UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG

Assessment of the invasive potential of *Foeniculum vulgare* (fennel) in the Sarah Baartman District and Nelson Mandela Bay Municipalities in South Africa`s Eastern Cape Province

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A research report submitted to the Faculty of Science, University of the Witwatersrand, in partial fulfilment of the requirements for the Degree of Masters of Science by Coursework and Research Report.

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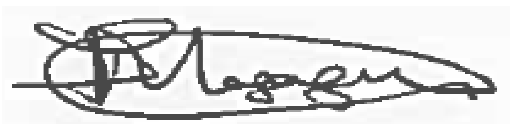
Declaration

I, Thokozane Innocent Pappa Magagula, declare that this research report, apart from the contributions mentioned in the acknowledgements, is my own, unaided work. It is submitted for the Degree of Master of Science by coursework and research report to the University of the Witwatersrand. It has not been presented before for any degree or examination to any other University.



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ABSTRACT

Foeniculum vulgare (Fennel) is native and widely distributed in many Mediterranean countries in Europe. Nowadays the species' distribution extends globally due to its cultivation as a food crop and its use as an herb. Fennel has been reported as invasive in Australia, New Zealand and California and reported as a naturalised garden escapee in South Africa. Because of similarities between the climates of the Western Cape Province in South Africa and Mediterranean countries the likelihood of the species becoming invasive in South Africa is high. In this report, the Sarah Baartman District and Nelson Mandela Bay Municipalities in the Eastern Cape Province, South Africa, were used as study areas to assess the invasive potential of Fennel. To this end, information from different sources was used to draw conclusions on the species' invasiveness in South Africa. These included using ArcGIS maps to estimate the current distribution of fennel in the study area and South Africa with the use of survey records, Herbarium data and SAPIA information; CLIMEX modelling to estimate the future potential distribution of the species based on climatic suitability; an assessment of major vegetation types where the species mostly occur; seed germination and reproductive output; and a risk assessment. A comparison of current distributional data with predicted future distribution of the species found that South Africa has a suitable climate for fennel and therefore the likelihood of the species establishing in many regions is high. Anthropogenic activities are anticipated to increase the potential of the species to become invasive. This conclusion is based on the observation that where vegetation has been degraded as a result of human influence, naturalised populations of the species were observed. High seed production capacity and high germination rates of Fennel also increase the likelihood of the species spreading now and in the future. The species also obtained high weed risk assessment score in South Africa, and swift action is required to control the species while populations are still manageable in size and before the species has a significant environmental impacts. Delayed action will result in the continued spread of this invasive species, making it more difficult to successfully curb the spread thereof in the future.

KEYWORDS: climate suitability modelling; fennel; invasive; Risk Assessment; South Africa

TABLE OF CONTENTS

PAGE

LIST OF FIGURERS

LIST OF TABLES

ABBREVIATIONS

%- Percentage

AIS- Alien and Invasive Species

ANOVA- Analysis of variance

BGIS- Biodiversity Global Information Systems

CM- Centimetre

CABI-Centre for Agriculture and Bioscience International

CARA- Conservation of Agricultural Resource Act

CAL-IPC- California Invasive Plant Council

DSIR- Department of Scientific and Industrial Research

EI- Ecoclimatic Index

GDD- Growing Degree-Days

GI- Germination Index

GIS- Global Information System

GPS-Global Positioning System

HEAR- Hawaiian Ecosystems At Risk

HWMA-Humboldt County Weed Management Area

IQR- Interquartile Range

LSD- Least Significance Difference

M- Meters

ML-Millilitre

M.A.S.L- Mean above Sea Level

NEMBA- National Environmental Management Biodiversity Act

NMBM- Nelson Mandela Bay Municipality

PH- Power of Hydrogen

PIER- Pacific Island Ecosystems at Risk

SANBI ISP- South African National Biodiversity Institute's Invasive Species Programme

SAPIA- South African Plant Invaders Atlas

SAWS-South African Weather Services

SOER-State of Environment Report

USDA-ARS-United States Department of Agriculture Agricultural Research Services

USDA-NRCS-United States Department of Agriculture-Natural Resources Conservation Services

WRC-Water Research Commission

WRA- Weed Risk Assessment

CHAPTER 1

1. INTRODUCTION

Invasive non-native species pose threats to biodiversity, have serious environmental impacts and have negative effects on the global economy (Pimentel *et al*., 2001; Rejmánek *et al*., 2005; Keller *et al*., 2011). The impact of invasive species on biodiversity is high, being second only after human-mediated habitat destruction (Hettinger, 2001; Pimentel, 2002; Chornesky and Randall, 2003). Non-native species are introduced either intentionally or unintentionally or for several purposes (Ruiz and Carlton, 2003). For example, some non-native species are introduced as ornamental species for their desirable qualities (Starfinger *et al*., 2003; Dehnen-Schmutz *et al*., 2007; Keller *et al*., 2011), while others are inadvertently introduced, e.g. as seed contaminants of crops taken from other countries, and then spread into the new environment (Levin, 1989; Razanajatovo *et al*., 2016).

Foeniculum vulgare (fennel) is a perennial member of the Apiaceae family (He and Huang, 2011; Salami *et al*., 2015; Bahmani *et al*., 2016) and is native to the southern part of Mediterranean Europe and northern Africa Mediterranean countries (Junak *et al*., 1995; Erskine-Ogden and Rejmánek, 2005; Badgujar *et al*., 2014). However, fennel has now naturalised in many parts of the world where it is often extensively cultivated in moderate climates (He and Huang, 2011). For example, fennel was brought to California in the 1850s by European immigrants to Santa Cruz Island where it has since become well established (Junak *et al*., 1995; van Driesche and van Driesche, 2000). The climatic conditions of Santa Cruz Island are similar to those in Mediterranean regions, which may explain the success of fennel there (van Driesche and van Driesche, 2000).

According to Henderson (2007), fennel is recorded in many places along coastal areas of the country`s Western Cape and Eastern Cape provinces and is found in five biomes in South Africa. It is most prevalent in Fynbos and Savanna vegetation type (Henderson, 2007). The high reproductive output of the species may explain its invasiveness. Capable of self-pollination, the species produces copious numbers of flowers and seeds (Salami *et al*., 2015; Moodley *et al*., 2016; Razanajatovo *et al*., 2016). Non-native species may become invasive due to many attributes, such as a lack of competitors, predators and a lack of competition (Cowling and Richardson, 1995; McNeely, 2001).

Alien plant species introduced as agricultural crops that become invasive often have much higher impacts compared to weeds arising in other ways (Rissler and Mellon, 1996). Several attributes of crop species have been found to contribute to the likelihood of them becoming weeds. These include high seed production (Gulden and Shirtliffe, 2003) and high levels of hybridization (Ellstrand and Schierenbeck 2000; Ellstrand *et al*., 2010). Besides these biological processes other major driving forces may contribute to agricultural crops becoming successful weeds. When there is homogeneity of environmental factors in cultivated and natural lands the likelihood of crops becoming weeds is enhanced (Ellestrand *et al*., 2010). Poor agricultural practices where unharvested seeds remain in the field can result in plants persisting and potentially becoming weeds (Campbell and Snow, 2009). Landscape alterations (disturbance), and therefore less competition with other species, have also created opportunities for many plant species to grow easily in the new environment. Repeated introductions of a species to a new environment (propagule pressure), can also aid in the naturalisation of an introduced crop species (Ruiz *et al*., 2000).

Fennel follows the so-called endo-ferality pathway of invasiveness (Ellestrand *et al.*, 2010). That is, it transitions directly from crop to weed without evolutionary change (Ellestrand *et al*., 2010). According to Greene (1887); Parsons and Cuthbertson (1992); Junak *et al*. (1995) and the PIER (2013) fennel is often introduced as a seed contaminant before becoming feral. Survival in most non-native regions is usually attributed to high seed output, dense population growth, and wide climatic tolerance (Beatty and Licari, 1992; Erskine-Orden, 2004; Thomlison, 2013; Brown and Bettink, 2016). Besides these attributes, opportunities created by humans have contributed to the species' invasive success. For example in Santa Cruz Island, there was an expansion spread of fennel after the exclusion of grazers from pastures (Brenton and Klinger, 1994).

Fennel is now distributed in most parts of South Africa and is currently listed as a Category 4 species in the list of invasive alien plants under “Conservation of Agricultural Resource Act (43 of 1983)”. Category 4 species are those under surveillance before they can be categorized for various management actions. In the replacement of the CARA, the “National Environmental Management Biodiversity Act 10 of 2004” lists fennel as uncategorized, pending further investigation (Wilson *et al*., 2013). Fennel was reported by the biannual newsletter (2012) of Cape Town as an intentionally introduced species that escaped from gardens and croplands and is now invading roadsides and open disturbed areas.

Invasions typically follow logarithmic growth, that is, a distinct lag phase followed by exponential growth until environmental saturation is reached (Shigesada and Kawasaki, 1997; Wangen and Webster, 2006). Invasive species management is most effective during the early lag stage of invasions. Early recognition of fennel as an invasive in South Africa would pose a good opportunity for early management of the species at a lower cost. Understanding the invasive potential can, therefore, help to prioritize management efforts and make optimum use of limited resources. The purpose of this research is to inform decision-makers of the current distribution of fennel in Sarah Baartman District and Nelson Mandela Bay Municipalities with the use current distributional data, establish the potential future distribution of fennel in South Africa using bioclimatic suitability modelling, determine the reproductive biology of the species, and to assess the risk posed by fennel to South African biodiversity, using a formal risk assessment protocol.

In South Africa several different entities, the Agricultural Research Council (ARC), South African National Biodiversity Institute and Working for Water (WfW) programme are responsible for the control of invasive species under the department of Environmental Affairs. Amongst the three aforementioned, the South African National Biodiversity Institute Invasive Species Programme (SANBI ISP) is the primary entity that manages invasive plants. The SANBI ISP support by funding research projects involving land surveys and research through partnership with South African University. SANBI ISP programme is enhance by working with stakeholders including the South Africa communities by distribution of pamphlets about invasive species of concern (Wilson *et al*., 2013). SANBI ISP has an effective unit with three components, early detection, post-border risk assessment and eradication (Wilson *et al*., 2013). Acts implemented by the Department of Environmental Affairs together with the Department of Agriculture and Fisheries on the management of invasive species has led to significant improvement of biodiversity management on private own land and local farms by preventing future biological invasion by alien species.

1.1. Significance of the study

Fennel is currently on the surveillance list of the South African National Biodiversity Institute, which means that its invasiveness in South African ecosystems is yet to be assessed or documented. The species is not listed in the South African "National Environmental Management Biodiversity, Act No 10 of 2004" list of non-native and invasive species. Research on this species will add value to the South African National Biodiversity Institute Invasive Species Programme dealing with alien invasive species and inform South African National Parks, landowners, land managers and the Department of Environmental Affairs. The research will assess the invasive potential of fennel before it has spread to all suitable areas of Sarah Baartman District and Nelson Mandela Bay Municipalities in the Eastern Cape. The end results of the study will be recommendations on appropriate policy responses to the management and control of fennel in South Africa. Results obtained from the small-scale investigation will be applied to indicate the invasive status of fennel in South Africa.

1.2. Aims and objectives

The overall aim of this project is to assess the current distribution and invasive potential of *Foeniculum vulgare* in the Sarah Baartman District and Nelson Mandela Bay Municipalities in Eastern Cape Province, South Africa.

1.3. Objectives

- To map the current distribution of fennel in South Africa.
- To determine potential distribution of fennel in the field sites and South Africa using correlative bioclimatic suitability modelling approaches.
- To determine the major vegetation types invaded by fennel in study areas.
- To determine the reproductive output of fennel.
- To determine seed germination potential of fennel.
- To determine the risk potential of fennel to the ecosystems in study areas.

1.4.Key research questions

- What is the extent of current distribution of fennel within the study area and South Africa?
- What is the reproductive output of fennel in different climatic regions within the study area?
- What is the potential future distribution of fennel within study area and South Africa?
- What is the risk level of fennel to South Africa`s ecosystems?

CHAPTER 2

2. LITERATURE REVIEW

2.1. Origin and history of fennel in South Africa

There is a long history of fennel cultivation in South Africa. The earliest fennel record is listed as an edible crop in the diary of Jan Van Riebeeck in entries for 22, 23 and 24 August 1652 (Karsten, 1951). The C.E.-Moss Herbarium at the University of Witwatersrand has a specimen of fennel collected from Lake Side in the Western Cape Province by Rogers on the 5th of February 1918. The National Herbarium in Pretoria has a specimen dating back to 1918 and collected from the Potchefstroom District (National Herbarium database). Fennel was listed as a surveillance species under "Conservation of Agricultural Resource Act (43 of 1983)" in the draft of categorization lists of Invasive Alien Plants Version 12 of March 2006 as category four (4). Kling *et al*. (1923) noted that fennel was used in Western Cape Province for medicinal purposes. In the biannual report of the city of Cape Town in Western Cape Province it is listed as plant escape from gardens affecting road verges and disturbed areas (Biannual environmental newsletter, 2012).

2.2. Distribution of fennel in South Africa

The South African National Herbarium database indicates that fennel is present in seven Provinces of South Africa, excluding the Free State and Limpopo Provinces. According to Baard and Kraaij (2014) fennel is naturalised in most parts of South Africa, mostly in disturbed and transformed areas. It is distributed particularly in Mediterranean climate regions of the Western Cape Province as well as along the coast and in inland areas (Henderson, 2007). Fennel is present in five biomes in South Africa, particularly in Savanna and Fynbos biomes, both as a naturalised and casual alien populations (Henderson, 2007). In South Africa, literature relates fennel growth to the Cape Provinces where it is mostly used as crop product (Baard and Kraaij, 2014).

2.3. Global distribution of fennel

The current global distribution of fennel shows that it is found on all continents except Antarctica as either native or non-native species (Fig.1). Fennel is native to southern European countries Albania, Bulgaria, Spain, Portugal, Greece, France and Italy (USDA-ARS, 2013). Fennel is also native in northern Africa and southern Europe Mediterranean countries, Egypt, Algeria, Libya, Tunisia, Morocco, Spain, Italy, France, Portugal, Greece and Albania (USDA-ARS, 2013). In two African countries, South Africa and Cape Verde Islands fennel occurs as a non-native species (USDA-ARS, 2013). According to Elzebroek and Wind (2008) fennel was introduced in North America and is now widely distributed due to the temperate climates that most favourable to fennel establishment, although it can also survive in tropical climates like those of Fiji and Hawaii (PIER, 2013). In South America, fennel was mainly used as a crop and became naturalised (Wagner *et al*., 1999). Fennel is reported to have been introduced in 19th century into the Oceania countries of Australia and New Zealand (Parsons and Cuthbertson, 1992; 2001), where it is has widely distributed and naturalised in many coastal areas. In Asian countries, fennel has been introduced and extensively distributed (eFloras, 2013). However, in South East Asia it is only present as a cultivated crop (Purwaningsih and Brink, 1999). Furthermore, its distribution is further extended to islands on the North Pacific and South Pacific Oceans (Fig. 1)(CABI, 2017).

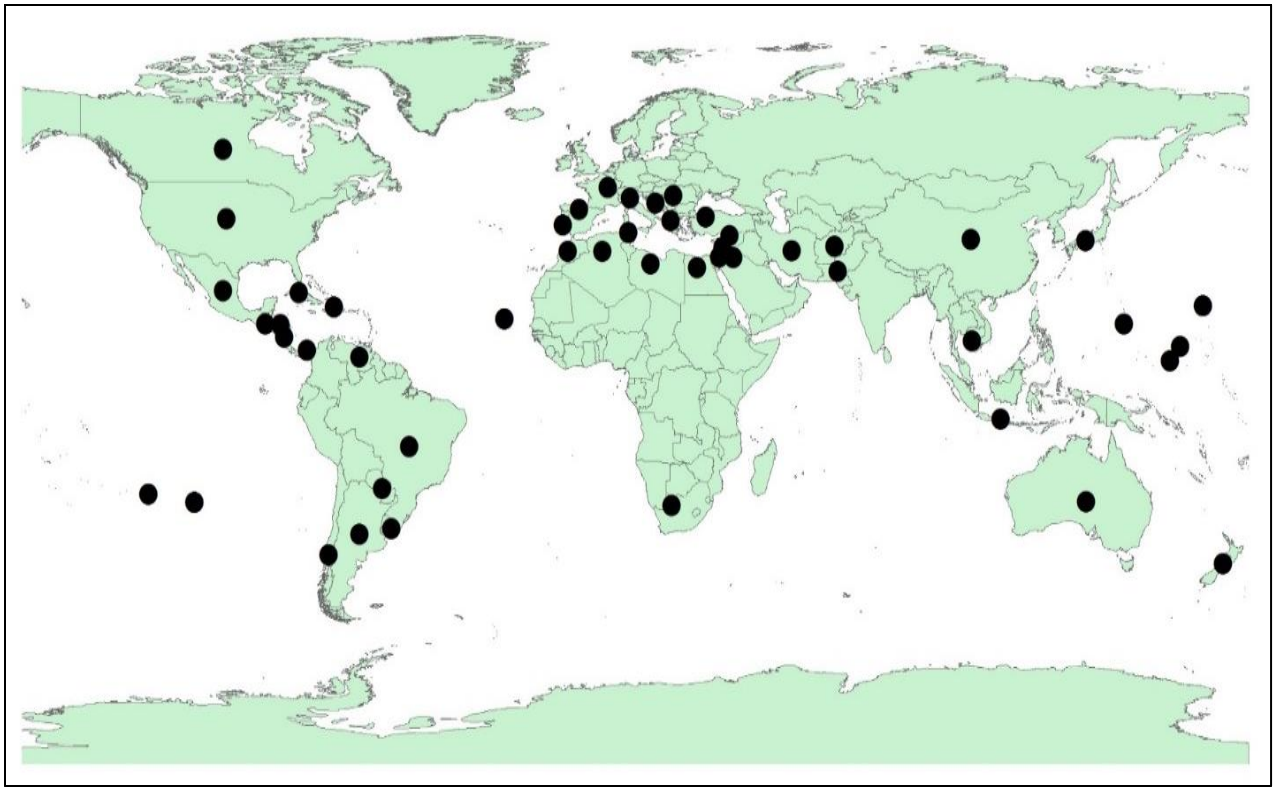

Figure 1. The current global distribution of *Foeniculum vulgare* (modified from CABI, 2017).

