and Scotch broom seedlings were significantly lower at elevated temperature but root: shoot ratios were not significantly different (Table 4.4). Total biomass was reduced by 96% and 86% in gorse and

Scotch broom seedlings, respectively (Fig. 4.14A & B). The biomass partitioning across treatments was similar in both species, with gorse seedlings producing more phyllode than shoot and root biomass, while Scotch broom seedlings produced more shoot than leaf and root biomass (Fig. 4.14A & B). The leaf area of gorse and Scotch broom was reduced by 90% and 60%, respectively, at elevated temperature (Table 4.4). Gorse and Scotch broom leaf area ratios were significantly reduced by 49% and 65%, respectively, at ambient temperature (Table 4.4).

Table 4.4: Root: shoot ratio, leaf area and leaf area ratio in gorse and Scotch broom seedlings produced and subsequently grown at ambient and elevated temperatures for four months. Values represent mean ± SD (n = 10), and are significantly different when labelled with different letters: for gorse; $p = 0.269$ for root: shoot ratio ($t = -1.141$) and $p < 0.0005$ for leaf area ($t = 8.793$) and leaf area ratio ($t = -4.050$). For Scotch broom; $p = 0.935$ for root: shoot ratio ($t = -0.082$,) and $p < 0.0005$ for leaf area ($t = 4.227$) and leaf area ratio ($t = -6.687$) (df = 18 Independent sample t-test).

Parameters	**Gorse**		**Scotch broom**	
	Ambient temperature	**Elevated temperature**	**Ambient temperature**	**Elevated temperature**
Root: shoot ratio	0.06 ± 0.04[a]	0.12 ± 0.15[a]	0.08 ± 0.03[b]	0.08 ± 0.03[b]
Leaf area (cm^2)	1007.20 ±450.20[c]	94.50 ± 55.70[d]	1079.10 ± 409.00[e]	425.90± 267.50[f]
Leaf area ratio	66.70 ± 21.50[g]	131.60 ± 53.50[h]	55.40 ± 21.70[i]	160.30 ± 58.00[j]

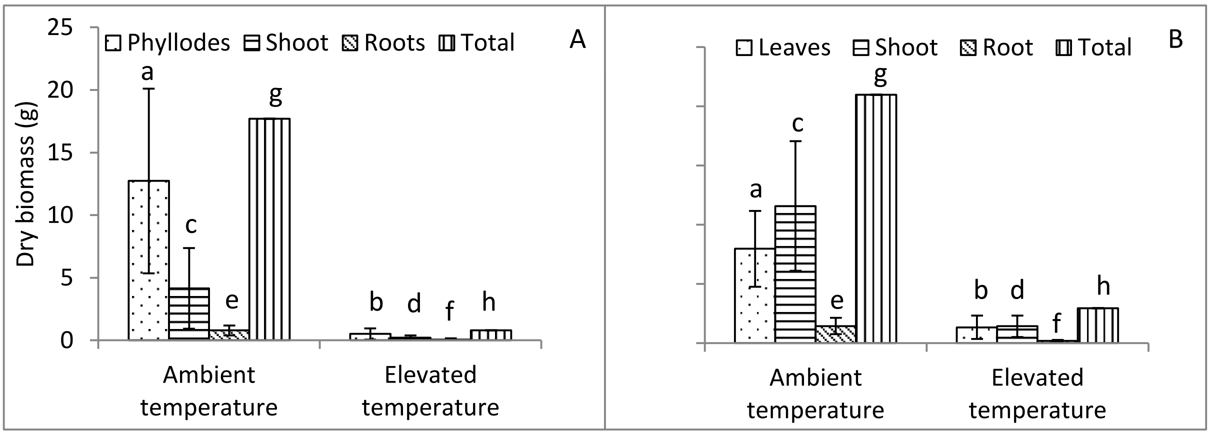

Figure 4.14: Biomass accumulation in (A) gorse and (B) Scotch broom produced and subsequently grown at ambient and elevated temperatures for four months. Values represent mean ± SD (n = 10), and are significantly different between treatments, within categories when labelled with different letters ($t = 9.085$, df = 18, $p < 0.0005$ for gorse and $t = 6.299$, df = 18, $p < 0.0005$ for Scotch broom [Independent sample t-test]).

The percentage biomass allocation of phyllodes (for gorse) or leaves (for Scotch broom), stems and roots relative to total biomass was not significantly different across treatments in gorse and Scotch broom seedlings (Fig. 4.15A & B). Phyllode production in gorse seedlings, however, was slightly higher by 11% at ambient temperature, whereas shoot and root production were slightly higher at elevated temperature by 7% and 4%, respectively. In Scotch broom seedlings, leaf production was slightly higher by 7% at elevated temperature, while shoot and root productions were slightly higher at ambient temperature by 7% and 0.1%, respectively.

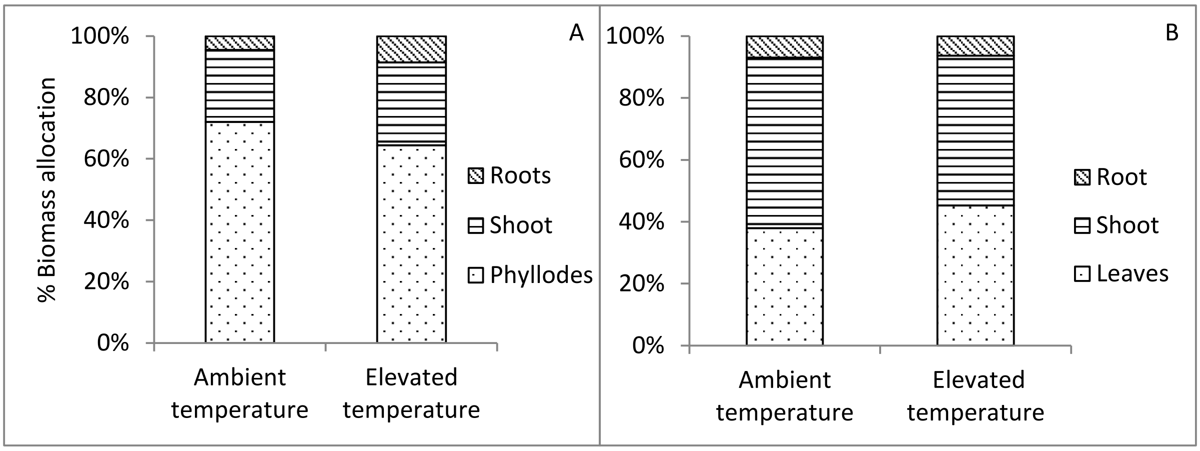

Figure 4.15: Percentage biomass allocation relative to total biomass in (A) gorse and (B) Scotch broom seedlings after four months of growth at ambient and elevated temperatures. Values represent means (n = 10). There were no significant differences between treatments, within categories. For gorse: Z = -1.663 and p = 0.096 (Mann-Witney U test) for phyllodes; Z = -0.907 and p = 0.364 (Mann-Witney U test) for shoots and t = -1.125, df = 18 and p = 0.275 (Independent sample t-test) for roots. For Scotch broom: t = -1.783 and p = 0.091 for leaves, t = 1.866, and p = 0.078 for shoots and t = 0.102, p = 0.920 for roots (df = 18, Independent sample t-test).

4.10. *Weed risk assessment*

Forty-one of the 49 questions in the weed risk assessment were answered for gorse while 42 were answered for Scotch broom thus meeting the minimum requirements for such an assessment (Pheloung *et al*., 1999). The answers to these questions came from the literature and the data collected in this study. The answers pertaining to gorse assessment are shown in Appendix vi, while those pertaining to Scotch broom assessment are shown in Appendix vii. The assessment for gorse resulted in a total score of 25 points: 11 points from the biogeography related questions, 6 points from questions related to undesirable traits and 8 points from questions related to biology/ecology. The assessment for Scotch broom resulted in a total score of 25 points: 11 points from the biogeography related questions, 6 points from questions related to undesirable traits and 8 points from questions related to biology/ecology. Both species therefore fail a post-border assessment as their scores are higher than six, which is the value beyond which a species can be considered potentially invasive (Pheloung *et al*., 1999). We therefore recommend an immediate implementation of management options for both species while the extent of spread is still minimal.