2.4. Social and economic benefits of fennel

Fennel has many uses throughout the world and this is the main reason why it is widely distributed. It has a number of human benefits and economical value in different countries. It is used for culinary and medicinal purposes and is widely cultivated. According to Parsons and Cuthbertson. (2001) the species' introduction to other countries is mainly as a result of human activities. Fennel is cultivated commercially in many countries for the production of Anethole (a carbon compound used for food flavouring and also widely used in medicine) (Parsons and Cuthbertson, 1992; 2001). In both its native and non-native ranges, fennel is used as an edible crop and for medicinal purposes (Purwaningsih and Brink, 1999; Tardio *et al*., 2006). In South Africa fennel is used for herbal medicine (Lewu and Afolayan, 2009) and it is currently available from food stores and in nurseries.

2.5. Invasive attributes of fennel

The invasive success of fennel is partly attributed to several life-history traits. These include large seed crop sizes (Beatty and Licari, 1992; West, 1996; Erskine-Ogden, 2004; Thomlinson, 2013; Brown and Bettink, 2016) and a short generation time, and being able to produce seeds at an early age (Thomlinson, 2013; Brown and Bettink, 2016). This high reproductive output was observed during field surveys in the field sites (Fig. 2). Fennel has photosynthetic stems that allow faster growth compared to other resident species (Thomlinson, 2013; Brown and Bettink, 2016). The species' long-lived seed bank, and high seed viability is another reason for the success of fennel (CAL-IPC, 2006; DiTomaso *et al*., 2013). Each Spring, fennel can produce flowers from the perennial crown (Parsons and Cuthbertson, 2001). Once established, the species forms dense stands and prevents other plants from further growth (West, 1996; DiTomaso *et al*., 2013). According to Beatty and Licari (1992) and Weber (2003) fennel can exploit resources early in Summer when some plants are still inactive. Fennel vegetative growth and seed production occur at the same time from the middle to late Summer (Brenton and Klinger, 1994). Competition for resources with other resident species that have already completed their reproductive cycle is thus lessened (Brenton and Klinger, 1994).

There are certain instances where fennel growth can be suppressed, e.g. under conditions of heavy grazing (Beatty and Licari, 1992). This can partially affect its normal growth and lessen its competitive ability with surrounding native species (Bossard *et al*., 2000). Usually grazers feed on early season regrowth but later it becomes unpalatable as a result of its strong smell (Parsons, 1973; Bossard *et al*., 2000). Fennel growth can also be impacted in areas where wild pigs are presence as they eat the roots and birds and rodent species eat the seeds which limits its spread (Bossard *et al*., 2000). Although the presence of the grazers and wild pigs has not shown any success in the control of fennel in instances where the species is regarded as an invasive. The success of fennel growth in many countries has also been associated with the absence of natural enemies and biological control agents (CABI, 2017).

Figure 2. Fennel (a) flowers with pollinator; (b) developing seeds; (c) umbels with ripe seeds in summer (d) mature seeds.

2.6. Ecological impacts of fennel

Fennel is a fire hazard because of its dense growth leading to high and fine fuel loads (Esler, 1988; Brown and Bettink, 2016). The previous years' growth remaining present in the field (Figs. 3a and 3b), make areas easily to catch fire because of dry stalks (Esler, 1988). Fennel competes with surrounding vegetation for essential nutrients, space and light and so alters native vegetation growth (CAL-IPC, 2005; HWMA, 2010). In addition, fennel changes the development patterns of natural flora causing dwarfism as it limits sunlight penetration and that in turn reduced photosynthesis (CAL-IPC, 2005). Native fauna can also be affected leading to reductions in ground cover vegetation and habitats of animal species (Queensland Government, 2013).

Figure 3. (a) Early growth of fennel in spring with previous season's dry stalks (b) late stage of fennel growth with combination of old and new stalks in De Mond Farm and Amanzi area at Sarah Baartman District and Nelson Mandela Bay Municipalities.

2.7. Weed status of fennel in other countries

Fennel has been declared a weed by many countries. These include Australia (Parsons and Cuthbertson, 1992; USDA-ARS, 2013); Chile, Cuba, Fiji (Oviedo Prieto *et al*., 2012); USA (CAL-IPC, 2005), (Hawaii) (PIER, 2013) and New Zealand (Esler, 1988; Webb *et al*., 1988). In Australia fennel is widespread and is reported to be causing severe ecosystem impacts (Parsons and Cuthbertson, 1992). Kloot (1987) stated that fennel was introduced in Australia for medicinal purposes. In Australia in 1880 it was reported that many populations of fennel has been naturalised in different parts of the country, particularly in New South Wales (Parsons and Cuthbertson, 2001). The Queensland Government (2013) states that fennel is affecting natural flora in the southern and eastern parts of the country. According to Parsons and Cuthbertson, (2001) highly disturbed land in Australia is more susceptible as it promotes denser growth of fennel. Fennel competes with indigenous shrubs and ground cover vegetation that is used by Australian fauna (Queensland Government, 2013). Conserved areas of Australia are highly impacted by fennel and endangered species are mostly affected (Queensland Government, 2013). Along water streams, the dense growth of fennel has a high impact as it interfere with water recreational activities (Muyt, 2001). In Australia, five vegetation types are impacted by the species including riparian, dry coastal, rock outcrop, grassy woodland and lowland vegetation types (Carr *et al*., 1992).

In New Zealand, fennel is abundant along roadsides, borders of railways, industrial areas and other waste areas where vegetation has been removed (Esler, 1988). Here, fennel severely impacts and outcompetes other species if left unmanaged and, when forming dense populations, limits the passage of humans, domestic and wild animals (Esler, 1988). Fennel is listed in two out of four categories for problematic weeds in New Zealand (Esler, 1988).

In the USA European settlers introduced fennel as a crop species (Junak *et al*., 1995; van Driesche and van Driesche, 2000). Fennel is now widely distributed in the USA with the exception of Northern Plain States (USDA-NRCS, 2013). In California fennel is ranked as a serious weed with high impacts on biodiversity by excluding native plant establishment (CAL-IPC, 2005). It is found in open disturbed areas, along roadsides, coastal scrub, grassland and wetland areas (DiTomaso *et al*., 2013). In California fennel is listed as “high” on the “Invasive Plant Inventory’’ as it has negative impacts on both plant and animal biodiversity (CAL-IPC, 2005). In Santa Cruz fennel tends to dominate riparian, coastal scrub vegetation and also affect grassland vegetation (Brumbaugh, 1980; Beatty and Licari, 1992; Bell *et al*., 2008).

2.8. Weed status of fennel in South Africa

In South Africa fennel is still regarded as a species under surveillance by South African National Biodiversity Institute Invasive Species Programme, as it has a potential to affect biodiversity based on its wide distribution in the country. The naturalisation of fennel in many places was confirmed by Henderson (2007) and Baard and Kraaij (2014) and means that the potential of fennel to be invasive is high. This risk is also high given the climatic similarity between parts of South Africa and the species' native range (Erskine-Ogden and Rejmánek, 2005; Thomlinson, 2013).

2.9. Invasive potential of plant .

Globally progress has been made to identify traits of species associated with invasiveness (Alpert, 2006). Species biological traits include wide environmental tolerance, high seed output, short generation and fast growing plant (Blanchard *et al*., 2017). Plants which have self-fertilisation, small seed size, seeds are disperse by animals or wind vegetative growth possesses potential to become invasive (Blanchard *et al*., 2017). Although this can be different amongst number of plant groups (Blanchard *et al*., 2017). Whether a plant can be invasive or not it depend on the environment (Lewis and Porter, 2014). An environment with suitable abiotic factors can easily allow alien plants to establish and spread further and faster than occurs in the original native environment (Burke and Grime, 1996). Climate and other environmental parameters can be used to make predictions of how invasive a plant may be.

2.10. Management and control of fennel

Control of fennel by fire proved unsuccessful in Santa Cruz Island (DiTomaso *et al*., 2013). In fact, following fire, fennel populations tend to recover quickly through the stimulation of dormant seeds (DiTomaso *et al*., 2013). Combining fire with chemical control is also not effective as this often leads to secondary invasions by other non-native species of grasses and forbs (Sugihara *et al*., 2006). Brenton and Klinger (1994) suggested that for control of fennel, several methods are needed which include the use of chemicals together with cultural approaches (Brenton and Klinger, 1994).

CHAPTER 3

3. MATERIALS AND METHODS

3.1. Description of study area

3.1.1. Climate and weather

This study was conducted in Sarah Baartman District and Nelson Mandela Bay Municipalities in the Eastern Cape province, South Africa (Fig.4). The Karoo region experiences dry hot summers and cold winters (Hamann and Tuinder, 2012). The study area received dissimilar rainfall patterns across the region as it is higher along the coastal region compared to the Karoo region. Rainfall occurs in Winter and Summer in the coastal region (Hamann and Tuinder, 2012). The study area has moderate weather along the coast (Sakulski and Jordaan, 2013). It is one of the districts in the Eastern Cape Province that is drought prone. Summer average temperature is 23°C and in Winter 17°C along the coastline (Sakulski and Jordaan, 2013). Annual rainfall averages 1000 mm in Tsitsikama region (Sakulski and Jordaan, 2013). The region of Nelson Mandela Bay Municipality receives an annual rainfall of 610 mm (Klages, 2011). Towards the East coast of the study area along the Indian Ocean to Port Alfred and extending to Grahamstown, the area receives moderate rainfall of 600 mm per year (Sakulski and Jordaan, 2013).

The Karoo region of Sarah Baartman District Municipality within Dr Beyers Naudé municipality, experiences hot summers and cold winters with an average Summer temperature of maximum 32°C to a minimum of 16°C and winter with a maximum average temperature of 20°C to a minimum of 6°C (Pretorius *et al*., 2009). The Karoo region has Summer rainfall with about 200 mm on average (Sakulski and Jordaan, 2013).Towards the central part of Sarah Baartman District towards Blue Crane Municipality, the mean annual rainfall is about 400 mm per year.

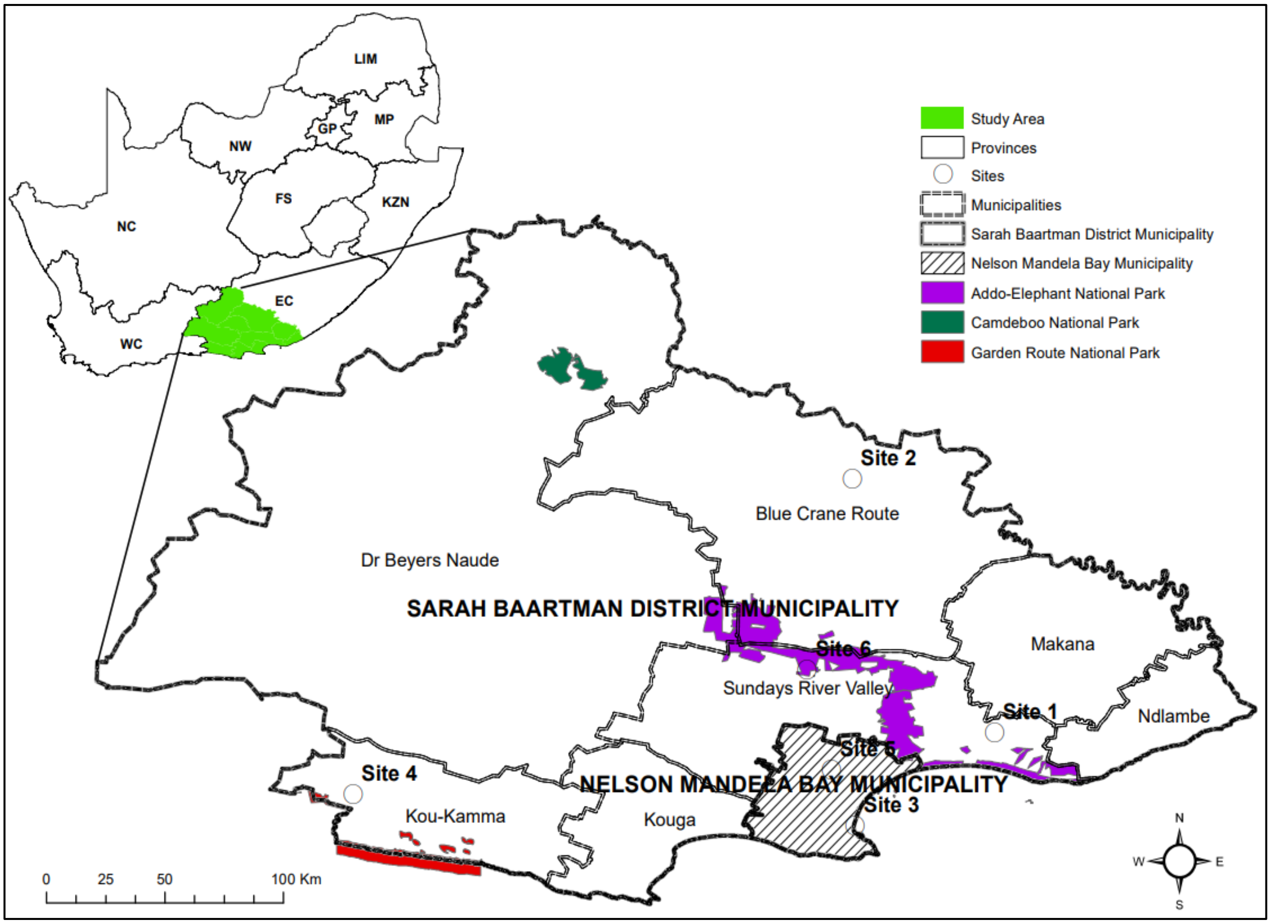

Figure 4. Study area in South Africa with the shaded area indicating location of Sarah Baartman District and Nelson Mandela Bay Municipalities with Addo Elephant , Camdeboo and Garden Route National Parks (The insert area of NMBM and Sarah Baartman District in relation the Eastern Cape Province (shaded in green), and the rest of South Africa).

3.1.2. Topography

The study area cover the two regions, the Sarah Baartman District and Nelson Mandela Bay Municipality on the region of Nelson Mandela Bay Municipality it has a wide valley near the end of the striking Cape fold belt (Klages, 2011). The floodplains of the study area are flanked by two rivers namely, the Little and Great Fish River (Coastal & Environmental Services, 2010). Topographically, the study area coastline near the Kou-Kamma municipality consists of a scarp that is 180 metres high (CEN, 2008). Furthermore, the coastal plain within the study areas extends five kilometres towards the west and eight kilometres towards the east. The Winterberg Mountains and the Great Fish River floodplain are located along the interior of the Sarah Baartman District Municipality (Coastal & Environmental Services, 2010). In addition, the Suurberg Mountain Range is located in the southern region of the Blue Crane Municipality.

3.1.3. Geology and soil

The coastal areas of the study region comprise strata of Table Mountain Group, Cretaceous Strata and Jurassic Eon Conglomerates (Carter, 1987; Büttner *et al*., 2015). Cape Supergroup is found further to the western region dominated by sedimentary rocks (Büttner *et al*., 2015). The interior of the study area consists of Uitenhage and Witteberg Groups (Büttner *et al*., 2015). Along the Grahamstown area towards Port Alfred, the geology consists of the Bokkeveld Group, Witteberg and Dwyka Formation, which are also found further north of study area (Büttner *et al*., 2015). The western region of the study area, covering most areas of Dr. Bayers Naudé municipality, has an underlying geology consisting of the Beaufort Group that extends further north towards Pearston area (Turner, 1981).

Nelson Mandela Bay Municipality soils are sandy, low pH, low in nutrients, and with an increased alkanity moving northwards (Klages, 2011). From Makana Municipality towards Sundays River Valley and part of Nelson Mandela Bay municipality the soil is derived from sandstones, shale and soil derived from sandy soil (Russell and Robison, 1981). Along the coastal region of the study area, the area is dominated by soil derived from shallow marine sandstones and Coastal dunes (Mucina and Rutherford, 2006). Western region of the study area at Kouga Municipality there is rocky and sandy-loamy soils (Mucina and Rutherford, 2006). The Sundays River Valley Municipality the soil is dominated by red, loamy to clay soil (Mucina and

Rutherford, 2006). Towards the inland soils are derived from shale and mudstones and have high density because of the high level of clay constituents (Mucina and Rutherford, 2006). Dr. Bayers Naudé municipality soil is derived from sandstones and mudstone making shallow skeletal soils of Mispah form (Mucina and Rutherford, 2006).

3.1.4. Vegetation

Five different biomes are found within study region, Fynbos, Forest, Thicket, Grasslands and Nama-Karoo (Palmer, 2004). Fynbos and Albany Thicket biomes dominate toward the western region (Mucina and Rutherford, 2006). Within the Fynbos biome there are three vegetation types, the Renosterveld, Strand and Fynbos where the Fynbos is dominated by coastal and inland azonal vegetation (Mucina and Rutherford, 2006). Towards the east of the study area the most dominant vegetation types are Albany Broken veld, Eastern Cape Thornveld. Kowie Thicket, Great Fish Noorsveld and Great Fish Thicket (Palmer, 2004). Southern Mistbelt Forest and Bedford Dry Grassland are also present in the study area (Palmer, 2004). Within Sundays River Valley Municipality the dominant vegetation is Xeric Succulent Thicket (Parker, 2008). The east coast of the study area consists of Old farmlands, Valley Thicket, Bushclump Savanna and Secondary Acacia Thicket vegetation (Parker, 2008).

The Nelson Mandela Bay Municipality is home to two global biodiversity hotspots, namely, the Cape Fynbos and Succulent Karoo (Hamann and Tuinder, 2012). Along the coast of the western side of the study area is the Sarah Baartman District that encompasses a small portion of the Fynbos biome (Mucina and Rutherford, 2006). Furthermore, the study area includes three major National Parks that is, the Camdeboo National Park within the Karoo region, Addo Elephant National Park within the Sundays River Valley Municipality, and Tsitsikamma National Park that includes Kou-Kamma Municipality along the Western Region coast. The Albany

Hotspot is found in the Grahamstown region in Makana Municipality and it is regarded as an important region for endemic plant taxa (van Wyk and Smith, 2001), where about 4000 different plant species are found (Dold and Victor 2003).

Invasion by alien plant species is also one of the major problems affecting biodiversity in the Sarah Baartman District and Nelson Mandela Bay Municipalities. A recent study conducted in the Karoo region (Dr Bayers Naudé Municipality) within the Camdeboo National Park indicated that 15 alien plant species were distributed in the park and along roadsides (Masubelele *et al*., 2009). However, moving towards the coast of Nelson Mandela Bay Municipality, non-native tree species were the most dominant invasive species (Klages, 2011). In a study undertaken by Klages (2011) it was estimated that in 2007 about 107 km^2 out of a total area of 1 954 km^2 (5.5 %) of Nelson Mandela Bay Municipality was invaded by alien plants.

3.2. Study species

3.2.1. The biology and ecology of fennel

Foeniculum vulgare, commonly known as fennel, is a perennial aromatic plant that grows 1-3.5 m tall (West, 1996; Parsons and Cuthbertson, 2001; CAL-PC, 2006; Power *et al*., 2014; Fig. 5a)**.** Fennel starts to grow at the beginning of spring and forms strong green propagative stalks (Power *et al*., 2014). The maximum flowering stage occurs when plant is about 18 to 24 months old (Parsons and Cuthbertson, 1992; Brown and Bettink, 2016). Flowers are bisexual and mainly insect pollinated (Brown and Bettink, 2016). The species is capable of self-pollination (Koul *et al*., 1996; Salami *et al*., 2016). Humid and temperate regions are favourable to fennel and the species appears to be little affected by soil types (Parsons and Cuthbertson, 1992). It occurs in waste areas, roadsides, next to railway lines and in disturbed areas (Beatty and Licari, 1992; Parsons and Cuthbertson, 1992; Weber, 2003).

It grows well in environments that have a mean yearly precipitation of 500-2000 mm (Purwaningsih and Brink, 1999). Temperature between 6°C and 24°C are the most favourable to fennel and it is not affected by frost (Parsons and Cuthbertson, 1992; Purwaningsih and Brink, 1999). Fennel grows well in soil with a pH between 6,3 and 8,3 and in a well-drained soil conditions (Simon, 1984; Purwaningsih and Brink, 1999). Fennel often disperses over distances of over 200 m from mother plants (Blood, 2001). Seeds are spread by water, by being trapped on car tires, and by passing through birds and small mammals that eat them (Bossard *et al*., 2000). Other seed dispersal methods include attachment to animal's fur and in mud adhering to animals (Parsons, 1973; West, 1996).

Figure 5. (a) Full-grown fennel plant in the field, and (b) Fennel with flowering umbels in spring.

3.3. Data sources

Field survey location point data for naturalised fennel populations in the Eastern Cape Province were collected from the field in Autumn (March 2016) and Summer (November to December 2016). The field survey was continued from the beginning of January 2017 until late April 2017. Desk top survey data from SAPIA (L. Henderson, personal communication, May 05, 2016), National Herbarium in Pretoria (N. Mthembi, personal communication, April 28, 2017) and ISPOT (http://www.ispot.org.za/) were used to find other localities. Other localities were found by the researcher by means of field surveys within the Sarah Baartman District and Nelson Mandela Bay Municipalities. Each search effort extended 200 meters around identified fennel populations. This was to locate any populations resulting from seed dispersal from parent plants. The initial desk top and field surveys covered all the records from the SAPIA database, including areas outside the field site. Due to financial constraints, the project was then scaled down to focus on Sarah Baartman District and Nelson Mandela Bay Municipalities.

Field surveys were conducted along national roads, regional roads, gravel roads, in disturbed areas, natural land, pastures, plantation field, illegal and legal dumping areas, abandoned areas, railway lines and roads in residential areas in Sarah Baartman District and Nelson Mandela Bay Municipalities, Eastern Cape Province. During November 2016 to April 2017, pamphlets were distributed to local communities, farmers and landowners in an effort to find additional localities. Enquiries were also done in the Albany District at the Working for Water project in Grahamstown to find out if they ever encountered the species in their area of jurisdiction. The survey excluded private game reserves, fenced places and strictly no personnel entry places.

GPS coordinates were used to locate fennel populations in the field that were recorded from SAPIA, ISPOT and herbarium records. New localities were added to SAPIA database. Where fennel populations were found, the extent of infestation and plant height were recorded as well as the number of plants in each population and land use types. Eighty-six fennel populations were identified in Eastern Cape Province with the aid of SAPIA, ISPOT information and personal searches for new localities. Only one population of fennel was found during a search in Dr.

Beyers Naudé Municipality (former Camdeboo Municipality). No records were reported in the study conducted by Masubelele *et al*. (2009) on the Alien Plants Species list and distribution for Camdeboo National Park.

Eighty-seven fennel populations from desk-top (SAPIA, Herbarium and Ispot network) and field survey were distributed around South Africa outside the study area. Six sample sites were chosen out of 86 fennel populations surveyed and recorded. The six fennel populations that met set of criteria of interest based on eco-region, environmental heterogeneity and population size were chosen. Sites selected had populations that exceeded 100 plants. Six field sites were selected from the study area based on geographic location and with maximum environmental heterogeneity.

3.3.1. Field sites selected in the study area

Information recorded for field sites selected within study area included their geographical location, annual rainfall and temperatures, habitat, population size, elevation and date when samples were collected (Table 1).

Table 1. Selected field sites with fennel locality records, habitat, population size, extent of infestation, altitude, climate and sampling date within study area.

Sites	De Mond Farm-1	Somerset East-2	Holland Park-3	Krakeel River-4	Amanzi Area-5	Kirkwood-6
Altitude	252 m.a.s.l	764 m.a.s.l	15 m.a.s.l	547 m.a.s.l	114 m.a.s.l	100 m.a.s.l
Habitat	Grazing land	Roadside	Rail siding	Roadside	Roadside	Roadside
Population size (n)	207	114	1 307	437	174	147
Infestation	> 1 ha	100-1000 m²	> 1 ha	> 1 ha	100-1000 m²	100-1000 m²
GPS location	S -33. 59897	S -32.72187	S -33.92840	S -33.81378	S -33.72290	S -33.39840
	E 26.11397	E 25.58686	E 25. 59545	E 23.73639	E 25. 50298	E 25. 42712
Mean annual rainfall	597 mm	512mm	526 mm	874 mm	427 mm	333mm
Mean annual temperature	17.8 °C	17.2 °C	17.3°C	15.2 °C	18.2 °C	19.0 °C
Sample collected date	18/04/17	28/03/17	12/04/17	21/04/17	14/04/17	17/04/17

Climate data were obtained from South African Weather Services (SAWS)

3.4.1. Mapping the current distribution of fennel in South Africa

Global Information System coordinates were recorded during the field survey. SAPIA, ISPOT, Herbaria and self-collected data were combined in ARC-GIS to make a distribution map for South Africa. Coordinates, used in ArcGIS as a point feature and the GPS coordinates were overlaid on Sarah Baartman District and Nelson Mandela Bay Municipalities and on the South African map to indicate current distribution range of fennel in South Africa.

3.4.2. Bioclimatic modeling approach for potential distribution of fennel in the study areas and South Africa

The potential distribution of fennel in South Africa based on bioclimatic suitability was determined with CLIMEX which predicts the suitable habitat of a species outside its current distribution. Such modeling approaches have been used in weed management and have provided key information to assist decision makers on management of invasive species (Kriticos *et al*., 2005). CLIMEX is a generic correlative model that can estimate a species' potential distribution based on climate data (Sutherst and Maywald, 1985). Using known occurrence data of a species and their dependency on climate, CLIMEX extrapolates potential bioclimatic niche space for the species.

CLIMEX uses two types of indices, the annual population Growth Index (GI) appropriate for population growth in a season and Stress Indices (cold, heat, dry and wet stresses), which explain the survival of the species population during unfavourable periods (Kriticos *et al*., 2003a; Kriticos *et al*., 2005). Stress index (SI) and Growth Index (GI) are combined to give a total sum which is called Ecoclimatic Index (EI) (Vera *et al*., 2002; Sutherst *et al*., 2007; McConnachie *et al*., 2011; Ma *et al*., 2012; da Silva *et al*., 2016). An Ecoclimatic Index (EI) calculated from the sum of Growth Index (GI) and stress indices (SI) indicates the potential distribution of species ranging from 0 to 100, where lower EI values will indicate unfavourable niches for the species and higher EI values indicate more suitable niche space and potential distribution for the species (Sridhar *et al*., 2014; Kumar *et al*., 2015).

3.4.2.1. Fitting CLIMEX parameters

Fennel-specific parameters for CLIMEX modeling were obtained by considering phenology of the species based on literature and field observations. Climatic variables for the Mediterranean climate were used as a starting point in determining suitable growth parameters for fennel. The Mediterranean parameters initial fitted on CLIMEX model were adjusted to give geographical distribution based on Ecoclimatic Index results from where the species is known to be native and its distribution range (Ma *et al.*, 2012). Kriticos and Randall (2001) stated that for best results for modeling of the climatic suitability of invasive species, both native range distribution and introduced distribution climatic data should be used. A species may be limited in its native area because of other limiting factors including dispersal barriers or competitive exclusion besides climatic suitability (Davis *et al*., 1998). Those limiting factors can be absent in areas where introduced and give the species wider suitable climatic distribution range compared to that of its native area (Davis *et al*., 1998).

3.4.2.1.1. Temperature index

Fennel is native in several Mediterranean countries (Erskine-Ogden and Rejmánek, 2005) which typically are characterized by wet winters and dry hot summers. Fennel has a wide temperature environment based on literature and field observation data in South Africa. Temperatures from 6 °C to 24°C are suitable for optimal fennel growth and development (Parsons and Cuthbertson, 1992; Purwaningsih and Brink, 1999), therefore chose these as lower and upper optimal temperatures for suitable growth. Fennel is a frost tolerant species (Parsons and Cuthbertson, 1992) and found in high altitude areas in South Africa that have extremes of temperature in winter and summer especially in the Karoo region. 0°C and 32 °C were made limiting low temperature and limiting high temperature respectively.

3.4.2.1.2. Moisture Index

Information from field surveys of the current study indicate that most fennel populations visited were present in dry soil conditions and along the water streams. Based on literature and field observations in the current study, limiting low moisture was assigned as 0.1 (proportion of soil capacity) and limiting high moisture as 1 (proportion of soil capacity). The lower optimum moisture was adjusted to 0.25 (proportion of soil capacity) and upper optimal moisture as 0.75 (proportion of soil capacity) for optimal growth of fennel.

3.4.2.1.3. Cold Stress

3.4.2.1.3.1. Cold stress temperature threshold (TTCS)

The cold stress temperature threshold of the Mediterranean template of 0°C was assigned to CLIMEX model. This value was used in the model as it is supported by literature information of the current known distribution from other countries where the species is successfully cultivated (Purwaningsih and Brink, 1999). This was also supported by fieldwork observation as other fennel population discovered were naturalised in areas of South Africa that have lower temperatures in winter.

3.4.2.1.3.2. Cold stress temperature rate (THCS)

Fennel has a wide climatic tolerance. In South Africa, its current distribution (Henderson, 2007) and current study field observations show that fennel can grow under a wide range of temperatures. Cold stress accumulation rate of -0.005/week taken from the Mediterranean template parameter was used for modelling. This was based on successful naturalisation of several fennel populations growing in the mild Mediterranean climate of South Africa and within the study area.

3.4.2.1.3.3. Cold stress degree-day temperature rate threshold (DTCS)

Cold stress degree-day temperature was set at 15 °C, from the Mediterranean template value. Field survey information indicated that fennel is mostly distributed in coastal provinces where average summer temperatures are above 15 °C. This value is an ultimate temperature as it is above fennel limiting cold temperature (DV0) in current known distribution countries. It can also allow optimal growth of the species to complete its generation time during the growing season in South Africa.

3.4.2.1.3.4. Cold stress degree-day rate (DHCS)

Fennel is a cold tolerant species (Parsons and Cuthbertson, 2001) hence the cold stress degree-day (DHCS) was adjusted during model fitting. The model default of -0.001/week for Mediterranean climate was decreased to -0.0005/week accumulation rate to allow for colder temperatures in some places where fennel occurs.

3.4.2.1.4. Heat stress

3.4.2.1.4.1 Heat stress temperature threshold (TTHS)

The CLIMEX model has a heat stress temperature threshold (TTHS) for the Mediterranean default of 30°C. Although fennel's distribution in South Africa is primarily limited to the coast, which is cooler compared to inland areas, the TTHS value was adjusted to 32°C, equivalent to the assigned value for maximum temperature threshold of fennel. The current distribution of fennel in South Africa indicates that fennel is not limited to the Mediterranean climate of the Western Cape

Province but it is widely distributed. Field surveys and literature identified fennel as well adapted areas characterized by high temperatures and drought.

3.4.2.1.4.2. Heat stress temperature rate (THHS)

Field surveys in the current study took place while South Africa was experiencing above normal temperatures due to lack of rain and included the Karoo region at a time when most of this area received little rainfall. Fennel was growing well in these regions. Heat stress temperature rate (THHS) therefore does not seem to have a great impact on fennel plants. THSS was decreased from the original default value of 0.002/week heat stress temperature rate for the Mediterranean and semi-arid template to a rate of 0.001/week.

3.4.2.1.5. Dry Stress

3.4.2.1.5.1. Dry stress moisture threshold (SMDS)

Fennel has adapted to survive in a Mediterranean climate which experiences winter rainfall and dry hot summers. Its morphological adaptation includes, amongst others, the elongation of its deep taproot. It has a taproot system which can measure between 0.9 m to 3.0 m (Erskine Ogden and Rejmánek, 2005). This adaptation allows the species to extract water from a distance where it grows. Fennel can survive under a wide range of climatic conditions and under severe water stress. However, drought can be considered a growth-limiting factor, for a plant to maintain its optimum growth.

The annual average rainfall range for fennel is relatively wide, as it is able to maintain its optimum growth between 500 mm and 2000 mm (Purwaningsih and Brink, 1999). In fact, field observations showed that it can also survive well on a mean average rainfall below 500 mm. At two sample sites, namely, Amanzi area and Kirkwood, the mean annual rainfalls were 427 mm and 333 mm respectively. In these two field sites the fennel populations were naturalised.

A value of 0.02 (proportion soil capacity) for Mediterranean region was left unchanged. Fennel can withstand summer drought and dry weather as experienced in regions with a Mediterranean climate in both native countries as well as non-native countries where it has been introduced and naturalized. In South Africa, fennel is mostly found in Fynbos vegetation of the Mediterranean climate region of Western Cape Province (Henderson, 2007). The climate in this region resembles that of its current known distribution ranges in native Mediterranean countries.

3.4.2.1.5.2. Dry stress rate (HDS)

Mediterranean plants can withstand long dry summers. For Mediterranean template, dry stress accumulation rate of -0.05/week was left unchanged. This value is also appropriate for semi-arid and desert regions of South Africa where field survey has shown that fennel occurs.