4.11. *Management options and the associated costs*

The use of Garlon triclopyr in the management of gorse and Scotch broom was effective in this study. This herbicide was 100% effective in killing gorse individuals at both, 1 and 2% concentrations. In Scotch broom, the 1, 2 and 4% concentrations were 99.1, 99.8 and 100% effective, respectively (Table 4.5). The labour and chemical costs associated with the initial clearing of one population (of known size) for either gorse or Scotch broom, are shown in Table 4.6. The estimated labour and chemical costs associated with the initial clearing of all identified gorse and Scotch broom populations in South Africa were c. ZAR 24100 and c. ZAR 534940, respectively (Table 4.7). The estimates presented here, however, do not cover costs for transport, equipment, camp allowances etc., which should ultimately also be taken into consideration.

Table 4.5: The efficacy of triclopyr in the clearing of selected gorse and Scotch broom populations in Hogsback (EC).

Species and locality	**Treatment**	**Herbicide usage**	**No. of treated individuals**	**No. of resprouts after one year**	**Plant mortality (%)**
Gorse (W14b)	Cut stump and foliar spray	Garlon (triclopyr butoxy ethyl ester 480 g/L) 1%	45	0	100
	Cut stump and foliar spray	Garlon (triclopyr butoxy ethyl ester 480 g/L) 2%	73	0	100
	Cutting	None	444	25	94.4
Scotch broom (X19, 1st population	Cut stump and foliar spray	Garlon (triclopyr butoxy ethyl ester 480 g/L) 1%	118	1	99.1
	Cut stump and foliar spray	Garlon (triclopyr butoxy ethyl ester 480 g/L) 2%	522	1	99.8
	Cut stump and foliar spray	Garlon (triclopyr butoxy ethyl ester 480 g/L) 4%	130	0	100
	Cutting	None	104	14	86.5

Table 4.6: Chemical and labour costs associated with the clearing of one gorse and Scotch broom populations in Hogsback (EC).

Amount of chemicals purchased (L)	**Unit price (R)**	**Populations treated**	**Area covered (m^2)**	**Amount of chemicals used (L)**	**Costs for herbicide and Eco-dye used**	**Labour costs (R)**	**Total costs (R)**
5 L triclopyr 1 L Eco-dye	R 795.7 R 106.9	Gorse (W14b)	538	0.15 L herbicide and 0,1 L Eco-dye	R 34.56	R 752.90	R 787.46
		Scotch broom (X19, 1st population)	1551	0.45 L herbicide and 0.2 L Eco-dye	R 92.99	R 752.90	R 845.89

Table 4.7: Estimated chemical and labour costs for the initial clearing of all known gorse and Scotch broom populations in South Africa. The costs presented here exclude additional costs (i.e. transport etc.).

Species	**Total area (m^2)**	**Chemical costs (ZAR)**		**Labour costs (ZAR)**		**Estimated total costs for initial clearing (ZAR)**
		per m^2	**For total area**	**per m^2**	**For total area**	
Gorse	16508	R 0.06	R 990.48	R 1.40	R 23111.20	R 24100
Scotch broom	972625	R 0.06	R 58375.50	R 0.49	R 476586.25	R 534960

Chapter 5: Discussion

5.1. *Introduction*

Gorse and Scotch broom are wide spread invaders worldwide, but empirical data on the invasive status in South Africa are limited. This study was therefore conducted to assess aspects related to species distribution and spread. It was evident that populations of gorse and Scotch broom are confined in areas where both species were initially introduced, and varied widely in size. As a result, factors that could possibly limit the species spread and population growth are discussed by relating findings from this study to those reported elsewhere on gorse and Scotch broom, or related species. Given the fact that both species have high invasive potential in South Africa, recommendations regarding the control of both species are given and suggestions for future studies are provided in the concluding chapter.

5.2. *Species distribution*

The distribution of gorse and Scotch broom is currently limited to the eastern part of South Africa, mostly in mountainous regions, as previously reported by Mgidi *et al*. (2007). These regions are most likely to have experienced high rates of introduction during the 1930s and 1940s because Seabloom *et al*. (2006) reported that exotic plants colonise region with high introductory rates. These species may have then persisted at these locations because regions of high altitudes have cool temperatures (Barry, 1992; Mgidi *et al*., 2007), which promote seed germination in gorse and Scotch broom (Bossard, 1993; Sixtus *et al*., 2003). The rainfall in these regions is also high (Barry, 1992; Mgidi *et al*., 2007), thus making conditions favourable for the establishment of gorse and Scotch broom, both of which are regarded as drought sensitive species (Fox and Steinmaus, 2001; Potter *et al*., 2009).

The limited distribution of these species to other parts of the country, however, could have been due to limited introductory efforts by humans (intentionally or accidentally) and lack of effective long-distance seed dispersers. According to Coutts *et al*. (2011), the dispersal of propagules facilitates the species spread. With limited dispersal, however, exotic plants fail to colonise suitable sites away from their geographical ranges (Primack and Miao, 1992; Boulangeat *et al*., 2012).

5.3. *Land-use type and population size*

Populations of gorse and Scotch broom colonised a wide range of land-use types (i.e. open sites, commercial forests, nature reserves, public and private properties) with contrasting levels of disturbance as reported elsewhere (Hill *et al*., 2001; Bellingham and Coomes, 2003; Harrington, 2009). Historical records do not provide details on how both species arrived in South Africa. The present study, however, suggests that these species may have arrived in commercial forests as contaminants. The presence of some populations in private or public properties suggests that gorse and Scotch broom were also introduced deliberately either as hedge or ornamental plants. Due to poor gardening practices (i.e. the cultivation of alien species along the garden margins in high abundances and the lack of proper species management) (Marco *et al*., 2010), these species could have then escaped to surrounding open areas. The lack of proper species management in open sites and commercial forests, and poor gardening practices in private properties appear to have resulted in an increase in number of individual plants within these land-use types.

The total area covered by both species was relatively small (i.e. < four ha for each species, see Appendix ii and iii) compared with those reported in other countries. In Hawaii, gorse is estimated to have covered 4000 ha of pastoral land (Leary *et al*., 2006) while Scotch broom has spread to over 250000 ha in California (Bossard, 1993). Population size of both species also differed widely across sites (Appendix ii and iii). The large variation in population size and low extent of invasion observed in this study may be attributed to propagule pressure, which is the number of introduced individuals and the associated introductory effort at a given site (Colautti *et al*., 2006). As reported previously, propagule pressure is positively correlated with species naturalisation (Warren *et al*., 2013), and therefore, large populations found in this study may have been associated with high propagule pressures and smaller ones with small propagule pressures. The overall propagule pressure in South Africa, however, may have been lower than the propagule pressures introduced into other countries such as California and New Zealand.

Another factor that could have contributed to variation in population size is residence time, defined as the period of population existence since from the date of first record (Wilson *et al*., 2007). According to Truemen *et al*. (2010), minimum residence time also correlate positively with species establishment and naturalisation. The high abundance of *Trifolium* sp. introduced for commercial purpose relative to those introduced for agricultural trials and horticulture in New Zealand, for example, was associated with long residence time (Gravuer *et al*., 2008). As a result, larger populations found in this study may have been introduced earlier than smaller populations.

Differences in the type and intensity of disturbance events may have also influenced the establishment of gorse and Scotch broom at certain sites. Disturbance such as fire for example, kills gorse and Scotch broom thus creating suitable sites for species establishment (Rees and Hill, 2001; Srinivasan *et al*., 2012). Fire also promote seedling recruitment (Srinivasan *et al*., 2012) by breaking seed dormancy (Paynter *et al*., 1998). Moreover, fire alters the availability of nutrients in the soil (Soto *et al*., 1997), and when reduced, the plant growth gets retarded (Huenneke *et al*., 1990). In the present study, the analysis of soil nutrients in disturbed habitats was not performed, but could have affected the growth and establishment of gorse and Scotch broom at different sites, thus leading to variation in population size.

Guilioni *et al*. (2003) reported that water deficit and heat stress reduce seed set per plant. These factors reduce seed set by lowering the plant growth, which then affects total plant biomass (McDonald and Paulsen, 1997; Guilioni *et al*., 2003). These factors may have also affected the population growth of gorse and Scotch broom in South Africa by lowering seed set at some sites (especially those receiving low rainfall and elevated temperatures).