3.4.2.1.6. Wet Stress

3.4.2.1.6.1. Wet stress moisture threshold (SMWS)

Field observations showed that many fennel populations were present in dry and well-drained environments. This is an indication that fennel was well adapted for these conditions. Mediterranean climate template value of 1.6 (proportion soil capacity) was used for best modeling in South Africa. 1.6 value is suitable for well-drained soil types including fine sandy loam and sandy loam that were dominating where fennel population occurs in the study area.

3.4.2.1.6.2. Wet stress rate (HWS)

Field observation shown that fennel is found in both dry and wet areas in the field sites. A wet stress rate of 0.0015/week from the Mediterranean template was left unchanged to allow moderate wet and dry areas being shown as suitable by the model.

3.4.2.1.7. Degree-days per generation (PDD)

Day Degree Celsius is the period of time above the species development threshold (DV0) suitable to complete its life cycle (Sutherst *et al*., 2007; Kriticos *et al*., 2015). The length of growing seasons is considered as a period that is suitable for growth of species until climate become unfavorable for growth. Growing degree day calculations take into consideration plant life cycle from seed germination, plant formation, flowering and fertilization stage to fruiting and seed development.

To determine the length of growing season for fennel in South Africa, one sample site in Port Elizabeth region (S -33.92840; E 25. 59545) located 15 m.a.s.l was used to calculate growing degree-days. Minimum and maximum temperatures were obtained from South African Weather Services (SAWS). Field observation from visited fennel population emergence started early November 2016 and in December and January 2017, most of the plants were in flower. February to March 2017 grain fill process happened and in April 2017, maturity started and fennel was already in fruiting and dry seeds were starting to fall. Although the phases can vary depend on regional location of fennel population. For example seeds collected from interior part of the study side in Somerset East had already ripened before the end of March 2017. Fennel sprouting on the field site was noticed early November 2016 and seeds collections and plant height measurement were done on the 12th of April 2017.

Daily minimum and maximum temperatures for growing degree-days calculation for the species were taken as from 01 November 2016 to 30 April 2017. Growing degree-days value was calculated using the following formula (Linares *et al*., 2012; Lindgren and Walker, 2012; Kara, 2015):

GDD daily = (Tmax+Tmin)/2-Tbase [equation was developed from anise GDD calculation (Kara, 2015)].

Where GDD is the growing degree-days of the species. Tmax and Tmin are the maximum and minimum temperature recorded daily and Tbase is the optimum temperature above limiting growth temperature (DV0) where species can grow (Kara, 2015). Based on field observation and literature 5°C was set as a Tbase temperature for fennel as above limiting growth temperature (DV0). Value of 2 902.65 °D Accumulated Growing Degree Days for fennel was calculated in (Appendix II).

3.4.2.1.8. Model Validation

To ensure precision, the CLIMEX model was set to predict the distribution of fennel in its current known distribution in other countries (Kriticos *et al*., 2003b; McConnachie *et al*., 2011). To confirm the results, places where the species were introduced and naturalised were also used to confirm the validity of the parameters used during the species modeling. Those countries include Australia, USA and New Zealand where the species were reported to be highly invasive. Predictions of the current known distribution of fennel in the world were also made for testing the model validity. CLIMEX was allowed to predict current known distribution of fennel in the Mediterranean countries of southern Europe and northern Africa where the species is native.

Parameter values for fennel were chosen as follows (Table 2) base on the biology of the species from literature and field observation.

Parameter values for fennel were chosen as follows (Table 2) base on the biology of the species from literature and field observations.

Table 2. Summary of CLIMEX parameter values for fennel in South Africa.

Index	Parameter	Assigned values	Unit
Temperature			
	DV0=Limiting low temperature	0	°C
	DV1=Lower optimal temperature	6	°C
	DV2=Upper optimal temperature	24	°C
	DV3= Limiting high temperature	32	°C
Moisture			
	SM0= Limiting low moisture	0.1	proportion of soil capacity
	SM1= Lower optimal moisture	0.25	proportion of soil capacity
	SM2= Upper optimal moisture	0.75	proportion of soil capacity
	SM3= Limiting high moisture	1	proportion of soil capacity
Cold Stress			
	TTCS= Cold Stress temperature threshold	0	°C
	THCS= Cold stress temperature rate	-0.005	per week

	DTCS= Cold stress degree-day temperature rate threshold	15	d°C
	DHCS= Cold stress degree-day rate	-0.0005	per week
Heat stress			
	TTHS= Heat stress temperature threshold	32	°C
	THHS= Heat stress temperature rate	0.001	per week
Dry Stress			
	SMDS= Dry stress moisture threshold	0.02	proportion soil capacity
	HDS= Dry stress rate	-0.05	per week
Wet Stress			
	SMWS= Wet stress moisture threshold	1.6	proportion soil capacity
	HWS= Wet stress rate	0.0015	per week
Degree-days			
	PDD= Degree-days per generation	2 902.65	°D

PDD value calculated in Appendix II.

3.4.2.1.9. CLIMEX results interpretation

CLIMEX model results were projected onto maps indicating values of EcoClimatic Index (EI), where EI values ranged from (0 to <10; 10 to < 20; 20 to < 30; 30< 40) and (40 to < 50) indicating minimum to moderate suitable habitat for the species. Highest values were ranges from (50< to 60; 60 to < 70; 70 to < 80; 80 to < 90) and (90 to < 100) indicating best to highly suitable habitat for the species.

3.4.3. Vegetation types identification, estimate on number and extent of fennel infestation approach in the study area

Vegetation type was identified during fieldwork through observation. It was confirmed by GPS coordinates recorded during field survey that corresponded with a South African vegetation map downloaded from "http://bgis.sanbi.org/DEA_Landcover/project.asp" (Musina and Rutherford, 2006). Eighty-six known localities of fennel were used to determine vegetation types mostly occupied by fennel excluding data from Herbarium and SAPIA where the species was recorded but not found in this study.

The procedure used to determine the extent of infestation from South African National Biodiversity Institute Invasive Alien Plant Recording form was used to record fennel populations per vegetation type. The quantitative estimate was used to indicate the number of plants per population and the extent of the infestation. In each population, fennel presence was rated by number of plants as follows -1, 2-5, 6-20, 20-50 and > 50 and extent of infestation as <1m^2, 1-10m^2, 10-100m^2, 100-1000m^2, >1 ha. SANBI BGIS land-cover dataset for South Africa, 2014 was used to determine the historical land cover of Sarah Baartman District and Nelson Mandela Bay Municipalities. Results were displayed with bar graphs.

3.4.4. Reproductive output

Plant heights were measured with a tape measure from the ground surface to the end of the last leaf on the tallest branch in all six selected field sites (Prévosto *et al*., 2004). Since plants varied in height an average plant height per field site was used to select randomly five individual fennel. This was to ensure that fennel plants chosen from each population were good representatives of the population. The total number of seeds per plant was calculated as follows:

(i) the number of stalks per plant were counted;

(ii) the number of branches of all stalks were counted;

(iii) the number of compound umbels of branches were counted;

(iv) the number of umbellets of compound umbels were counted;

(v) the number of flowers of umbellets were counted, and

(vi) the total number of seeds of flowers were counted;

(vii) The total seed count was estimated by multiplying these counts.

Comparison for differences in seed production and plant heights per field sites were analysed by analysis of variance (ANOVA) and presented in box and whisker plots.

3.4.5. Seed germination test

Six collections of fennel seeds were obtained from the six field sites within the study area. More than 100 seeds were collected from each locality in the month of March and April, 2017 and placed in brown paper envelopes. Seeds were examined for holes that may be caused by predators.

From the field sites, seeds were taken to Port Elizabeth where they were dried in the sun for five days on trays, seeds were then packed into dry 250 ml bottles labeled with the date and the place when/where they were collected. Bottle lids were left open for airflow and were stored at room temperature. On the 3rd of October 2017 seeds were placed in the mini greenhouse with 12 Jiffy peat pellets watered to moisturize seeds for germination. The 12 pellets were divided into six pairs and were labeled accordingly, a pair for each field site. A representative sample consisting of twenty-five seeds was placed on each peat pellet to make a total of 50 seeds per site. The tray was covered with a dome and wrapped with aluminium foil and it was placed at a room temperature windowsill for 14 days. Germinated seeds were counted and recorded each day for 14 days. Only seeds germinated within 14 days were counted, as it is the normal period taken by fennel seeds to germinate (Ioana *et al*., 2015).The germination index for 50 seeds was calculated from the number of days taken by the seeds to germinate and results were presented graphically. Germinating Index was used because it shows the percentage of germination and at the same time it includes the rate of germinating (Kader, 2005).

3.4.6. Weed risk assessments (WRA) of fennel in the study area

Weed risk assessments (WRA) have been used to assess the likelihood of invasion by introduced species to new regions and takes into consideration environmental and socio-economic impacts (Gasso *et al*., 2009). It is based on giving aspects of the species of concern a score (Pheloung *et al*., 1999). Forty-nine questions based on existing status of fennel in South Africa were used and a score rating per each question were assigned as per the risk assessment protocol (Pheloung *et al*., 1999; Gordon *et al*., 2010). Questions were designed to accommodate the two study regions of Sarah Baartman District and Nelson Mandela Bay Municipalities based on field observation and literature. To determine the potential risk of fennel to South African biodiversity, a weed risk assessment procedure available in New Zealand and Australia was used (Pheloung *et al*, 1999). The risk assessment questions designed for New Zealand were used. Scores were based on answering questions about fennel history divided into three sections (Pheloung *et al*., 1999; Gordon *et al*., 2010):

(i) Domestication/cultivation.

(ii) Climate and distribution.

(iii) Weed status elsewhere.

Biological questions were divided into five sections based on the following information (Pheloung *et al*., 1999; Gordon *et al*., 2010):

(i) undesirable traits of the species.

(ii) reproductive biology.

(iii) plant type.

(iv) dispersal mechanisms.

(v) persistence attributes.

A quantitative score that ranges between -14 to 29 was used to indicate the likelihood of fennel becoming invasive or not in South Africa which was adapted from the Australian Weed Risk Assessment (Pheloung *et al*., 1999; Gordon *et al*., 2010). A conclusion was based on obtaining a score under the following three criteria (Pheloung *et al*., 1999; Gordon *et al*., 2010):

(i) a total score of less than one would indicate that the chance of species becoming invasive is very low;

(ii) a total score of from one to six would indicate a need for further evaluation of the species before a final conclusion can be made;

(iii) a total score of greater than six would indicate high probability of species becoming a weed.

The risk assessment questions were answered by the researcher based on information from literature and fieldwork observations.

CHAPTER 4

4. RESULTS

4.1. Current distribution map of fennel in South Africa

Eighty six populations were within the field study area of a total of one hundred and seventy three (173) populations obtained through field surveys and SAPIA, Herbarium and ISPOT network records (Fig. 6)(Appendix I). There was no response from the pamphlets distributed to local communities, farmers and landowners. Most fennel populations are in the Western and Eastern Cape Provinces with a few records in Northern Cape, North West, KwaZulu-Natal, Gauteng and Mpumalanga (Fig. 6).

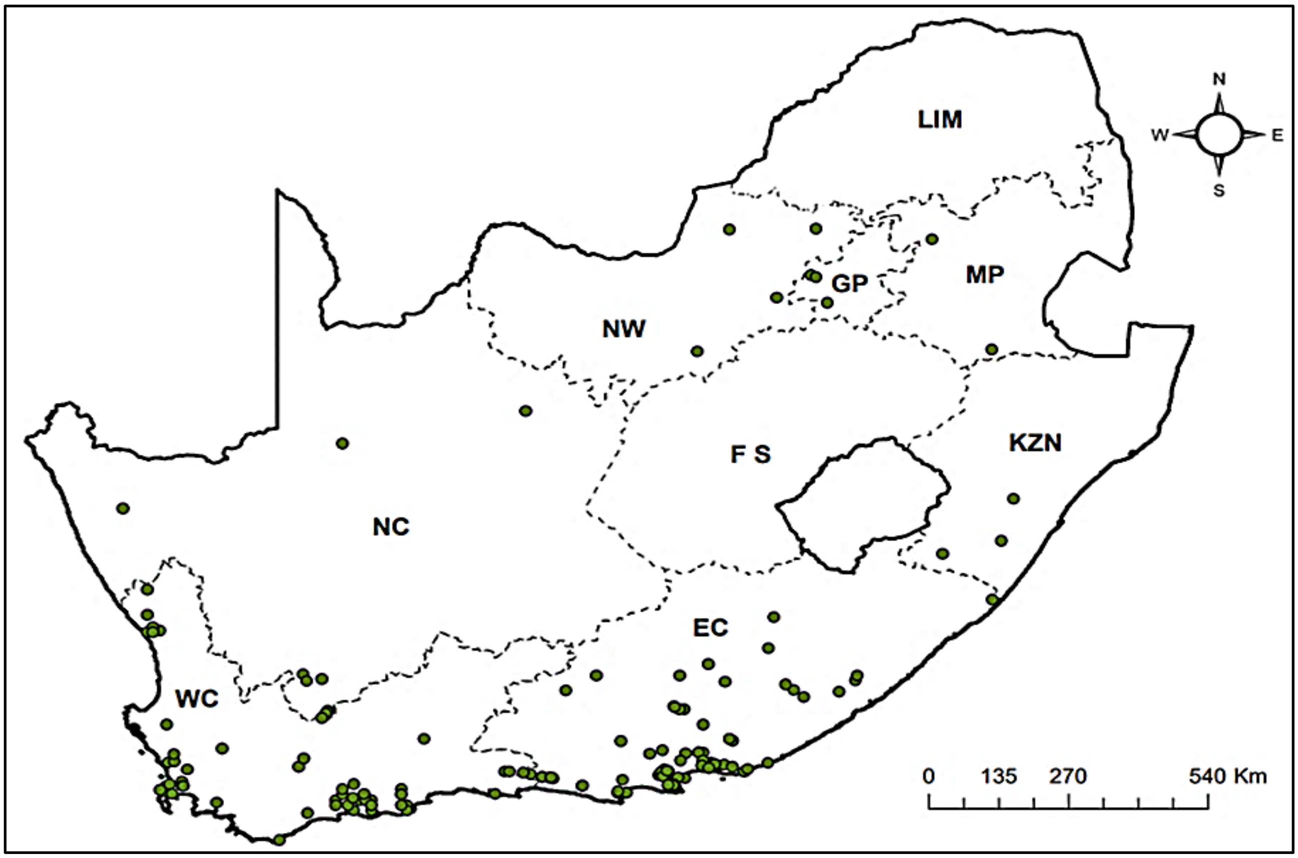

Figure 6. Current distribution of fennel in South Africa (based on records obtained from SAPIA, Herbarium, field surveys and ISPOT network).

In the study area fennel populations were described as scattered (sparse plants growth), medium (small patches among plant growth) or dense (plants grow close each other) (Fig.7). Dense fennel populations were distributed towards the coast including the Kou-Kamma, Kouga and Nelson Mandela Bay Municipalities and most of the region of the Sundays River Valley Municipality. Medium and scattered populations were distributed away from the coastal areas, including Dr Beyers Naudé Municipality, which covers a large area within the study area (Fig. 7). Fennel populations visited occur in different habitats within the study area (Fig. 7). Areas away from the coast were least affected by fennel, as the fennel populations were distributed in a scattered pattern (Fig.7).

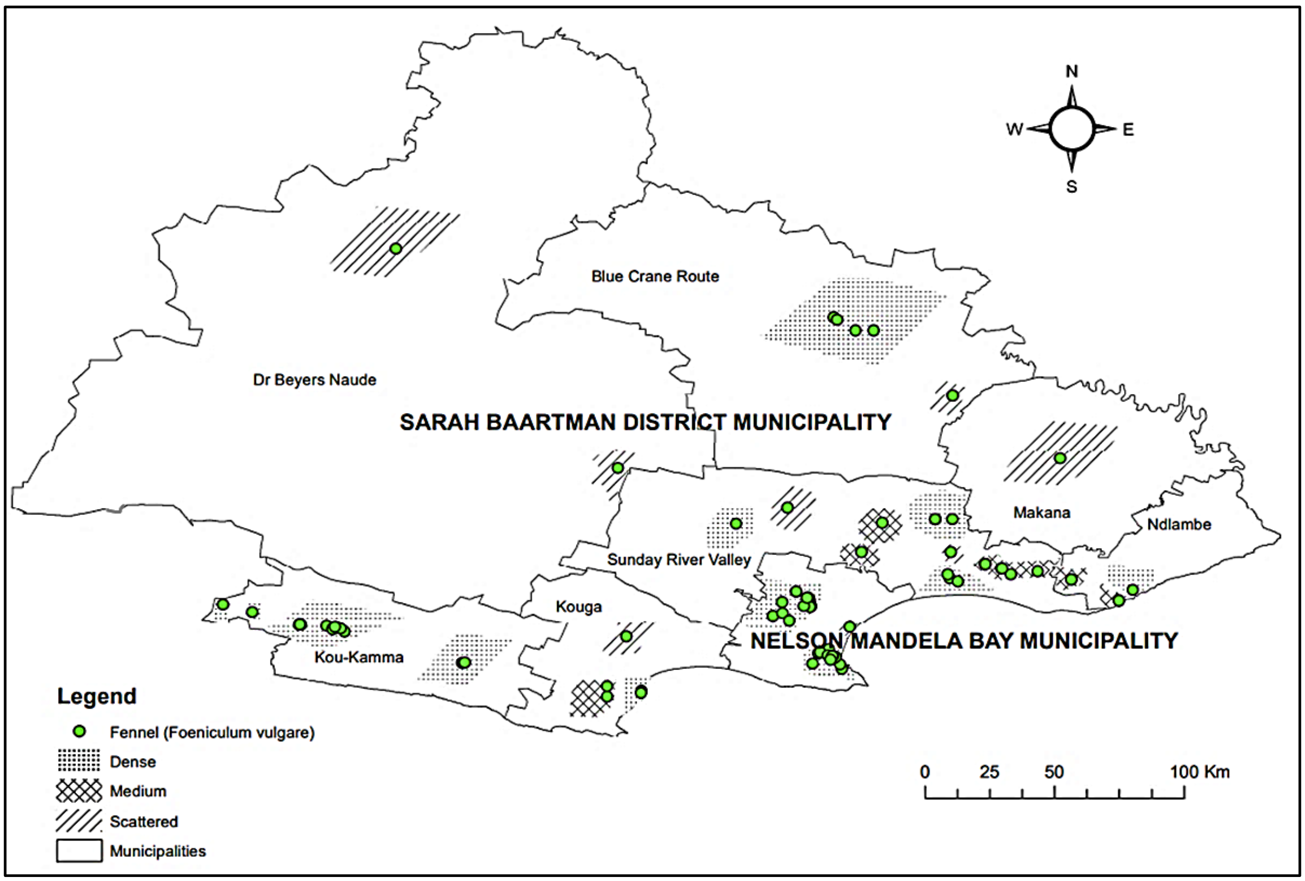

Figure 7. Distribution and quantitative estimate of fennel populations observed at around habitation, orchards, pastoral land, rail sidings, roadside, transformed and waste land (scattered, medium and dense) within study area.

Fennel's preferred habitats within the study area were next to gravel roads (Fig. 8a), included along unused rail sidings in Port Elizabeth (Fig. 8b). In Joubertina in the Kou-Kamma Municipality fennel was most prevalent in abandoned agricultural fields at (Fig. 8c), where an estimated area of more than one hectare and extended towards residential areas was identified. Linear patterns distribution of fennel population found along roadside in Uitenhage farm (Fig. 8d).

Figure 8. Naturalised fennel populations in different preferred habitats (a) gravel road in Krakiel River, (b) along an old railway line in Port Elizabeth, Holland Park; (c) at an abandoned agricultural field in Joubertina and (d) along a regional road in the Nelson Mandela Bay Municipality.

4.1.2. Preferred fennel habitats in the study area

The preferred habitat of fennel populations in the study area were recorded during the field survey. Roadsides represented the prevalent habitat of fennel populations in this study (65 records, Fig. 9). Rail sidings and transformed areas have the next highest number of fennel records with four and 16 records, respectively (Fig. 9). Fewer fennel populations were recorded in and around habitation (3 records), in pastoral land (2 records) and wasteland (1 record, Fig. 9). All fennel populations found along railways, were along abandoned railway lines. The high occurrence of fennel along roadsides may often be associated with more disturbed and nutrient rich runoff onto road verges. This may also due to easy dispersal of the species by car tires and extra water runoff and/or ease of accessibility of these sites during the survey for the species, i.e. due to oversampling during data collections. The results are in agreement with those of invasive fennel in Australia (Parsons and Cuthbertson, 2001), New Zealand (Esler, 1988) and California (DiTomaso *et al.*, 2013), which indicated that fennel occurs mostly at roadsides and transformed areas.

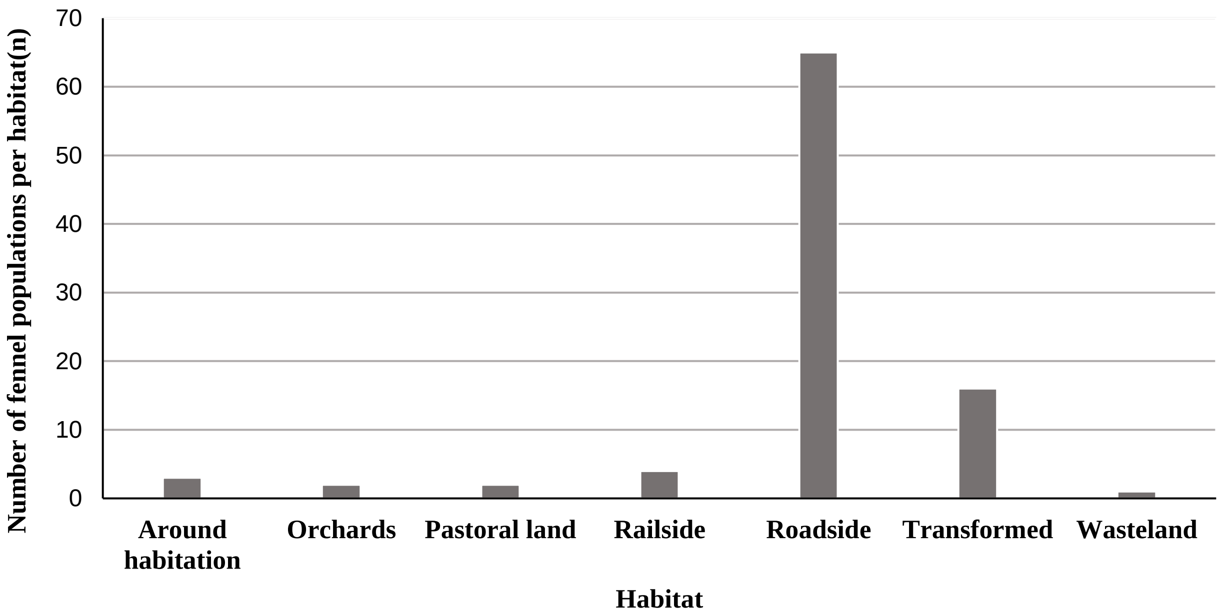

Figure 9. The number of fennel population per habitat types in the study area.

4.2. Potential distribution of fennel using the CLIMEX model in the study areas and South Africa

The potential distribution of fennel using the CLIMEX model in the study area and South Africa predicted more or less the same patterns as its current known distribution (Fig. 6). CLIMEX also predicted some areas in other inland provinces in South Africa that have suitable climate for fennel (Fig. 10). CLIMEX predicted a high climatic suitability along the East coast, from the southern Cape, which have winter rain to the East coast of the Indian Ocean. EI values between (80 to < 90 and 90 to < 100) were predicted from its current known distribution within its native Mediterranean climate of the Western Cape Province, becoming more favourable in the southern Cape with EI values of (90 to < 100) extended towards the western part of the Eastern Cape Province. Climatic suitability increases with EI values of (60 to < 70) towards the east coast region of Port Alfred. CLIMEX predicted a slight decrease of the potential distribution of fennel along the east coast towards Durban in KwaZulu-Natal from (60 to < 70) (Fig. 10). The decrease in potential distribution of the species in some areas of KZN coast could be the result of low Growth Index (GI) predicted by CLIMEX in parts of KZN coast, which can cause the species fail to complete its growth cycle (Kriticos *et al*., 2003a; Kriticos *et al*., 2005).

Low climatic suitability areas were predicted westwards between the Eastern Cape and KwaZulu-Natal (Fig. 10). Decreases in climate suitability in the aforementioned areas may be mainly due to the cold stress during the night. Climate conditions are only slightly suitable in the inland provinces of Gauteng and Mpumalanga that have high Growth Index and favourable total rainfall. Significant decreases of climatic suitability for fennel was predicted in the arid region of South Africa, namely, in the Great Karoo of the Northern Cape and Western Cape Provinces (Fig. 10). Climatic suitability decreases significantly when moving towards the west coast of South

Africa in the Northern Cape as the CLIMEX model predicted (0 to < 10) EI values (Fig. 10). The decreases in climatic suitability in the Great Karoo are the high cold stress and low total rainfall that decrease plant growth (Kriticos *et al*., 2015).

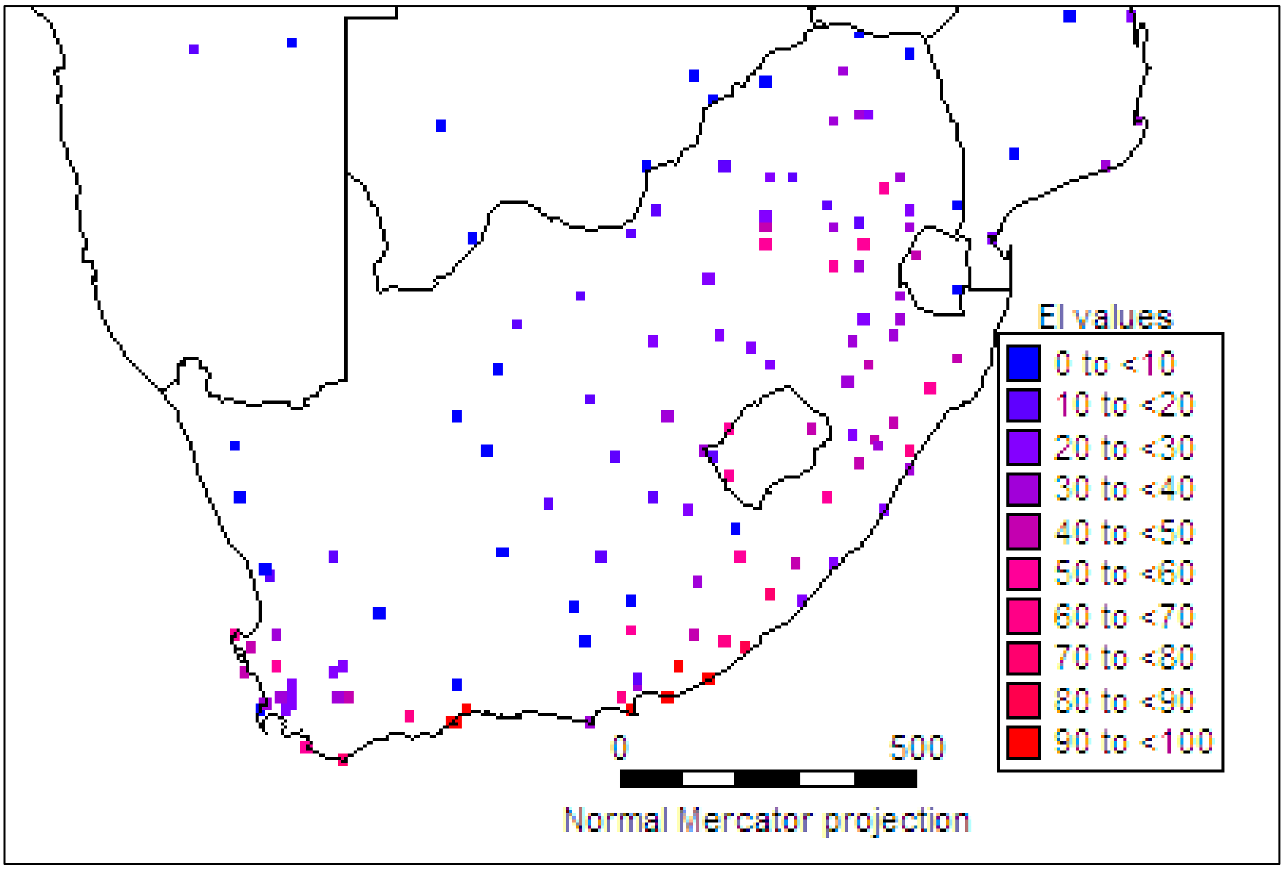

Figure 10. Potential distribution of fennel in study area and South Africa using CLIMEX model with Ecoclimatic Index values (suitable climatic areas increases as the colour change from blue to red).

To confirm results, current known distribution of fennel was compared with CLIMEX results for potential distribution to all known countries and where it is established and invasive. This potential distribution showed similar results with countries reported to have fennel as either non-native or native (Fig. 1). It also shows similar trends in North America and Asian countries compared to its current known distribution (Fig. 11). In Australia, the potential distribution of fennel is indicated in similar areas as the current known distribution, with EI values of (60 to < 70) on the coast of Western Australia, (80 to < 90 and 90 < 100) in New South Wales and Victoria (Fig. 11). CLIMEX results predicted the current known distribution of the species in the Mediterranean countries of southern Europe and North Africa, well with EI values of (70 to < 80 and 80 to < 90) (Fig. 11).

In addition to the high climatic suitability predicted for the East coast of South Africa, there was an area of high suitability in western Tanzania. Subtropical and tropical places in Africa along the Indian Ocean showed a low potential distribution of the species with EI values of (40 to < 50)(Fig. 11). There are fewer suitable climates along the coast of Asia. The two stress indexes predicted by CLIMEX model that limit potential distribution of fennel in Asia are: heat stress in India, Pakistan and Thailand and cold stress in China with EI values of (20 to < 30) (Fig. 11).

In New Zealand, CLIMEX predicted similar potential distribution to known current distribution with EI values ranges from (50 to < 60; 60 to < 70 and 80 to < 90) (Fig. 11). In South America, Chile and Argentina there is wider potential distribution of fennel, with EI values of (70 to < 80, 80 to < 90 and 90 to < 100) and an extensive distribution is noticed in those areas where the current distribution of the species is known. The high potential distribution is the result of favorable annual growth (GI), less stress indices especially heat and dry stresses that have detrimental effects in plant growth and favorable annual rainfall that can support the plant to growth (Kriticos *et al*., 2003; Kriticos *et al*., 2005). The low EI values predicted for much of South Africa are due mainly to the extreme heat stress in dry areas during the day, cold stress at night especial in desert areas and low annual rainfall. Cold persisting temperatures prevent the establishment of fennel (Purwaningsih and Brink, 1999). In the moisture areas of Africa heat stress is the main contributor to low EI, and in much of north Africa dry stresses are the main contributor to low EI.

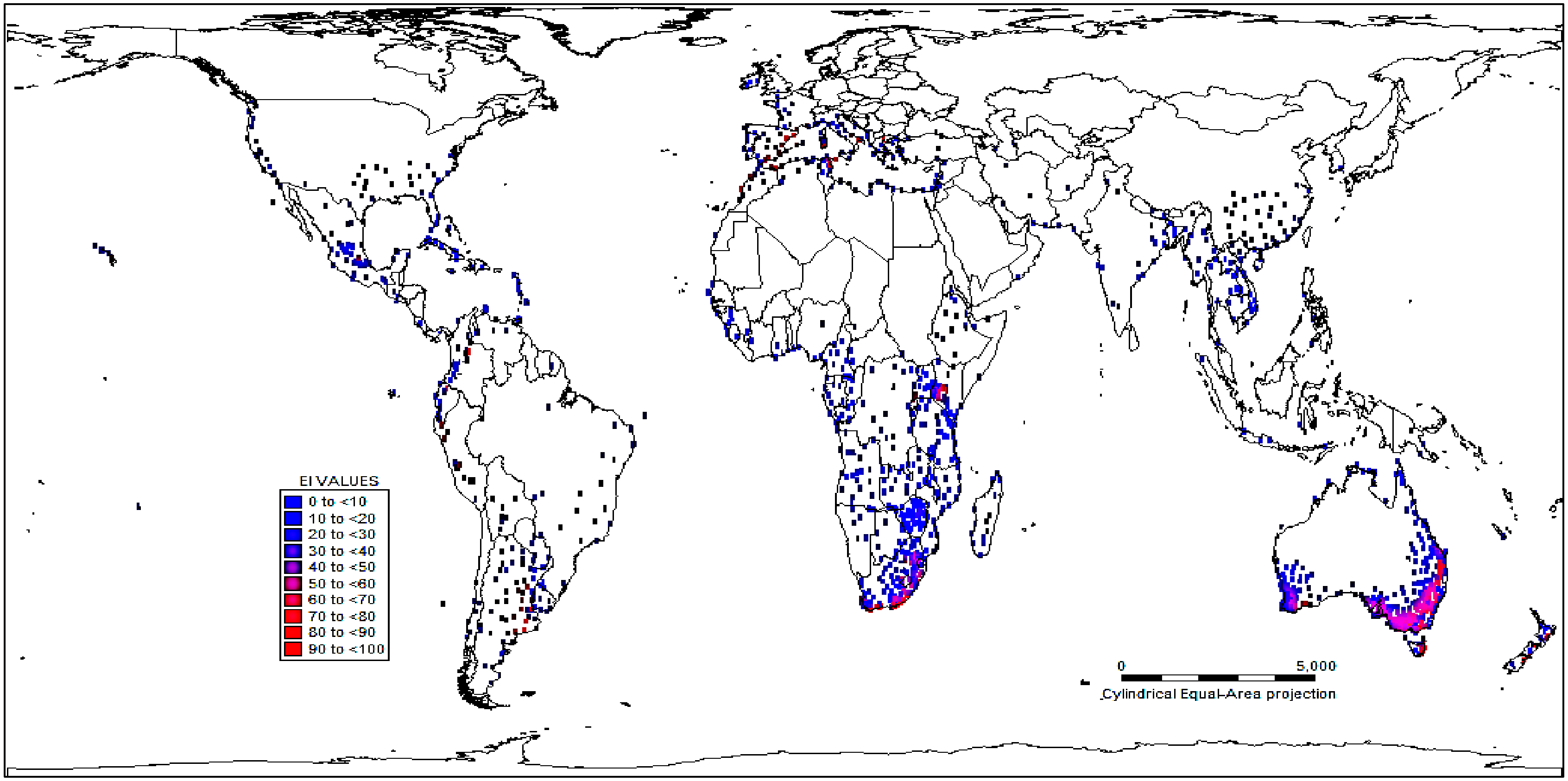

Figure 11. Global map indicating the potential distribution of fennel with CLIMEX model (suitable climatic areas increases as the colour change from blue to red).