5.4. *Population structure*

This study confirmed that both species grow above 4 m tall (Fig. 4.3 and 4.4) in mountainous regions with moderate climatic conditions. Similarly, Lee *et al*. (1986) observed similar trends in gorse, and reported the species to grow up to 7 m tall in disturbed hilly regions of South Island, New Zealand with moist costal climates. Downey and Smith (2000) reported Scotch broom to grow up to 6.7 m tall in regions of high altitude (i.e. 1500 m above sea level, receiving 1700 mm annual precipitation) at Barrington Tops, New South Wales. When comparing the growth form of Scotch broom between native and introduced ranges, Fowler *et al*. (1996) reported the species to grow much taller in the introduced compared to native regions. The enhanced growth in the introduced regions is attributed variation in climate and soil types (Fowler *et al*., 1996). These factors could have enhanced the growth of individual plants for both species in sites with moist climatic conditions, where individuals of both species were growing above 4 m tall. Some populations of both species, however, had individual plants with maximum heights less than 3 m tall (Fig. 4.3A & B; Appendix iv; Appendix v). Such poor growth may be attributed to intraspecific competition within populations and the unsuitability of environmental conditions, while other populations may have had short minimum residence time.

Populations of gorse and Scotch broom were dominated by smaller plants as noted by Kaplan *et al*. (2012) for *Acacia implexa* in Western Cape, South Africa, and the seedling recruitment was higher in open canopy and along populations' periphery as reported by Downey and Smith (2000) for Scotch broom. In general, low numbers or absence of seedlings from dense stands occurs due to predation pressure (from natural enemies and pathogens), shading and competition for resources such as water and light (Fowler *et al*., 1996; Paynter *et al*., 1998). In the present study, shading and competition for resources are most likely to have reduced seedling recruitment in dense stands. Predation pressure and the effect of pathogens may have also affected seedling recruitment, but no evidence of this was observed throughout the course of this study.

5.5. *Reproductive biology*

The flowering onset (often driven by precipitation and seasonal temperatures) (Crimmins *et al*., 2010; Crimmins *et al*., 2013) and pod production (often controlled by the pollinator availability) (Mahoro, 2002) in individuals of both species were prolonged (i.e. occurred over a period of eight months). The long flowering phenotype observed suggests that the areas invaded by both species had climatic conditions suitable for the triggering of flowering onset. The extended flowering in invasive plants is advantageous because it allows the species to escape seed predation pressure (Atlan *et al*., 2010), and there was no seed predation observed in this study. Moreover, the long flowering phenology increases chances of plant pollination during the reproductive seasons (Petanidou *et al*., 2014). The prolonged pod production on the other side, suggests that pollinators for both species are active and are available throughout the reproductive seasons (Mahoro, 2002).

Gorse and Scotch broom started to show signs of sexual reproduction at an early stage of plant regrowth (Fig. 4.5) from previously cut stumps or predated individual plants. This therefore suggest that both species are actively reproducing and utilise multiple reproductive mechanisms to aid in population recovery and growth. In addition, matured individuals of these species produced high seed set. This high seed productivity may be attributed to the fact that Scotch broom (Parker *et al*., 2002) and gorse (Bowman *et al*. (2008) produce more pollen as a reward in order to increase the pollinator visitation rate (Suzuki, 2000).

5.6. *Post-harvest seed biology*

Seeds of both species were small with a seed mass less than 12.45 mg. According to Brewer (2001), species that produce small seeds experience less seed predation and have high seed survival and low mortality rates compared with those producing large seeds. Findings by Pizo *et al*. (2006), however, contradict those of Brewer (2001). For example, Pizo *et al*. (2006) reported that seed predators do not target seeds based on size in other plant species. In addition, Malcolm *et al*. (2003) and Pizo *et al*. (2006) reported seed germination and seedling growth to increase with an increase in seed size. High seed germinability in large seeds and enhanced growth in seedlings from those seeds are attributed to high nutrient availability to the developing embryo (Malcolm *et al*., 2003). In some species polyploidy can also enhance seed germinability (Bretagnolle *et al*., 1995) and this may have been the case in the small seeds of both species investigated here, as both species are allopolyploid (i.e. have more than two sets of chromosomes [Misset *et al*., 1996; Aguinagalde *et al*., 2002]).

The germination trials indicated that seeds of gorse and Scotch broom exhibited physical dormancy. The water impermeable seed coat reduced the water uptake and the germination success in unnicked seeds (Table 4.2). Dormancy breaking through mechanical scarification, however, increased seed water uptake and hence the germination success within a 14-day incubation period (Table 4.2). Similar findings were also reported by Tarrega *et al*. (1992) in Scotch broom seeds. An increase in water uptake and germination success after mechanical scarification is proposed to have occurred through water gaps created during seed scarification (Turner *et al*., 2009). Heat plus smoke treatments also enhanced the seed germinability in both species, but not as much as mechanical scarification (Table 4.2). Enhanced seed germinability following smoke treatment is common in a number of species, especially those colonising fire-prone habitats (Dixon *et al*., 1995; Crosti *et al*., 2006). This enhanced germinability in seeds of gorse and Scotch broom, may have occurred because smoke sends signals to seeds that there has been fire, and that conditions are favourable for seed germination (Roche *et al*., 1997). Moreover, direct heat may have also influenced seed germinability because some seeds of both species were having few cracks following the exposure to heat and smoke treatment.

Other scarification methods such as hot water and sulphuric acid did not enhanced germinability in seeds of gorse and Scotch broom (Table 4.2). Bossard (1993), however, reported that heat scarification resulted in 98% germination success in Scotch broom seeds while Sixtus *et al*. (2003) reported the germination success of 81% in gorse seeds following sulphuric acid scarification. The poor seed germinability observed in this study following heat scarification suggests that seeds of both species required an incubation period longer than two weeks (Núñez and Calvo, 2000). The poor germinability observed in this study following acid scarification is not clear, but may have occurred due to fungal contamination observed in seeds of both species in this study.

5.7. *Seed bank studies*

Seed bank studies revealed that populations of gorse and Scotch broom have accumulated large seed banks in South Africa (Table 4.3) which could possibly increase the invasive potential. The large range in seed bank densities (736-54624 seeds/m^2 for gorse; and 1856-79248 seed/m^2 for Scotch broom) across populations was also comparable with those reported in the literature. Gonzalez *et al*. (2010) reported seed banks of gorse to range from 0 to 1658 seeds/m^2, while Sheppard *et al*. (2002) reported those of Scotch broom to range from 4229 to 21012 seeds/m^2. Maximum seed bank densities observed in this study, however, were significantly higher than those reported in other countries. This may have been due to lack of seed predators (e.g. weevils), which often reduce plant seed banks (Hill *et al*., 1996) or disturbance events. Disturbance events remove the vegetation cover and promote seedling recruitments in invasive alien plants thus reducing seed banks (Paynter *et al*., 1998; Paynter *et al*., 2003). Huge variations in seed banks observed across populations may be attributed to differences in stand maturity (Sheppard *et al*., 2002), with older stands associated with high seed bank densities. Wang *et al*. (2009) also reported that seed production and the aboveground biomass correlate positively with seed bank densities in some plant species. Poor seedling recruitment from under mature dense stands as a result of shading (Paynter *et* *al*., 2003) may have also contributed to high seed bank densities compared to in immature stands, where seedling recruitments are high (Gonzalez *et al*., 2010).

There was a significant decline in seed bank density of both species from under the parent plants to a four-meter distance away. These findings support those of Hill *et al*. (1996) who reported that the seed bank density of gorse declined to 1.9% at 2.4-2.5 m away from the dense stands. Sheppard *et al*. (2002) also observed similar trends in Scotch broom. Those authors reported that the seed banks of Scotch broom declined to 0.25% at a five-meter distance away from the dense stands. This study therefore suggests that wind and ants disperse seeds of gorse and Scotch broom over a short distance in South Africa.