4.3. The vegetation types in which fennel mostly occurs in the local study areas

Fennel is most common in the coastal areas, highly degraded by human activities, including urban development and agricultural activities (Parsons and Cuthbertson, 2001) (Fig. 12). Cultivation in the study area includes citrus and apple orchards. Livestock farming is also found in the study area as well as degraded land, which left only a small part of the total study area still regarded as of significant ecological value. The interior study site dominated by Low Shrubland vegetation consists of private lands and goat and sheep farming which has shown no indication of fennel occurrence.

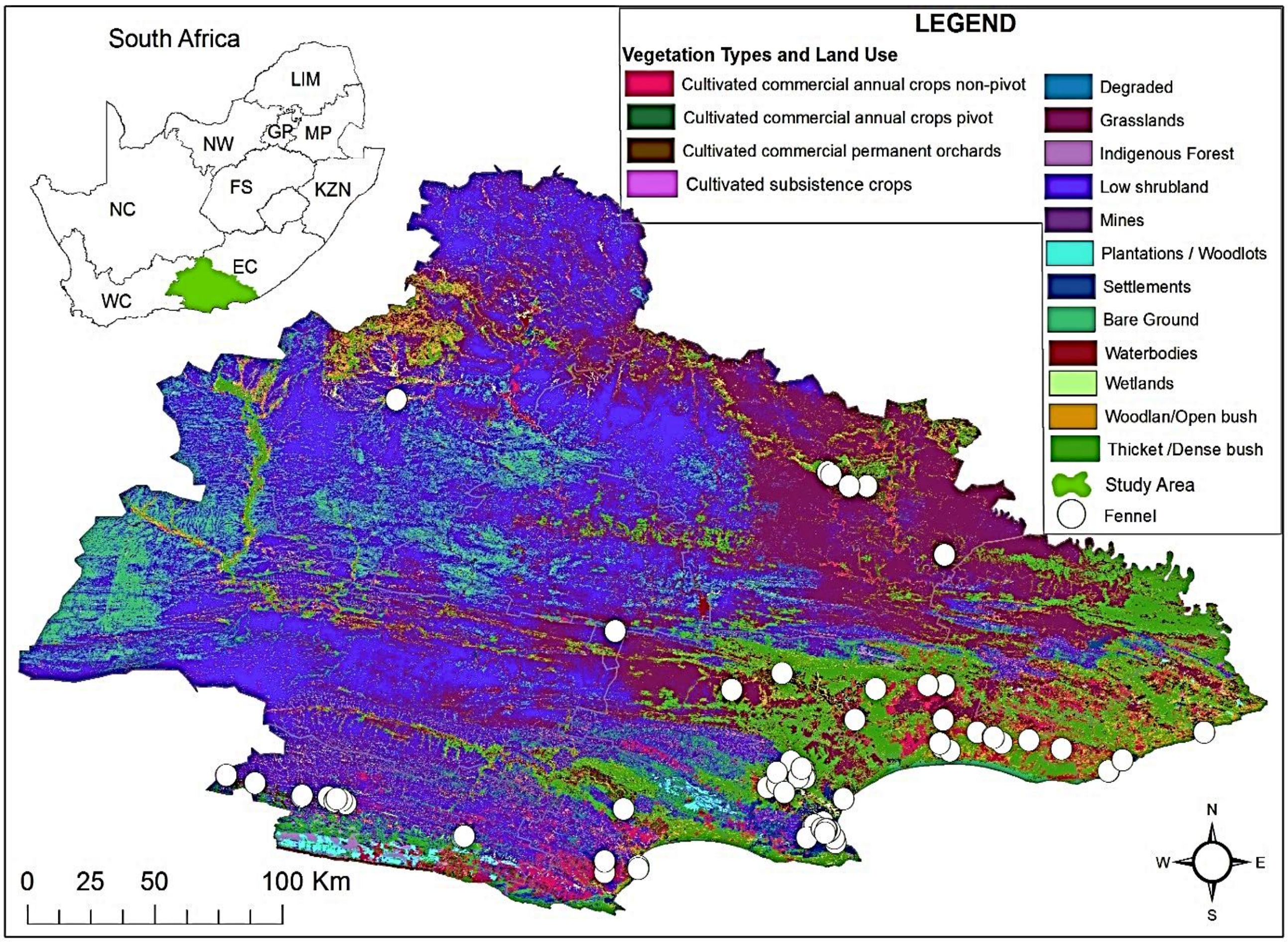

Figure 12. Fennel records (indicated with white circles) within vegetation types and land use types in the study area (SANBI BGIS land-cover dataset for South Africa, 2014).

The number of fennel populations per vegetation type from 86 fennel populations, 43 records of fennel population were found in five vegetation types identified in Sarah Baartman District and Nelson Mandela Bay Municipalities during field surveys and confirmed from "SANBI BGIS land-cover dataset for South Africa, 2014" (Fig. 13). From the 43 records of fennel populations, Thicket/Dense bush showed the highest frequency with 47%, followed by Woodland/Open bush with 21%. The lowest fennel frequency was noted in Low Shrubland and Wetlands both with 9% each and Grasslands with 14% (Fig. 13). All remaining fennel populations (43) were found at residential road-sides, citrus and apple plantations, degraded land and cultivated land distributed along gravel roadsides.

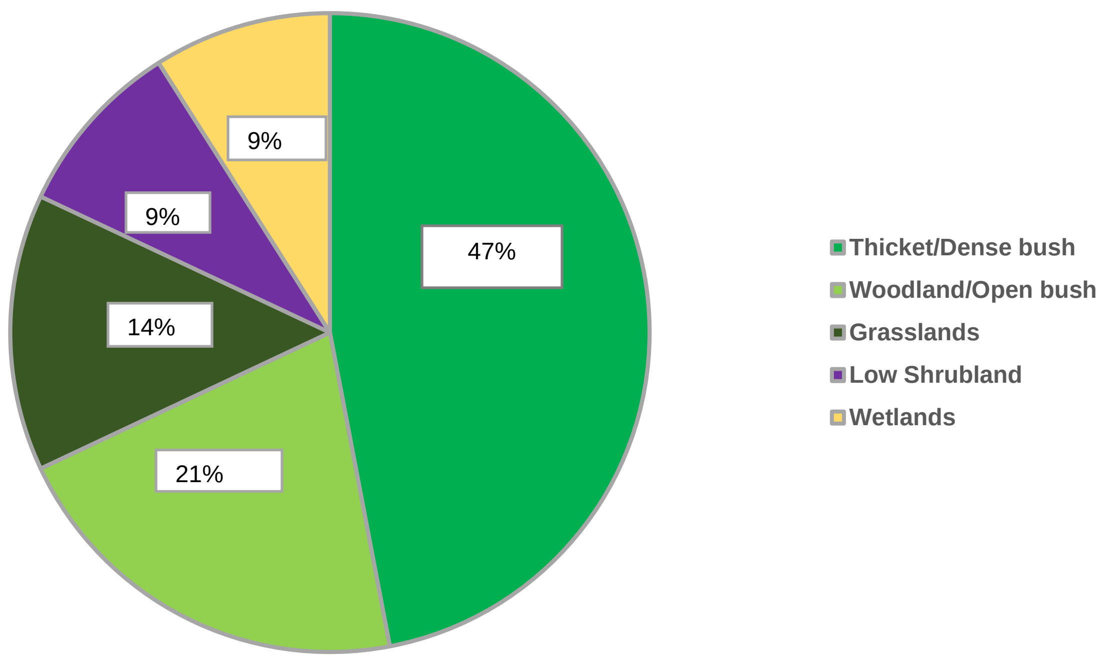

Figure 13. Proportion of occurrences calculated from number of observed fennel populations per vegetation type in the Sarah Baartman District and Nelson Mandela Bay Municipalities in the study area obtained from (SANBI BGIS land-cover dataset for South Africa, 2014).

4.3.1. Historical vegetation cover in the study area

Within the study area, the historical background vegetation types downloaded from "SANBI BGIS land-cover dataset for South Africa, 2014" showed that Low Shrubland and Grasslands vegetation comprise a large total area, Low Shrubland covered about 46% and Grasslands 29% (Fig. 14). The 3 historic vegetation types with least coverage were Thicket/Dense bush with 19%, Woodland/Open bush 6% and Wetlands with 1% (Fig. 14).

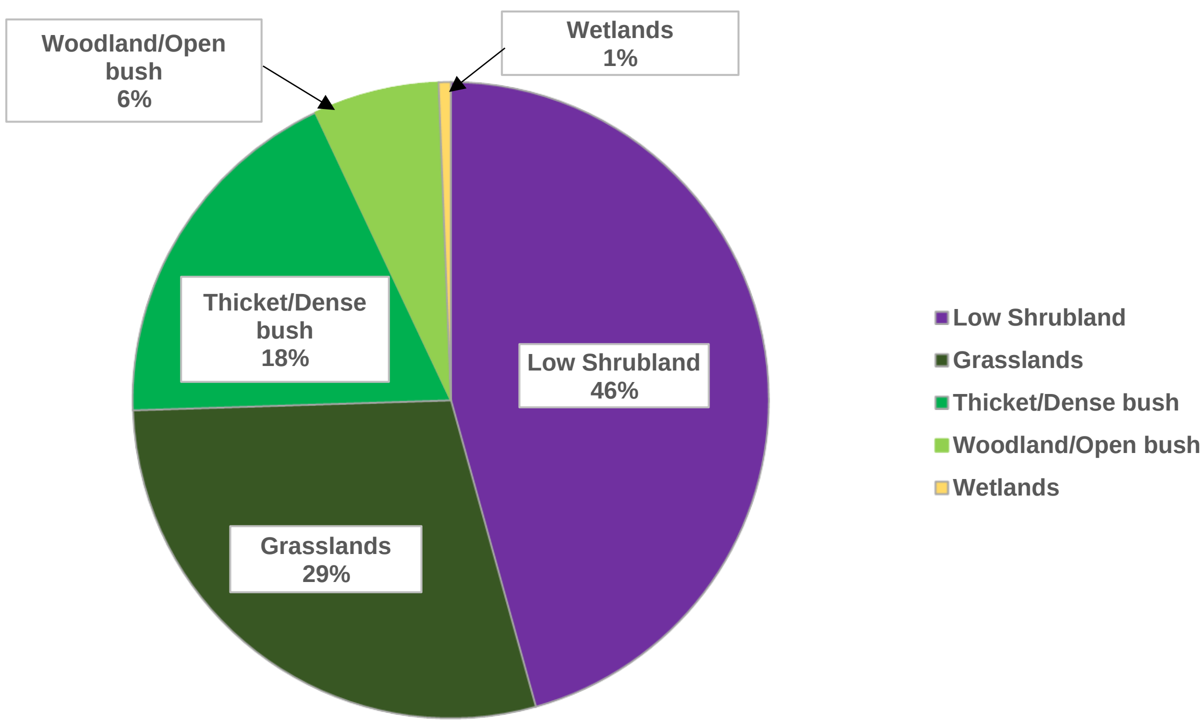

Figure 14. Proportion of original land cover vegetation types at the study area calculated from SANBI BGIS land-cover dataset for South Africa, 2014.

For each of the five vegetation types identified in the study area (Fig. 13), the researcher made an estimate the number of fennel plants per vegetation type (Fig. 15), and extent of infestation per observation (Fig. 16).

For Grasslands vegetation, three of the sites had a number of fennel plant estimate (6-20) (Fig.15). Low Shrubland vegetation had the lowest estimated number of fennel plants. Four fennel populations were recorded in the Low Shrubland vegetation, two records of fennel populations were estimated between 20-50, and one each estimated between (2-5) and number of plants greater than 50 plants/ha (Fig.15). Thicket/Dense bush sites had the high numbers of fennel plants with 9 sites estimated as greater than 50 plants (Fig. 15). Like Low Shrubland there were only four sites in Wetlands but overall there were more plants per sites and sites were usually larger (Fig. 15). The Woodland/Open bush had high numbers of fennel plants, as five populations were estimated as having a plant density greater than 50, three were estimated (20-50) and one at (6-20)(Fig. 15).

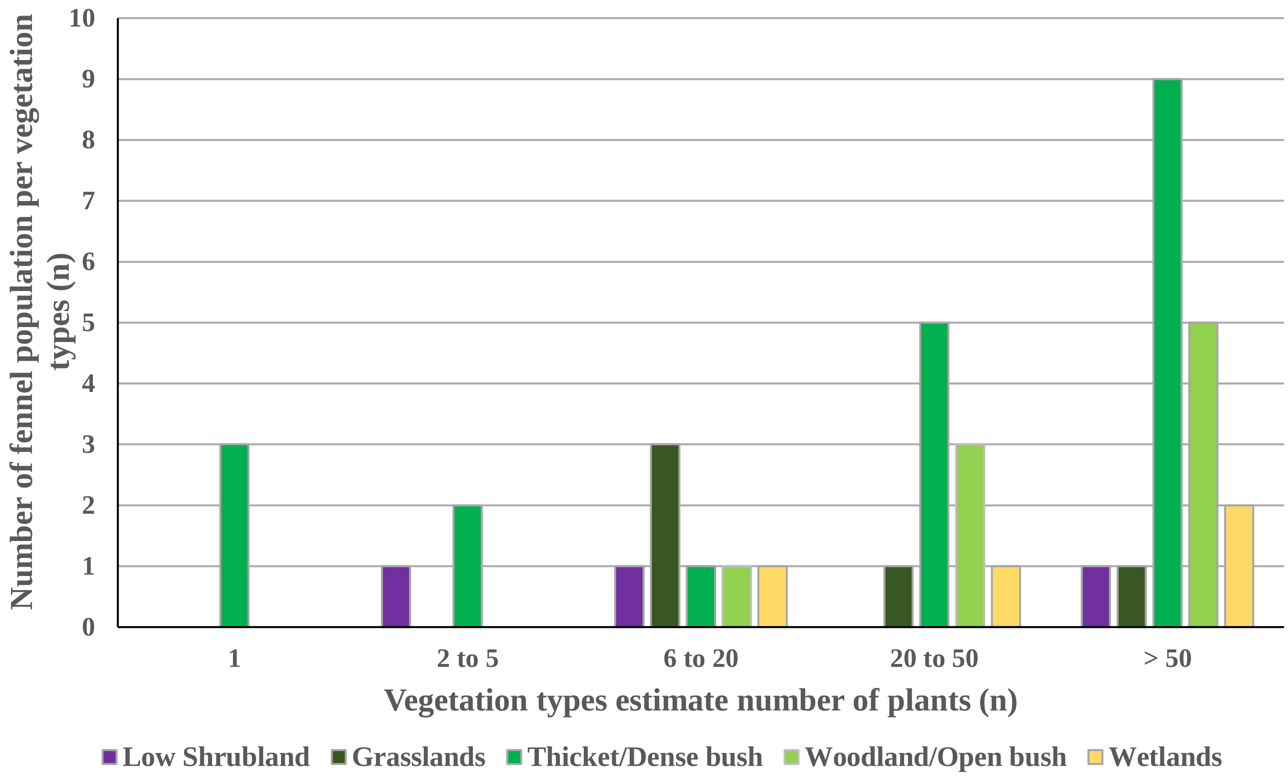

Figure 15. Estimate of fennel invasion per vegetation types in the Sarah Baartman District and Nelson Mandela Bay Municipalities showing estimated number of plants.

The extent of infestation for Grasslands was the third highest from the five vegetation types with four sites (10-100m²) and two sites of (100-1000m²) in extent (Fig. 16). The extent of the invasion was large with eight observation of (100-1000m²) and five (> 50) and five observations were greater than one hectare (Fig. 16). This showed that Thicket/Dense bush was the most invaded land use type both in number of plants and in extent of invasion within the study area. The woodland/Open bush habitat is the second most invaded vegetation types after Thicket/Dense bush in the study area with four sites estimated at a fennel density of (10-100m²), two at (100-1000m²) and three at (> 1h)(Fig. 16).

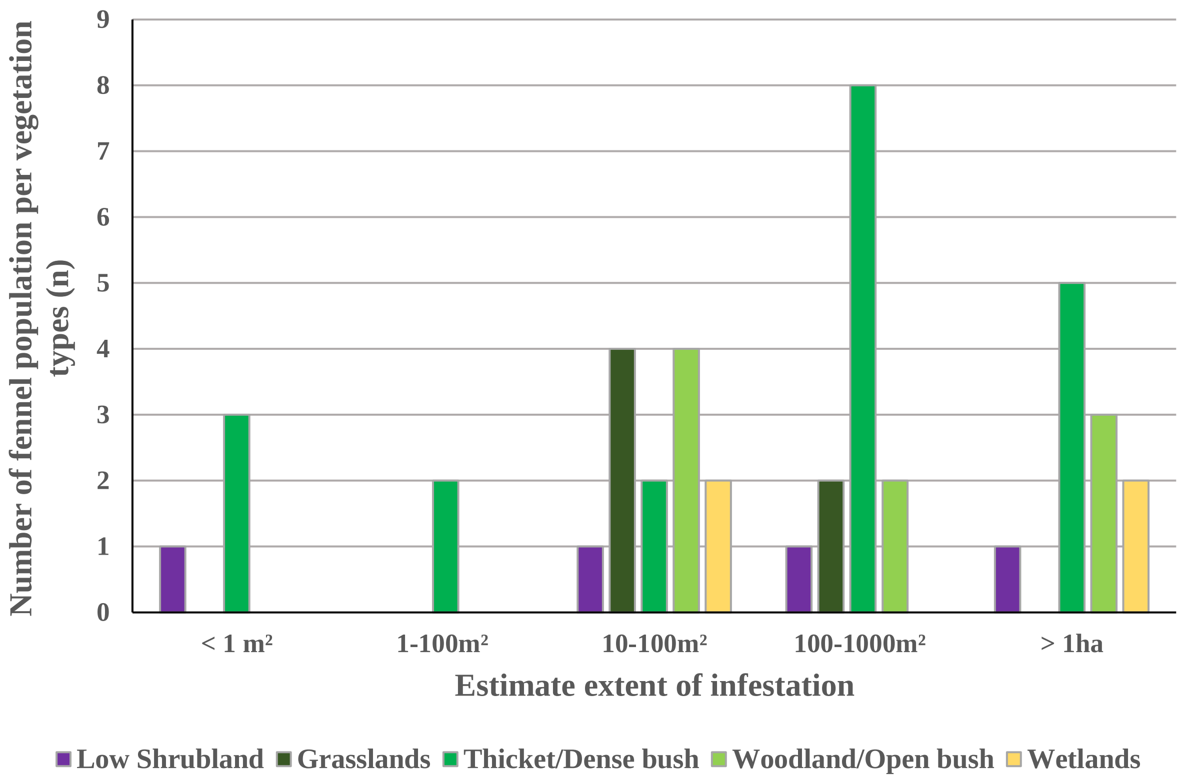

Figure 16. Estimate of fennel invasion per vegetation types (Grasslands, Low Shrubland, Thicket/Dense bush, Wetlands and Woodland/Open bush) showing extent of infestation per observation.

4.1.4. Reproductive output

4.1.4.1. Seed production per field site

Individual fennel plants have high seed production often up to 500 000 and mostly over 200 000 seeds per plant was estimated in Somerset East (Fig. 17). Altitude does not appear to affect seed production as the two field sites with the highest seed production were at different ends of the spectrum. The second highest mean seed yield per plant was at Holland Park in Port Elizabeth (Fig. 17). The lowest mean seed production per plant was recorded in the Amanzi area (Fig. 17). Amanzi area also had the lowest average seed production calculated from five plants.

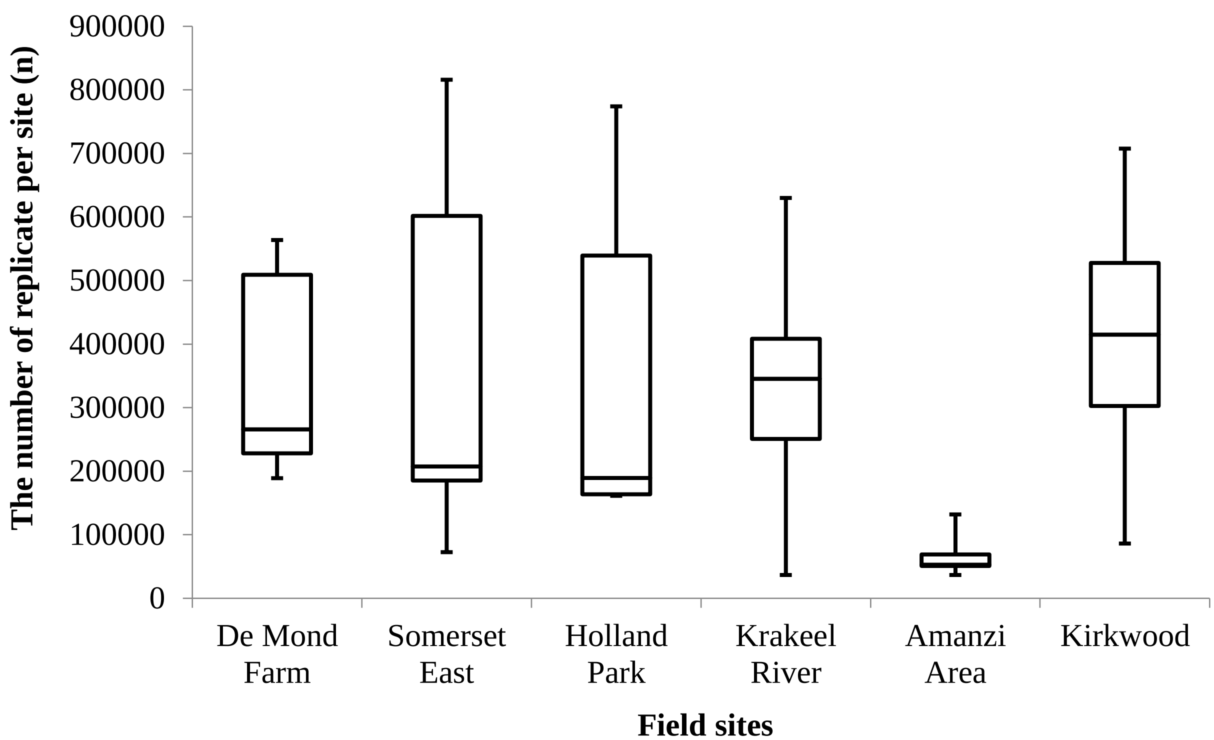

Figure 17. Mean seed production per field site, box and whisker plot display data distribution range of number of replicates per field site.

4.1.4.2. Plant height per field site

The tallest plants were recorded in Holland Park and Krakeel River at an altitude of 15 metres above sea level (m.a.s.l) and 547 m.a.s.l respectively (Fig. 18). From the five individual fennel plants selected from the six (6) field sites, plant heights ranged from 1.5 m to 2.5 m (Fig. 18). Three sample sites showed similar heights, namely, Kirkwood, Somerset East and De Mond Farm with an average of 2 m. Plant height at the Amanzi area was the shortest compared to other sample sites and ranged from 1.3 to 1.4 m (95% CI: 1.7-1.5) (Fig. 18). Average plant height was 2.01 m (95% CI: 1.9-2.1) at the Karoo region and 2.38 m (95% CI: 2.2-2.5) at coastal region, taller at coastal than Karoo region.

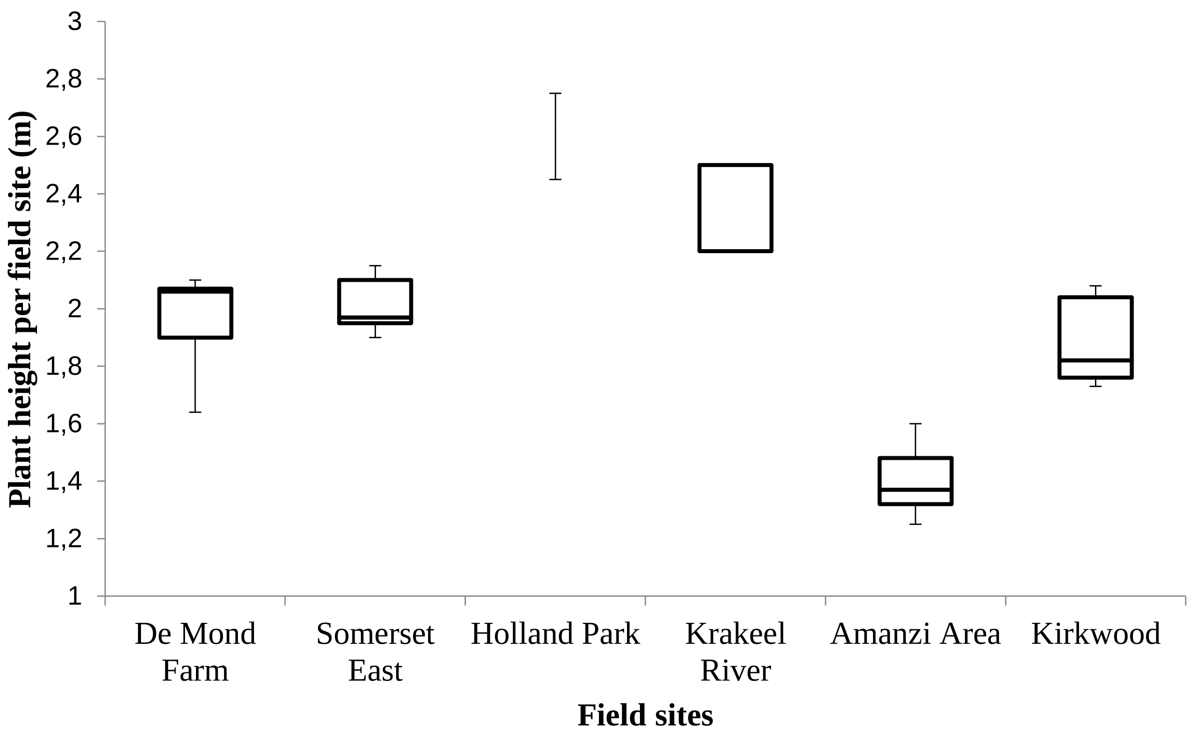

Figure 18. Mean plant height per field site, box and whisker plot display data distribution range, the minimum, lower quartile (25%), median (50%), upper quartile 25% and maximum values (n= replicate per site).

Table 3. Summary of ANOVA with degrees of freedom, sum of squares, mean square, F statistic and probability value for seed production and plant height at the field sites.

ANOVA	*df*	Sum Square	Mean Square	F value	P value
Seed production	5	3.9369e+11	7.8738e+10	1. 5964	0.1992
Residuals	24	1. 1837e+12	4.9322e+10		
Plant height	5	4.4993	0.89985	40.711	5.892e-11
Residuals	24	0.5305	0.02210		

Using ANOVA at α =0.05 level significance, the mean square seed production was 7.8738e+10 and the results showed that there was no statistical difference in seed production between field sites (Table 3). Plant height results showed that there was statistical significance between the field sites (Table 3). Post Hoc test indicate that statistical significance were in Somerset East and Amanzi Area (Table 4), Krakeel River and Kirkwood and Holland Park and Kirkwood (Table 4)

Table 4. Post Hoc Test on plant height per field site (LSD= 0.46), statistical significance at field sites, De Mond Farm and Holland Park; Holland Park and Amanzi; Somerset East and Holland Park; Somerset East and Amanzi area; Holland Park and Amanzi Area; Holland Park and Kirkwood; Krakeel River and Amanzi Area; Krakeel River and Kirkwood; Amanzi and Kirkwood.

Field sites		**Mean Differences**
De Mond Farm (m1)=	1.95 m	m1- m2 = |-0.06| (ns) m1-m3 = |-0.68| (s) m1-m4 = 0.43 (ns) m1-m5 = |-0.55| (s) m1-m6 = 0.05 (ns)
Somerset East (m2) =	2. 01 m	m2-m3 = |-0.62| (s) m2-m4 = -0.37 (ns) m2-m5= 0.61 (s) m2-m6= 0.11 (ns)
Holland Park (m3 =	2.63 m	m3-m4 = 0.25 (ns) m3-m5= 1.23 (s) m3-m6= |-0.73| (s)
Krakeel River (m4) =	2.38 m	m4-m5 = |-0.98| (s) m4-m6 = 0.48 (s)
Amanzi Area (m5) =	1.40 m	m5-m6 = |-0.5| (s)
Kirkwood (m6) =	1.9m	

ns = no statistical difference different

s= honestly statistical significance

4.5. Seed germinability

With all six field sites with 50 seeds each, the Amanzi area germinated 50 seeds within the shortest time of nine days (Fig. 19a). At Holland Park, 47 seeds germinated within 14 days, and another three days thereafter (Fig. 19b). At Kirkwood, 48 seeds germinated within 11 days to reach its maximum germination (Fig. 19c). At Krakeel River, 47 seeds germinated which took 12 days (Fig. 19d). Seeds taken from the interior of the study site at Somerset East, 48 germinated seeds within ten days (Fig. 19e) and in De Mond Farm 47 seeds germinated within 11 days (Fig. 19f).

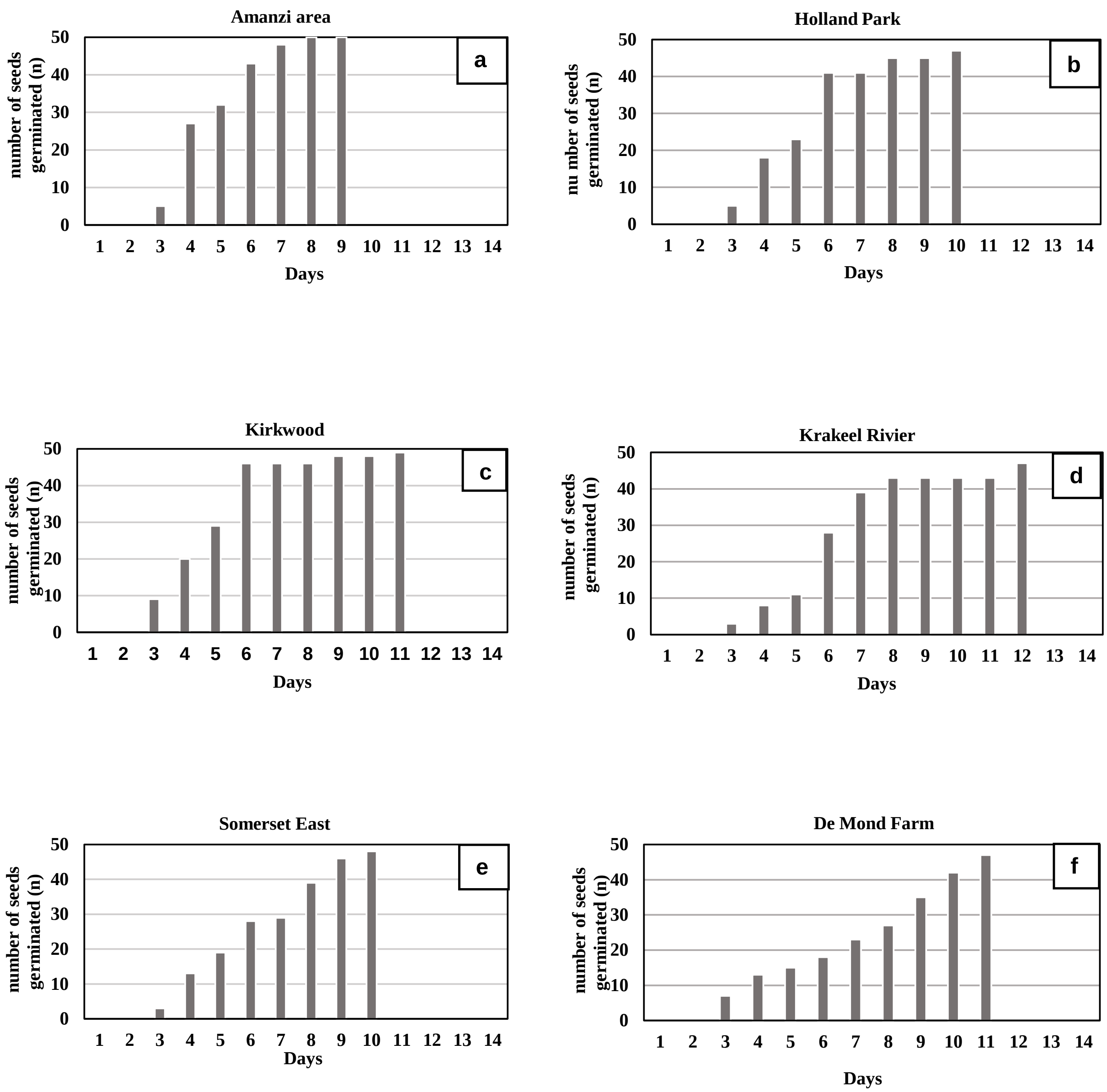

Figure 19. Cumulative graphs showing germination times of fennel seeds taken from six different field sites in the Sarah Baartman District and Nelson Mandela Bay Municipalities: (a) Amanzi area; (b) Holland Park; (c) Kirkwood; (d) Krakeel River; (e) Somerset East; and (f) De Mond Farm.

Three hundred seeds were used in the experiment, 287 germinated within the expected seed germination period for fennel, which indicated a 96% success. The Germination Index was calculated using the following formula (Kader, 2005):

Germinating Index (GI) = (10 x n1) + (9x n2) +. . . +(1x n10),   n1, n2. . .n10 number of germinated seeds from the 1st, the 2nd until the tenth day.

Day three until day 12 were the days, when the seed germination rates were highest. 12 seeds did not germinate within the 14 days. The Germinating Index (GI) was calculated at all sample sites (Table 5) and the results were different from each site.