5.8. *Post-fire survey*

A post-fire survey conducted in Scotch broom population three months after burning showed that fire killed all adult plants together with seedlings (Fig. 4.9B). These findings support those of Srinivasan *et al*. (2012) who also reported a 98% death in Scotch broom individuals following fire in Nilgiris, south India. According to those authors, the ability of plants to resprout depends on the intensity of fire, which is determined by plant density. If population density is too high, the intensity of fire increases thus leading to a high number of plant deaths, as was observed in this study.

The density of plants as a result of germinants (as opposed to resprouts) in burnt compared with unburnt plots, however, increased significantly fifteen months after the burning (Fig. 4.9D; Fig. 4.10A). Fire could have induced seed germination and seedling recruitment in burnt plots (Lloret, 1998), thus increasing the abundance and vegetation cover of plants (Tyler, 1995). Plant canopies in burnt and unburnt plots, however, were not significantly different. The reason for comparable plant canopies across burnt and unburnt plots may be due to self-thinning. According to van der Weft *et al*. (1995), the density of living plants decreases with an increase in population density, but the aboveground biomass increases. The second survey conducted 15 months also showed that the abundance of seedlings in burnt and unburnt plots was very low. Seedling emergence at that time could have been supressed by high plant densities which could have prevented light from reaching the understory plants and seeds (van der Weft *et al*., 1995; Gray and Spies, 1996; Dupuy and Chazdon, 2008).

5.9. *Seed and seedling responses to elevated temperatures*

High germinability observed in seeds of gorse and Scotch broom germinated in Petri-dishes in growth chambers (Table 4.2) did not translate to high seedling emergence from seeds sown at ambient and elevated temperatures. After seed sowing, the final seedling emergence was reduced by more than 70% in both species (Fig. 4.12). Similar reduction in seedling emergence was reported by Wang *at al*. (2006) for *Krascheninnikovia lanata*. In this study, a number of factors could have reduced seedling emergence from seeds of both species sown in the soil. According to Williams (1981), course soil material can retard seedling emergence. It is therefore proposed that hard soil crust, which may have formed during the watering of soil in seedling trays, could have reduced seedling emergence in both species.

The irrigation process could have also moved some seeds deeper down into the soil. This could have made it difficult for shoots from germinated seeds to reach the soil surface (Tobe *et al*., 2005). The failure of germinated seeds from deeper soil levels to reach the soil surface is common in small seeds (Forcella *et al*., 2000; Wang *et al*., 2006). This failure often occurs as a result of seedling mortality caused by the shortage or the depletion of seed reserves needed to provide energy for hypocotyl elongation following germination (Forcella *et al*., 2000). Some buried seeds lose vigour, and that could have reduced seedling emergence (Williams, 1981).

There was no difference in percentage seedling emergence between ambient and elevated temperatures (Fig. 4.12), however, the plant growth (in terms of plant biomass and leaf area) were significantly higher at ambient temperatures for both species except for leaf area ratio, which was higher at elevated temperature (Table 4.4 and Fig. 4.14). Findings from this study support Guilioni *et al*. (2003) findings that heat stress reduces plant growth. McDonald and Paulsen (1997) also reported a reduction in height and biomass of plants grown at higher temperatures. In this study, a reduction in plant growth at elevated temperatures may be attributed to a reduction in photosynthetic rates (Shah and Paulsen, 2003; Haldimann and Feller, 2005) caused by the deactivation of ribulose 1, 5-bisphosphate carboxylase/oxygenase (Rubisco) (Haldimann and Feller, 2004), which is the enzyme responsible for carbon fixation during the process of photosynthesis.

Above optimum temperatures, heat stress reduces chlorophyll *a* fluorescence, stomatal conductance and increases leaf transpiration intracellular CO_2 (Leakey *et al*., 2003; Haldimann and Feller, 2004). This could have been the case in gorse and Scotch broom seedlings grown at elevated temperature in this study. Based on these findings, it is evident that climate change (associated with high temperatures, extended warm seasons and low annual precipitation) (van Jaarsveld and Chown, 2001) is most likely to narrow the climatic envelops of gorse and Scotch broom in South Africa because the growth of both species was compromised at elevated temperatures. These findings therefore validate predictions by Fox and Steinmaus (2001), Potter *et al*. (2009) and Mgidi *et al*. (2007) that both species are most likely to invade regions with moderate climatic conditions.

The root: shoot ratios and biomass allocation patterns in both species were not significantly different between treatments (Table 4.4; Fig. 4.15). This could have been because seedlings of both species were receiving comparable amount of nutrients at ambient and elevated temperatures, as these nutrients influence root: shoot ratios and biomass allocation patterns (Davidson, 1969; Müller *et al*., 2000; Poorter *et al*., 2012).

5.10. *Weed risk assessment and the management options*

The weed risk assessments conducted for both species in this study suggest that gorse and Scotch broom pose serious threats to South African biodiversity. Questions related to species biogeography, undesirable traits, and biology/ecology scored high in the assessments thus confirming both species to be potentially invasive (Pheloung *et al*., 1999). Similar findings on the assessment of gorse (http://www.hear.org/pier/species/*Ulex_europaeus*.htm) and Scotch broom (http://dpipwe.tas.gov.au/invasive-species/weeds/environmental-weeds/weed-risk) were reported in Australia. Other species similar to gorse and Scotch broom (i.e. *Genista monspessulana* and *Spartium junceum*) were also reported to be potential invasive in South Africa (Geerts *et al*., 2013). It is therefore necessary to implement management options as early as possible to prevent population growth and spread. Since gorse and Scotch broom are emerging invaders (Nel *et al*., 2004; Mgidi *et al*., 2007), and have not spread widely, mechanical and chemical methods are proposed over biological control methods (which is suitable for the management of invasive species that have established) (Culliney, 2005).

This study therefore recommends the herbicide triclopyr in conjunction with controlled burning in the management of both species because this herbicide was > 90% effective in the killing of both species, as was reported for gorse in South Africa (Viljoen and Stoltsz, 2007) and Scotch broom in California (Oneto *et al*., 2010). With this proposed integrated management option, fire can reduce the aboveground biomass, induce seed germination and kill high proportion of seeds from seed banks thus reducing seed banks (Bossard 1993; Tyler, 1995; Lloret, 1998; Paynter *et al*., 1998; Downey and Smith, 2000). Thereafter, herbicides can reduce seed input by preventing resprouting (Ketchum and Rose, 2003; Herrera-Reddy *et al*., 2012). The species monitoring, however, will have to be conducted over a minimum period of 10 years since seeds of both species are long lived (Hill *et al*., 2001; Magda *et al*., 2013) and are likely to form persistent seed banks. This prolonged monitoring period can allow for a significant reduction of seed banks in order to reduce chances of population recovery.

Chapter 6: Conclusion

6.1. *Major findings*

This study assessed the current distribution, population size and structure and the demography of gorse and Scotch broom in South Africa. Despite several attempts to locate new populations outside areas where both species were reported, none was found. Both species were restricted to regions of initial introductions. Populations in commercial forests and open sites are presumed to have arrived at these sites as contaminants or garden escapes, while those in private and public properties may have been introduced for ornamental purposes. Both species are now prolific seed producers and have naturalised in South Africa. Although gorse and Scotch broom seem to be sensitive to elevated temperatures and hence climate change, the accumulated large seed banks in areas with suitable conditions put the country at the invasion debt. Both species should therefore provisionally remain as Category 1a, which means they require compulsory control.

The costs associated with the initial clearing of both species are a bit high, but worth spending now than later when populations have grown to big sizes. This study recommends the use of Garlon triclopyr at a 1-4% concentrations applied to cut stumps of adult plants and foliar spray for seedlings and prescribed burning. In both species, the herbicide can kill the aboveground biomass (Rees and Hill, 2001; Viljoen and Stoltsz, 2007; Oneto *et al*., 2010) while prescribed burning can break dormancy in seeds of both species, thus reducing the seed banks (Dennehy *et al*., 2011). This proposed integrated management action for gorse and Scotch broom, however, will need to be monitored over a long period to prevent population recovery from seed banks as seeds of both species persist in seed banks (Hill *et al*., 2001; Magda *et al*., 2013). For an effective management of both species, follow-up inspections will have to be conducted at four-month intervals during phase when seedlings of both species have not reached reproductive maturity. Young individuals of both species at this time can also be pulled out easily by hand thus reducing costs associated with the machinery use.

6.2. *Challenges faced by the study and recommendations for future studies*

This study aimed at locating all populations of gorse and Scotch broom in South Africa. The ability to detect these populations, however, relied on responses from the public and landowners. It is therefore impossible to conclude that populations found in this study are the only ones existing in South Africa, as many others may do exist as silent populations not identified up to date. As a result, the reported invasive status and estimated costs associated with initial clearing of both species in South Africa may change owing to the identification of more populations. It is therefore imperative to develop more accurate distribution models that can assist in optimising the species search and identification. Based on these models, areas with high probability of species occurrence will need intense species searches to verify species presence or absence.

Moreover, findings on herbicide efficacy reported in this study may not be reliable as this was monitored for only one year, and these trials were conducted on a very small scale due to time constrains. In future, studies of this nature may require multiple herbicide trials at different sites for comparative purposes because populations in certain sites may fail to recover from herbicide treatment not because of the herbicide efficacy, but because of the environmental conditions not suitable for population recovery/individual resprouting. Extended periods for monitoring herbicide efficacy is also recommended in order to come up with more robust and reliable conclusions on whether or not the herbicide is effective.

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Appendices

Appendix i: Vegetation types of the grassland biome invaded by gorse and Scotch broom in South Africa. Vegetation types: Gd 1 (Amathole Montane Grassland), Gd 5 (Northern Drakensberg Highland Grassland), Gd 10 (Drakensberg Afroalpine Heathland), Gm 4 (Eastern Free State Sandy Grassland), Gs 8 (Mooi River Highland Grassland), Gs 10 (Drakensberg Foothill Moist Grassland).

Species	**Locality**	**Population names**	**Biome**	**Vegetation types**
Gorse	Estcourt	White Mountain Lodge, White Mountain	Grassland	Gs 10
	Hogsback	W18a, Opposite to W14b, Arminel hotel, W17b (1st and 2nd populations), W16, W14b, W24a	Grassland	Gd 1
	Kamberg	Kamberg Rock Art Centre, Kamberg Research Centre	Grassland	Gd 5
	Underberg	Ekhubeni (1st and 2nd populations)	Grassland	Gs 10
Scotch broom	Bulwer	Engen petrol station	Grassland	Gs 10
	Himville	Faithway College, Himville Police station	Grassland	Gs 10
	Hogsback	Roadside to Amathole Forestry Offices, Mahlinza, Opposite to Foresters Guest Houses, X19 (1st and 2nd populations), Dingliz, Amathole Guest Houses, Crossways Road, Gaika Road, Tayler's farm, Entrance to Amathole Forestry (Gaika Road), Uwe's property, Kokopelli	Grassland	Gd 1
	Kamberg	Kamberg Rock Art centre (1st and 2nd populations) Tony and Kathy's property, Roadside near Butt Farming, Butt Farming (1st and 2nd populations), Kamberg Nature Reserve (main entrance), Near Spotted Horse Country Inn	Grassland Grassland	Gd5 Gd 10
	Rosseta	King's school, The Fairy Fax (1st and 2nd populations) The Quinns's property, The Cardoness cottage, Roadside to Lower Loteni, Stratearn Farm	Grassland Grassland	Gs10 Gs 8
	Underberg	Ekhubeni (1st, 2nd, 3rd and 4th populations), F128, Main road, Near the Family Literacy Club, Underberg Mall	Grassland	Gs 10
	Van Reenen	1st, 2nd, 3rd, 4th, 5th, 6th and population in Van Reenen Cemetery	Grassland	Gm 4

Appendix ii: Summary details showing the locality, area and the density of 14 gorse populations found in South Africa. In some cases, more than one population were found in the same area but a distance apart. These were categorized as either the 1st, 2nd or 3rd population but under the same locality name. The table is arranged in order of increasing in abundance. (EC = Eastern Cape, KZN = KwaZulu-Natal).

Population locality	Province	GPS co-ordinates		Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
		Latitude (S)	Longitude (E)					
Underberg (Ekhubeni, 2nd population)	KZN	-29.8772	29.4196	1	_	_	Casual	One individual plant (in private property)
Estcourt (White Mountain)	KZN	-29.1124	29.6176	2	_	_	Casual	Two individual plants along the roadside (in open site)
Kamberg Research Centre	KZN	-29.3824	29.6492	10	20	0.5	Casual	Few individual plants in Kamberg Nature Reserve
Hogsback (Amathole Forestry, W18a)	EC	-32.5825	26.9656	12	7	1.71	Casual	Few individual plants in commercial forest
Kamberg Rock Art Centre	KZN	-29.3865	29.6686	14	64	0.21875	Casual	Few individual plants under plantation trees (all are resprouts from burning).
Hogsback (Amathole Foresry, Opposite to population in W14b)	EC	-32.5832	26.9593	24	3	8.00	Casual	Few individual plants in commercial forest

Appendix ii continued

Population locality	Province	GPS co-ordinates		Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
		Latitude (S)	Longitude (E)					
Underberg (Ekhubeni, 1st population)	KZN	-29.8783	29.4204	31	25	1.24	Casual	Garden plants in loam soil. One adult plant and 30 small seedlings
Hogsback (Arminel Hotel)	EC	-32.5914	26.9326	52	58	0.90	Casual	Plant along the hotel fence
Hogsback (Amathole Forestry; W17b, 1st population)	EC	-32.5829	26.9685	69	116	0.59	Casual	Population in commercial forest on the driveway and is dominated by dwarf plants
Hogsback (Amathole Forestry, W16)	EC	-32.5811	26.9579	389	927	0.42	Naturalised	Population in commercial forest
Hogsback (Amathole Forestry, W14b)	EC	-32.5819	26.9583	397	538	0.74	Naturalised	Population in commercial forest
Hogsback (Amathole Forestry; W17b, 2nd population)	EC	-32.5877	26.9633	511	1466	0.35	Naturalised	Population in commercial forest on the driveway and is dominated by dwarf plants
Hogsback (Amathole Forestry, W24a)	EC	-32.5875	26.9667	561	6018	0.09	Naturalised	Population in commercial forest
Estcourt (White Mountain Lodge)	KZN	-29.111	29.6121	1878	7266	0.26	Naturalised	Population in open site and displacing understory plants in dense thickets
Total				**3951**	**16510**			

Appendix iii: Summary details showing the locality, area and the density of 46 Scotch broom populations found in South Africa. In some cases, more than one population were found in the same area but a distance apart. These were categorized as either the 1st, 2nd, 3rd or 4th population but under the same locality name. The table is arranged in order of increasing species abundance. (EC = Eastern Cape, FS = Free State, KZN = KwaZulu-Natal).

Population locality	**Province**	**GPS co-ordinates**		**Abundance**	**Area covered (m^2)**	**Densities (plants/m^2)**	**Extent of invasion**	**Field observations**
		Latitude (S)	**Longitude (E)**					
Van Reenen (1st population)	FS	-28.3774	29.3672	2	-	-	Casual	<0,5 m tall plants in private property, dry soil type
Van Reenen (2nd population)	FS	-28.3774	29.3680	5	-	-	Casual	<0,5 m tall plants in private property, dry soil type
Van Reenen (3rd population opposite to cemetery)	FS	-28.3767	29.3800	9	100	0.09	Casual	9 plants ≥3 m tall in private property
Underberg (Ekhubeni, 3rd population)	KZN	-29.8714	29.4252	9	25	0.36	Casual	Population in open grassland on a moderate hill slope and is fully exposed to sunlight
Rosetta (King's School)	KZN	-29.3511	29.9862	17	64	0.27	Casual	Unmanaged garden plant in public property
Underberg (Ekhubeni, 4th population)	KZN	-29.8763	29.4193	27	64	0.42	Casual	Few individual plants along the roadside in open grassland

Appendix iii continued

Population locality	Province	GPS co-ordinates Latitude (S)	Longitude (E)	Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
Rosetta (The Quinns's property, Overdale Rd.)	KZN	-29.3049	29.971	28	81	0.35	Casual	Garden plant in loam soil, the population is well managed and partially shaded by other garden plants
Bulwer (near Engen petrol station)	KZN	-29.8121	29.7687	42	150	0.28	Naturalised	Population in open site with damp loam soil and fully exposed to sun
Himville (Faithway College)	KZN	-29.7393	29.5156	45	25	1.80	Casual	Well managed hedge and garden plant in public property
Kamberg Rock Art Centre (2nd population)	KZN	-29.3866	29.6684	51	100	0.51	Casual	Few individual plants in Kamberg Nature Reserve (all are resprouts from fire)
Underberg (F128 Main Road)	KZN	-29.7980	29.5016	73	100	0.73	Naturalised	Garden plants in moist loam soil, starting to spread out of the private property
Van Reenen (4th population in natural forest)	FS	-28.3715	29.3677	83	64	1.3	Naturalised	1,5-2 m tall plants in natural forest

Appendix iii continued

Population locality	Province	GPS co-ordinates		Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
		Latitude (S)	Longitude (E)					
Hogsback (Roadside to Amathole Forestry Offices)	EC	-32.5892	26.9306	96			Naturalised	Few individual plants along the roadside (open site)
Hogsback (Amathole Forestry, Mahlinza)	EC	-32.5704	26.9211	107	174	0.61	Naturalised	Small population in open grassland along gentle hill slope
Himville Police Station	KZN	-29.7518	29.5114	110	25	4.40	Casual	Well managed hedge plant in public property
Kamberg (Tony and Kathy's property)	KZN	-29.3784	29.6737	111	100	1.11	Naturalised	Unmanaged garden plant in private property
Rosetta (The Fairy Fax, 2nd population)	KZN	-29.3394	29.9906	131	40	3.28	Naturalised	Some plants are in garden and others are out of the property near the stream in loam soil (private property)
Van Reenen (5th population in private property)	FS	-28.3738	29.3753	174	100	1.74	Naturalised	Population in natural forest (private property)
Hogsback (Kokopelli)	EC	-32.6036	26.9192	187	44	4.25	Naturalised	Small population in natural forest within private property

Appendix iii continued

Population locality	Province	GPS co-ordinates Latitude (S)	Longitude (E)	Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
Rosetta (The Cardoness Cottage)	KZN	-29.3048	29.9715	198	400	0.50	Naturalised	Unmanaged garden plant in private property
Hogsback (Opposite to Foresters Guest Houses)	EC	-32.5893	26.9298	206	293	0.70	Naturalised	Small population in open site along the roadside of Hogsback main road (open site)
Kamberg Rock Art Centre (1st population)	KZN	-29.3878	29.6691	238	1812	0.13	Naturalised	Population in Kamberg Nature Reserve
Kamberg (Roadside near Butt Farming)	KZN	-29.3141	29.7673	280	3415	0.08	Naturalised	Population along the roadside near Butt Farming (private property).
Hogsback (Amathole Forestry; X19, 2nd population)	EC	-32.5626	26.9109	334	643	0.52	Naturalised	Population in commercial forest
Rosetta (The Fairy Fax, 1st population)	KZN	-29.3366	29.9906	343	36	9.53	Casual	Population in grazing pasture on and dominated by seedlings in private property

Appendix iii continued

Population locality	Province	GPS co-ordinates		Abundance	Area covered (m^2)	Densities ($plants/m^2$)	Extent of invasion	Field observations
		Latitude (S)	Longitude (E)					
Van Reenen (6th population in private property)	FS	-28.3731	29.3753	349	50	6.98	Naturalised	Garden plant dominated by seedlings and adult plants are scattered
Hogsback (Amathole Forestry; X19, 1st population)	EC	-32.5617	26.9149	362	1551	0.23	Naturalised	Population along the roadside in commercial forest
Estcourt (White Mountain Lodge)	KZN	-29.1067	29.6131	404	419	0.96	Naturalised	Population in open site, it invades natural forest and the individual plants are scattered
Hogsback (Dingliz)	EC	-32.6021	26.9201	448	237	1.89	Naturalised	Population along the roadside (private property)
Hogsback (Amathole Guest Houses)	EC	-32.589	26.9302	488	1772	0.28	Naturalised	Population in horse grazing pasture (private property)
Kamberg Nature Reserve (main entrance)	KZN	-29.378	29.6727	500	225	2.22	Naturalised	Population near the stream and is under shade from forest trees in nature reserve)
Underberg (near the Family Literacy Club)	KZN	-29.7907	29.5003	503	400	1.26	Naturalised	The population is in fertile loam soil (private property)

Appendix iii continued

Population locality	Province	GPS co-ordinates		Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
		Latitude (S)	Longitude (E)					
Hogsback (Crossways Road)	EC	-32.5951	26.9237	582	292	1.99	Naturalised	The population is spreading out of natural forest in private property
Rosetta (roadside to Lower Loteni)	KZN	-29.3475	29.9565	599	2440	0.25	Naturalised	Population along the roadside to Lower Loteni (open site)
Underberg (Ekhubeni, 1st population)	KZN	-29.8783	29.4171	668	11551	0.06	Naturalised	Population in mountain peak on rocky gravel (private property)
Hogsback (Gaika Road)	EC	-32.5738	26.9163	679	421	1.61	Naturalised	Population along the roadside (open site)
Rosetta (Stratean Farm)	KZN	-29.3522	29.9479	686	2456	0.28	Naturalised	Population in grazing pasture (private property)
Van Reenen Cemetry (along the N3 roadside)	FS	-28.3762	29.3801	873	2764.5	0.31	Naturalised	Population in public property (cemetery), 238 plants are resprouts from cut plants
Underberg Mall	KZN	-29.789	29.4987	895	5030	0.18	Naturalised	Population in open grassland with gravel sand and is partially shaded by plantation trees

Appendix iii continued

Population locality	Province	GPS co-ordinates		Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
		Latitude (S)	Longitude (E)					
Kamberg (Butt Farming, 1st population)	KZN	-29.3132	29.7714	2182	5147	0.42	Naturalised	Population in private property near the stream. It has displaced understory plants. There is low seedling recruitment under the dense thicket stands but higher from under the canopy gaps
Hogsback (Tayler's Farm)	EC	-32.5720	26.9064	3128	5559	0.56	Naturalised	Garden plants that has established and is actively reproducing (private property)
Hogsback (Entrance to Amathole Forestry, Gaika Road)	EC	-32.5724	26.9212	4281	1935	2.21	Naturalised	Population in natural forest (private property)
Hogsback (Uwe's property)	EC	-32.5954	26.9218	4347	3312	1.31	Naturalised	Garden plants that are actively reproducing (private property)

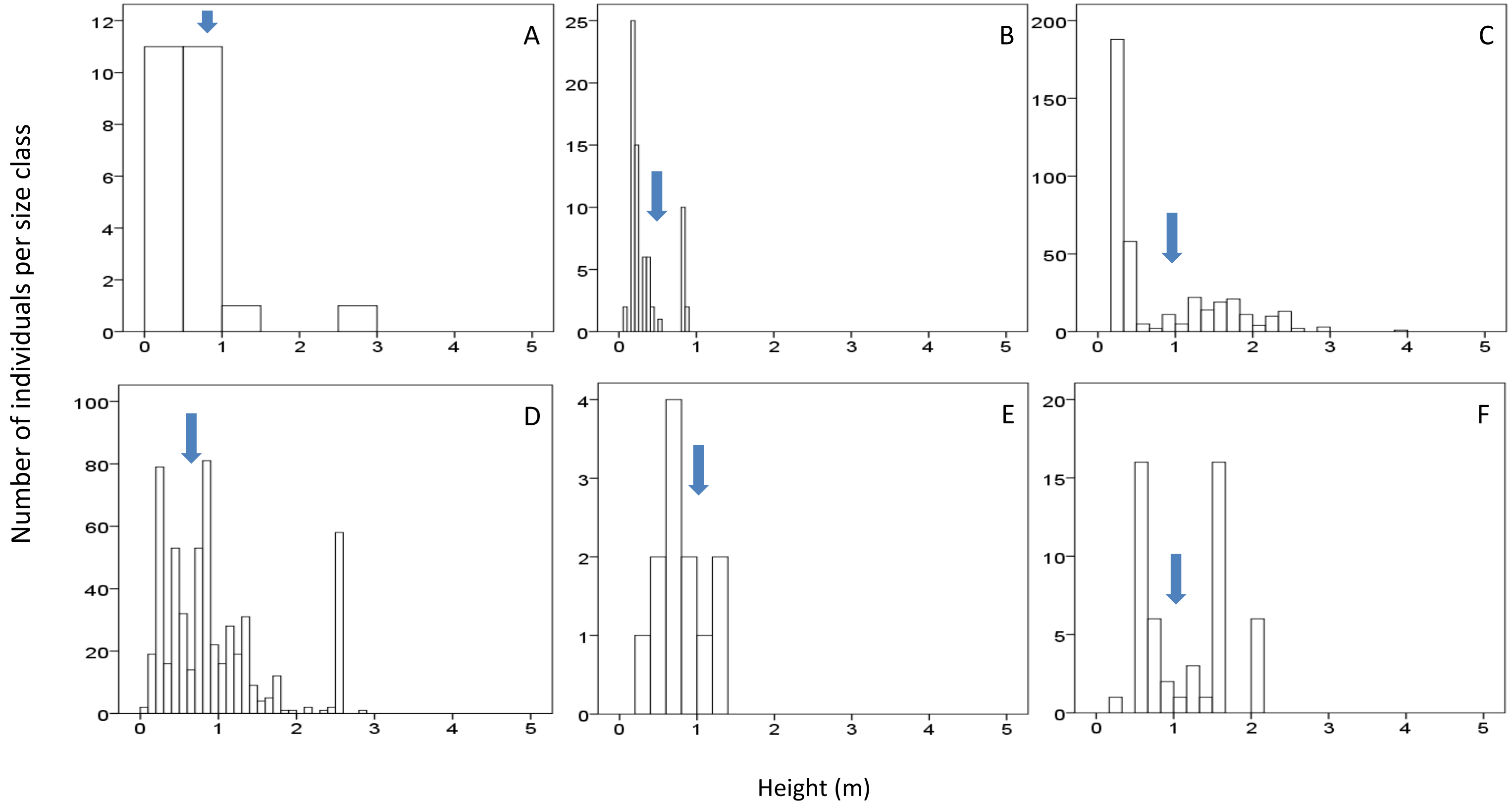
Appendix iii continued

Population locality	Province	GPS co-ordinates		Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
		Latitude (S)	Longitude (E)					
Kamberg (Butt Farming, 2nd population)	KZN	-29.3161	29.7718	5846	3392	1.72	Naturalised	Population in private property. This population is near the stream and has displaced understory plants. There is low seedling recruitment from under dense stands and higher from under canopy gaps
Underberg (Ekhubeni, 2nd population)	KZN	-29.8781	29.4203	9387	11925	0.79	Naturalised	Garden plants that has established and is actively reproducing (private property)

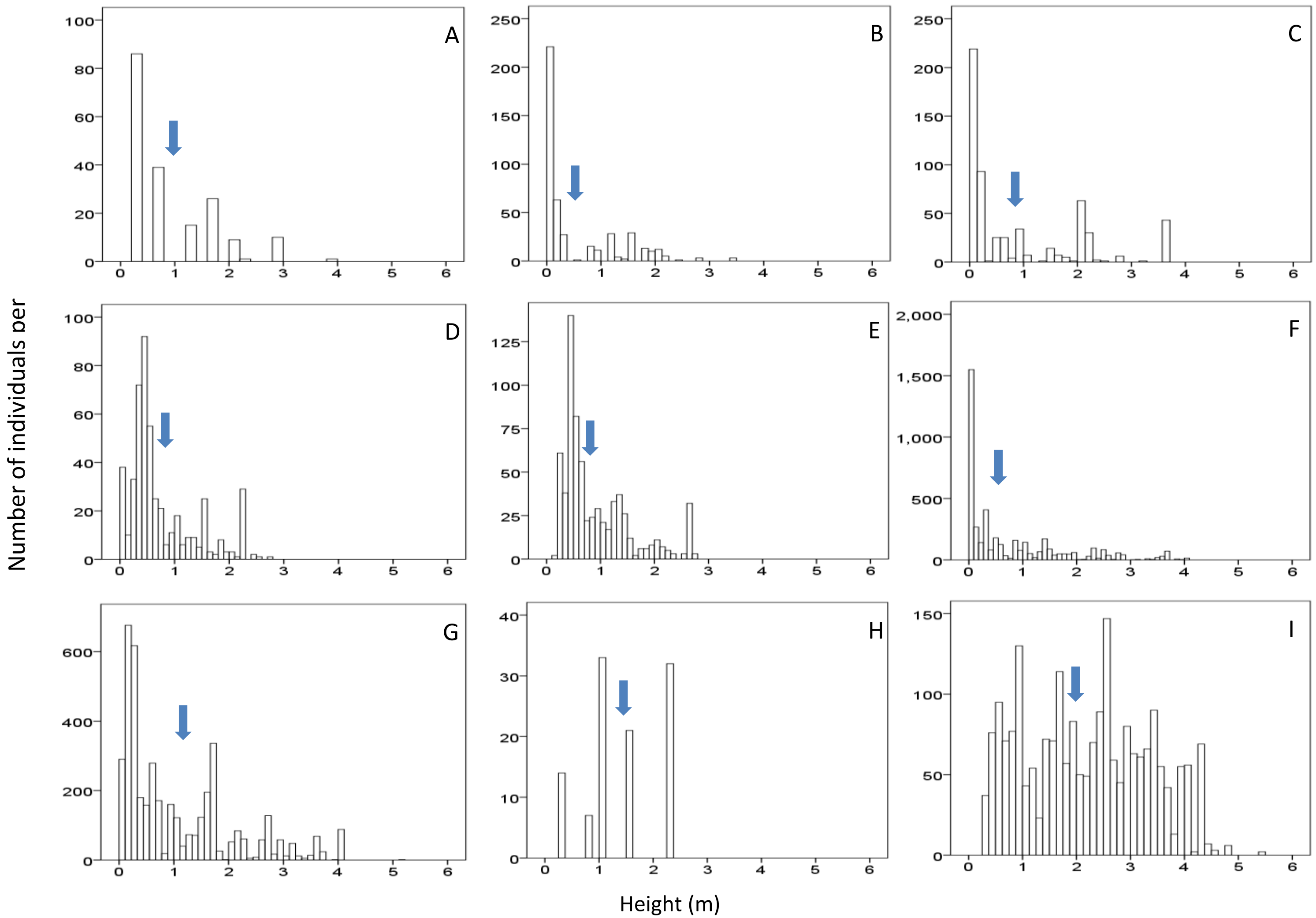
Appendix iii continued

Population locality	Province	GPS co-ordinates		Abundance	Area covered (m^2)	Densities (plants/m^2)	Extent of invasion	Field observations
		Latitude (S)	Longitude (E)					
Kamberg (near Spotted Horse Country Inn	KZN	-29.2958	29.7387	81022	28529	2.84	Naturalised	Big population in plantation forest and is in seasonally water logged fertile loam soil. It is actively reproducing with few seedlings from under dense stands
Total				**121135**	**97260**			

Appendix iv: Plant height frequency distribution for gorse: (A) Opposite to W14b, (B) W17b (1st population), (C) W16, (D) W24, (E) W18a, (F) Arminel hotel. Plant mean heights are presented by arrows above the bars.



Appendix v: Plant height frequency distribution for Scotch broom: (A) Kokopelli, (B) Dingliz, (C) Crossways road, (D) Forestry Guest Houses, (E) Stratearn Farm, (F) Uwe's property, (G) Entrance to Amathole Forestry, (H) Mahlinza, (I) Butt Farming (1st population). Plant mean heights are presented by arrows above the bars.



Appendix vi: The weed risk assessment of gorse in South Africa.

Question	Response	References	Score	Range of possible scores
Is the species highly domesticated?	No, there is no evidence of strong selection		0	0 or -3
Species suited to South African climates (0-low; 1-intermediate; 2-high)	Intermediate	20	1	0, 1 or 2
Quality of climate match data (0-low; 1-intermediate; 2-high)	Unknown		?	0, 1 or 2
Broad climate suitability (environmental versatility)	Yes	1	1	0, 1 or 2
Native or naturalised in regions with extended dry periods	No, the species do not grow well in harsh conditions	1, this study	0	0 or 1
Does the species have a history of repeated introductions outside its natural range?	Yes	2, 3, 4	2	0 or 1
Naturalised beyond native range	Yes	5	1	0, 1, 2, -1, or -2
Garden/amenity/disturbance weed	Yes, it is used as a hedge plant	6	1	0, 1 or 2
Weed of agriculture/horticulture/forestry	Yes, most populations were found in commercial forests	This study	2	0, 1, 2, 3 or 4
Environmental weed	Unknown		?	0, 1, 2, 3 or 4
Congeneric weed	Yes	5	1	0, 1 or 2
Produces spines, thorns or burrs	Yes	5	1	0 or 1
Allelopathic	Yes, it reduces the species richness	7	1	0 or 1
Parasitic	No		0	0 or 1
Unpalatable to grazing animals	No, sheep and goat forage on it seedlings	8	-1	1 or -1
Toxic to animals	Yes, it contains alkaloid	8	1	0 or 1
Host for recognised pests and pathogens	Unknown		?	0 or 1
Causes allergies or is otherwise toxic to humans	Unknown		?	0 or 1
Creates a fire hazard in natural ecosystems	Yes	9, 10	1	0 or 1
Is a shade tolerant plant at some stage of its life cycle	Yes		1	0 or 1
Grows on infertile soils	Yes	11	1	0 or 1
Climbing or smothering growth habit	No		0	0 or 1
Forms dense thickets	Yes	5, this study	1	0 or 1
Aquatic	No		0	0 or 5

Appendix vi continued

Question	**Response**	**References**	**Score**	**Range of possible scores**
Grass	No		0	0 or 1
Nitrogen fixing woody plant	Yes	12	1	0 or 1
Geophyte	No		0	0 or 1
Evidence of substantial reproductive failure in native habitat	No		0	0 or 1
Produces viable seeds	Yes	13, 14	1	1 or -1
Hybridises naturally	Yes	5	1	1 or -1
Self-fertilisation	No	15	-1	1 or -1
Requires specialist pollinators	Yes	15	-1	0 or -1
Reproduction by vegetative propagation	Yes	16	1	1 or -1
Minimum generative time (years)	Yes		1	0, 1 or 2
Propagules likely to be dispersed unintentionally	Yes		1	1 or -1
Propagules dispersed intentionally by people	Yes	6	1	1 or -1
Propagules likely to disperse as a produce contaminant	Yes, seed size is very small and can be accidentally dispersed		1	1 or -1
Propagules adapted to wind dispersal	No, no special adaptation for wind dispersal		-1	1 or -1
Propagules buoyant	No, no special adaptation for buoyance but can be transported through water	5	-1	1 or -1
Propagules bird dispersed	Yes	17	1	1 or -1
Propagules dispersed by other animals (externally)	Yes, dispersed by ants	5	1	1 or -1
Propagules dispersed by other animals (internally)	Unknown		?	1 or -1
Prolific seed production	Yes	18	1	1 or -1
Evidence that a persistent propagule bank is formed (>1 yr)	Yes, seeds can remain viable for 10 years in seed banks	13	1	1 or -1
Well controlled by herbicides	Yes	19	-1	1 or -1
Tolerates or benefits from mutilation, cultivation or fire	Yes	16	1	1 or -1
Effective natural enemies present in South Africa	Unknown		?	1 or -1

(1) Fox and Steinmaus (2001); (2) Hill and Grourlay (2002); (3) Hill *et al*. (2008); (4) Ireson *et al*. (2008); (5) Clement *et al*. (2001); (6) Isern (2007); (7) Sullivan *et al*. (2007); (8) Hornoy (2012); (9) Marino *et al*. (2011); (10) Madrigal *et al*. (2012); (11) Leary *et al*. (2006); (12) Cavard *et al*. (2007); (13) Hill *et al*. (2001); (14) Sixtus (2003); (15) Bowman *et al*. (2008); (16) Rolston and Talbot (1980); (17) Chater (1931); (18) Hill *et al*. (2000); (19) Viljoen and Stoltsz (2007); (20) Mgidi *et al*. (2007)

Appendix vii: The weed risk assessment of Scotch broom in South Africa.

Question	Response	References	Score	Range of possible scores
Is the species highly domesticated?	No, no evidence of strong selection has been reported		0	0 or -3
Species suited to South African climates (0-low; 1-intermediate; 2-high)	Intermediate	16	2	0, 1 or 2
Quality of climate match data (0-low; 1-intermediate; 2-high)	Unknown		?	0, 1 or 2
Broad climate suitability (environmental versatility)	Yes	1	1	0, 1 or 2
Native or naturalised in regions with extended dry periods	No, this species does not grow well in harsh conditions	1	0	0 or 1
Does the species have a history of repeated introductions outside its natural range?	Yes	2, 3	2	0, 1 or 2
Naturalised beyond native range	Yes	This study	1	0, 1, 2, -1, or -2
Garden/amenity/disturbance weed	Yes	This study	1	0, 1 or 2
Weed of agriculture/horticulture/forestry	Yes, it is used as a hedge or garden plant	This study	2	0, 1, 2, 3 or 4
Environmental weed	Unknown		?	0, 1, 2, 3 or 4
Congeneric weed	Yes		1	0, 1 or 2
Produces spines, thorns or burrs	No		0	0 or 1
Allelopathic	Yes, it reduces the growth of other species	4	1	0 or 1
Parasitic	No		0	0 or 1
Unpalatable to grazing animals	No		-1	1 or -1
Toxic to animals	Yes	2	1	0 or 1
Host for recognised pests and pathogens	Unknown		?	0 or 1
Causes allergies or is otherwise toxic to humans	Yes	2	1	0 or 1
Creates a fire hazard in natural ecosystems	Yes	Personal observation	1	0 or 1
Is a shade tolerant plant at some stage of its life cycle	Yes	Personal observation	1	0 or 1
Grows on infertile soils	Yes	2	1	0 or 1
Climbing or smothering growth habit	No, it is a shrub		0	0 or 1
Forms dense thickets	Yes	5	1	0 or 1
Aquatic	No		0	0 or 5
Grass	No		0	0 or 1

Appendix vii continued

Question	Response	References	Score	Range of possible scores
Nitrogen fixing woody plant	Yes	6	1	0 or 1
Geophyte	No		0	0 or 1
Evidence of substantial reproductive failure in native habitat	No		0	0 or 1
Produces viable seeds	Yes	7	1	1 or -1
Hybridises naturally	Unknown		?	1 or -1
Self-fertilisation	No	This study	-1	1 or -1
Requires specialist pollinators	Yes	8	-1	0 or -1
Reproduction by vegetative propagation	Yes	9	1	1 or -1
Minimum generative time (years)	Yes, it reproduces yearly	1	1	0, 1 or 2
Propagules likely to be dispersed unintentionally	Yes	2	1	1 or -1
Propagules dispersed intentionally by people	Yes	2	1	1 or -1
Propagules likely to disperse as a produce contaminant	Yes, because of the small seed size		1	1 or -1
Propagules adapted to wind dispersal	No		-1	1 or -1
Propagules buoyant	No, but can be transported through water	10	-1	1 or -1
Propagules bird dispersed	Yes		1	1 or -1
Propagules dispersed by other animals (externally)	Yes	11	1	1 or -1
Propagules dispersed by other animals (internally)	Yes	12	1	1 or -1
Prolific seed production	Yes	13	1	1 or -1
Evidence that a persistent propagule bank is formed (>1 yr)	Yes, seeds can remain viable for 5 years in seed banks	14	1	1 or -1
Well controlled by herbicides	Yes	9	-1	1 or -1
Tolerates or benefits from mutilation, cultivation or fire	Yes	15	1	1 or -1
Effective natural enemies present in South Africa	Unknown		?	1 or -1

(1) Potter *et al*. (2009); (2) Peterson and Prasad (1998); (3) Herrera-Reddy *et al*. (2012); (4) Grove *et al*. (2012); (5) Slesak *et al*. (2016); (6) Watt *et al*. (2003); (7) Bossard (1993); (8) Suzuki (2003); (9) Oneto *et al*. (2010); (10) Williams (1981); (11) Bossard (1991); (12) Holst *et al*. (2004); (13) Rees and Paynter (1997); (14) Magda *et al*. (2013); (15) Srinivasan *et al*. (2012); (16) Mgidi *et al*. (2007)