Table 5. Number of seeds samples, number of seed germinated and Germinating Index (GI) calculated from the six field sites in Sarah Baartman District and Nelson Mandela Bay Municipalities.

Sample sites	**number of seeds sample(n)**	**number of seeds germinated(n)**	**GI**
De Mond Farm	50	47	368
Somerset East	50	48	417
Holland Park	50	47	453
Krakeel River	50	47	402
Amanzi Area	50	50	505
Kirkwood	50	48	488

4.6. Risk of fennel in the study area

Of 49 questions from the risk assessment template, 43 questions were answered (Appendix V). Questions not answered reflect the fact that information on the species in South

Africa was not available and there was not enough evidence to support the statements. Fennel results in South Africa are indicated on (Appendix V), questions from the original risk assessment template as per Pheloung *et al*. (1999) and Gordon *et al*. (2010) and supplementary information based on the species history and biology are listed on (Appendix VI). Risk assessment results were summarised as follows (Table 6):

Table 6. Summary of weed risk assessment score for fennel based on domestication, climatic suitability, weed status, undesirable traits, category to which the species belongs, reproductive output, dispersal mechanism and factors that increase or decrease the species` where it grows in South Africa.

Question category	**Score**
Domestication of the species	-2
Climatic suitability and weed status in South Africa	2
Fennel's weed status elsewhere	5
Undesirable traits	3
The category, to which the species belong, either aquatic, grass or nitrogen-fixing plants	0
Reproductive output	0
Dispersal mechanism	2
Factors that increase or decrease the species' persistence where it grows	1
Total score	11

Fennel obtained a total score of 11, which means its score is above the minimum score of six, indicating that the probability of the species to become invasive is high (Pheloung *et al*., 1999). The score results indicated that in future, fennel could be problematic to the South African ecosystems.

CHAPTER 5

5. DISCUSSION

5.1. Current distribution of fennel in South Africa

Using desk top studies and field surveys to map the current distribution of fennel in South Africa, It was found that fennel is widely distributed in South Africa. Fennel is more widespread in coastal provinces and decreases inland. The current distribution of fennel in South Africa indicates that it is present in seven of the nine provinces, excluding the Free State and Limpopo Provinces (Henderson, 2007). Populations mostly appeared less established in inland Provinces, maybe as a result of unfavourable climate. The Western Cape and western part of Eastern Cape Provinces and adjacent areas, represent areas with the greatest occurrences of naturalised fennel. Distribution to other parts of the country probably resulted both through deliberate planting and escape, and long distance dispersal by humans.

Within the region of the Sarah Baartman District and Nelson Mandela Bay municipalities, fennel was found along roadsides, including national, regional and gravel roads. The high occurrence of fennel along roadsides may often be associated with more disturbed and nutrient rich runoff onto road verges. The distribution patterns are similar among all locations included in this study. Fennel most likely occurs along roadsides as a result of seeds being trapped on car tires (Parsons and Cuthbertson, 1992; Bossard *et al*., 2000). Alternatively, road maintenance, which includes the use of grass mowers, can easily disperse seeds to the surrounding environment (Parsons and Cuthbertson, 1992). The distribution of fennel within the study area was categorised per infestation. Noticeable differences have been observed between apple and citrus orchards and grazing areas as fennel tends to be denser in orchard areas compared to pastures. During the survey, it was observed that in areas with pastures, for example Cannon Rocks, the fennel infestation was lower when compared to areas without grazers such as in Kirkwood and Joubertina. This concurs with most of the findings indicating that grazers, especially mammals, consume the species, while it is still young (Parsons and Cuthbertson, 2001; Breton & Klinger, 1994; Erskine-Ogden and Rejmánek, 2005). Other factors that explain the lower population in grazing areas could be that seeds are more easily seen and hence eaten by rodents and birds (Bossard *et al*., 2000), it could be that soil is generally more compacted and seed does not easily get planted. There are however many aspects of agriculture that may promote fennel establishment, including tilling and adding organic amendments. These activities could also result in movement of soil contaminated with seed to different areas (Ratnayake, 2014) and so increase the population.

Fennel populations were dense along the coast within the city of Port Elizabeth and surrounding areas, becoming less dense further away from the coast and scattered towards the interior of the study area where there was less degraded land. In Jeffreys Bay, Port Elizabeth and Uitenhage fennel populations were intensely distributed in transformed areas due to high disturbance. Seeds may come with garden waste to illegal dumping areas and disturbance creates suitable habitat (Parsons and Cuthbertson, 2001). Competition in a disturbed habitat is less and this may promote fennel establishment (Power *et al*., 2014).

Within the study area, few populations of fennel were found close to watercourses. This is contrary to reports from other countries where fennel is found along watercourses, often causing socio-economic impacts (Esler, 1988; Muty, 2001). In this study, fennel populations found along roadsides had grown much taller compared to fennel growing adjacent to watercourses in the same area. Possibly the natural vegetation observed in these areas out-competed fennel for light and space, the tall aquatic plants growing in dense stands.

Fennel is distributed and naturalised far beyond the Mediterranean climate of the Western Cape Province. Naturalised fennel populations were found in the Karoo region which has lower temperatures and lower rainfall than the species' native range. For example at a sample site located at Kirkwood, a fennel population survived well with an annual average rainfall of 333 mm- far less than its normal average rainfall of 500-2000 mm (Purwaningsih and Brink, 1999). The climate was more suitable for fennel along the garden route towards Port Elizabeth compared to Northern Cape Province. The extreme cold and heat and lower average rainfall in the Northern Cape Province may be unsuitable for fennel establishment. Although there are records from higher altitude in Mpumalanga, North West and Gauteng Provinces, these are from old herbarium specimens and so it seems not to naturalise easily in these areas observed during initial field surveys.

5.2. Potential distribution of fennel in the study areas and South Africa

Potentially suitable areas predicted for fennel by CLIMEX included countries in East Africa with tropical climates - Kenya, Uganda and Tanzania. Potential distribution is also indicated in Mozambique, Zimbabwe and the island of Madagascar in southern Africa. The potential distribution of the species in other countries concur well with the known current global distribution of the species (CABI, 2017). The CLIMEX model correctly predicted the actual distribution in northern African Mediterranean countries (Egypt, Libya, Tunisia, Algeria and Morocco) (USDA-ARS. 2013). In Oceania countries of Australia and New Zealand the potential distribution was the same as the current known distribution. Similar potential distribution with current known distribution patterns of fennel was also observed in southern Europe and North America where the species is reported to be highly invasive (CAL IPC, 2005).

In South Africa climatic suitability for the establishment persistence of fennel was greatest in cape coastal regions and decreased northwards where there was low suitability in northern Karoo because there are several limiting stress indices namely heat, cold and dry conditions. It decreased northwards due to heat stress and low total rainfall conditions. Areas away from the coast were unfavourable because of extremes of temperature experienced during Winter and Summer. The actual distribution of fennel matches these predictions well.

5.3. Vegetation types in which fennel mostly occurs in the Sarah Baartman District and Nelson Mandela Municipalities

Based on observation through field surveys and confirmation through "SANBI BGIS land-cover dataset for South Africa, 2014", five vegetation types were identified within the study area that currently have fennel populations. These vegetation types are Grasslands, Wetlands, Woodland/Open bush, Low Shrubland and Thicket/Dense bush. Settlements and cultivated land are the other land use types where fennel populations are dominant and are where many records of fennel populations have been noted. Within the study area, the highest number of fennel populations are in fragmented Thicket/Dense bush and Woodland/Open bush vegetation. The lowest number of fennel populations are found in the Grasslands with a very few populations on Wetlands and Low Shrubland vegetation.

Vegetation types, shown to have a high density of fennel per site, are found within Thicket/Dense bush vegetation. The fragmented Thicket/Dense bush may easily promote fennel populations establishment. As per land cover and land use calculated from "BGIS 2014", Thicket/Dense bush is the third biggest vegetation type in the study area and it is located in close proximity to cities where there is high human impact. It is one of the vegetation types with the highest number of ruderal fennel populations. This concurs with the findings from Parsons and Cuthbertson (2001) in Australia, that degree of land utilization promotes the establishment of fennel.

Compared to other vegetation types where fennel populations found in Sarah Baartman District and Nelson Mandela Bay Municipalities, Grassland was the most invaded vegetation type. In Grassland vegetation fennel populations were found to occur in less degraded areas and extended into undisturbed areas. This corresponds with the findings of the study conducted by Beatty and Licari (1992) that in California fennel tends to invade Grassland vegetation. This can be due to the absence of a vegetation canopy in Grassland such that fennel grows fully exposed to sunlight with no competition for light, as an essential growth requirement (Purwaningsih and Brink, 1999; Parsons and Cuthbertson, 2001). This suggests grassland vegetation may in future be the most vulnerable to invasion by fennel.

The Low Shrubland had a low level of infestation but occupied a large part of the study area (cover about 46%), but it has the least number of fennel populations which are dispersed in the large area. This is due to the location of Low Shrubland vegetation that is far from developing areas. Less open patches within Low Shrubland vegetation also prevent fennel populations from establishing. Low Shrubland vegetation is found in the dry region (North West) of the study area which the stress indices of cold, dry and heat can be a limiting factor for fennel establishment. A high number of grazers as both livestock and a large number of wild grazers may be the agents that keep fennel population low as reported by Breton & Klinger, 1994; Parsons and Cuthbertson, 2001 and Erskine-Ogden and Rejmánek, 2005).

Wetlands vegetation type invaded by fennel is directly proportional to its size in the study area. The low fennel invasion observed in the Wetlands vegetation is probably due to less disturbance observed during field surveys. The tall dense reed vegetation in the Wetlands of study area also appeared to play a crucial role to prevent the establishment of fennel populations by preventing sunlight penetration. The presence of fennel populations observed in Wetlands of Sarah Baartman District and Nelson Mandela Bay Municipalities add to the dense growth already created by reed vegetation. This may interfere with Wetlands species.

Woodland/Open bush has the second highest frequency of fennel populations after Thicket/Dense bush vegetation. It is occurs on the eastern side of the study area, where the area is dominated by pastures. It has a high number of naturalised fennel populations. There are two possible reasons for presence of many fennel populations in this vegetation type. Open patches give the sunlit environment which fennel prefers. Secondly, the east side of the study area is located in the favourable climate of the coastal of Indian Ocean with moderate rainfall and temperatures, these can promote fennel population establishment (Parsons and Cuthbertson, 1992).

5.4. Reproductive output

5.4.1. Seed production per field site

Fennel had a high seed output and this concurs with other research conducted by Erskine-Orden, 2004; Thomlinson, 2013 and Brown and Bettink, 2016. Each plant could yield an estimated half a million seeds. Fennel shown to have well adapted in the region of Sarah Baartman and Nelson Mandela Bay Municipalities as seed production per field site did not differ between sites at the coastal and inland areas. Field site in the driest region of Karoo with lowest temperatures in winter had almost the same number of seeds produced as the field sites found in coastal regions with moderate temperatures. The high seed output of fennel increases its potential invasiveness (Baker, 1965). Many different pollinators were observed during field work, ensuring pollination and hence high numbers of seeds.

Large seed output in plants is one of the key determinants for the success of non-native species and to compete with native species (Flores-Moreno and Moles, 2013). Seeds are also regarded as a key principle for the spread of invasive species that can invade disturbed and pristine environment (Witkowski and Garner, 2008). Large seed output per generation cycle in an invasive plant can increase the number of plantlets over a wide area (Ratnayake, 2014), hence easily out-compete native plants. The high seed output is the reason why fennel is listed as a highly invasive species in California (DiTomaso *et al*., 2013), in Australia (Parsons and Cuthbertson, 1992; USDA-ARS, 2013) and in New Zealand (Esler, 1988; Webb *et al*., 1988) as it can easily be spread after being introduced.

5.4.2. Average plant height

Fennel found in regions with less rainfall and higher temperatures, such as the Amanzi area and Kirkwood, have grown shorter than plants from other regions. There is little variation in plants height of fennel populations in the coastal and semi-Karoo regions. The lower variation of fennel height in those regions can indicate the widely climatic suitability of the areas. Compared to the height recorded in other countries where fennel grows, its height ranges from 1-3.5 m (Parsons and Cuthbertson, 2001; Erskine Ogden and Rejmánek, 2005; CAL-IPC, 2006; Badgujar *et al*., 2014), whereas in South Africa, 2.04 m was the average height of all fennel populations measured in the sample sites. This was within the known average height of fennel compared to other countries.

5.5. Germinating test

A germinating experiment conducted to find fennel seed`s germination potential showed that they have a short germination time. There was little variation in germination success for seeds collected from all sample sites. In all field sites, germination occurred within the normal fennel short germinating time of 14 days (Ioana *et al*. 2015). The percentage germination was high from 98% at Amanzi and 100% at Kirkwood. Heidari *et al*. (2014) also revealed that fennel seed has a wide germination temperature range. High rates of germination are important contributor to invasive success and to high density which can also ensure invasive success (Beatty and Licari, 1992; Heidari *et al*., 2014).

5.6. Risk assessment of fennel in the study area and South Africa

The risk assessment results indicated that likelihood of fennel becoming invasive in South Africa is very high. Fennel received a total score of 11 within the Sarah Baartman District and Nelson Mandela Bay Municipalities on the New Zealand weed risk assessment. According to Pheloung *et al*. (1999) and Gordon *et al*. (2010) a score higher than six indicates a high probability of a species becoming a weed in that particular country. Fennel exceeded that minimum score of a species to become invasive that is used in other countries. Factors that contributed to the high score are undesirable traits, invasive status in other countries and the broadly suitable climate for the species in South Africa. As the Western Cape province has a Mediterranean climate, similar to the species’ native range (Erskine-Ogden and Rejmánek, 2005; Thomlinson, 2013) climate is not a limitation in this region. Bossard *et al*. (2000) state that if a plant is native to Spain and regarded as invasive in Western Australia, the chances that it will become invasive in California and South Africa are very high.

The species reproductive output has contributed to the risk score level because fennel could outperform other competing species easily (Beatty and Licari, 1992; Erskine-Orden, 2004; Thomlinson, 2013; Brown and Bettink, 2016). Rejmánek and Richardson, (1996) state that plants with high production output and short maturity periods have an increased probability of becoming invasive plants. Fennel has these attributes (Bossard *et al*., 2000). The long-lived nature of fennel seed in the environment (DiTomaso *et al*., 2013; Beatty and Licari, 1992), make it difficult to control once it establishes in the ecosystem.

There are certain features considered to increase the invasive risk for a species and are absent in the case of fennel. The risk score level of fennel was reduced by its domestication attribute. Invasive species escape from cultivation their invasiveness cannot be compared to wild species as there is a certain stage during development that can rely on a human for optimum growing. Hence, domestic traits retained by species escaped from cultivation decrease the risk level in the ecosystem compared to wild species as fennel populations increases are mostly in disturbed areas compare to natural areas. Another feature is a non-nitrogen-fixing of fennel which lower it’s competitive ability if it grows with another, native species. The last feature is the non-hybridizing of fennel with other species. Hybridizing may increase invasiveness as species turn to tolerate wide environmental condition for example climate compare to parent plant (Weber and D`Antonio, 1999; Ridley and Ellstrand, 2010).

CHAPTER 6

6. RECOMMENDATIONS AND CONCLUSION

6.1. Recommendations

Based on the findings of this study, the current and potential future distribution, preferred habitats of fennel, dispersal mechanisms and the risk assessment score of fennel, we suggest the following recommendations:

(i) Conduct more surveys in the Highveld region of South Africa where CLIMEX results indicated suitable climate for potential distribution of fennel.

(ii) Monitor populations in undisturbed sites and see if and at what rate fennel populations are increasing, to see if management options are needed for future clearing.

(iii) Regulate the growing of fennel and require permitting by area in the regions that have favourable climate (Western and Eastern Cape Provinces).

(iv) Research the effect on economy if declared an invasive species and to what extend would be the industry affected?

6.2. Conclusion

There are many fennel populations in the coastal regions of Eastern and Western Cape Provinces, some in less favourable conditions indicating adaptability. CLIMEX was found to be a useful tool as it correctly predicted current and future distribution. It indicated other areas suitable for fennel and these areas are a priority for monitoring and for the future management of fennel in South Africa.

The high number of fennel populations in Thicket/Dense bush vegetation do not seem to pose a high risk to biodiversity as they are mostly in transformed areas. In contrast, a number of fennel populations penetrate undisturbed areas in the Grasslands vegetation type. This shows that more attention is needed in Grasslands vegetation for future management of fennel in South Africa.

Climatic difference between the six regions where sampling was conducted in the Sarah Baartman District and Nelson Mandela Bay Municipalities did not have an effect on seed output and indicate a wide climatic tolerance by fennel. High seed germination rate indicates absence of physical dormancy in fennel.

Risk assessment shows that fennel received a score within the range for species that become invasive. Records of a number of naturalised populations in the study area indicate its invasive potential. It is invasive in other countries with regions of Mediterranean climate namely parts of Australia and America (California) an impact on biodiversity was noted within a century. In South Africa the current distribution of fennel is largely limited to disturbed areas and it has economic importance (seeds sold in the food market and seeds and plantlets sold in nurseries) we conclude with two fennel management options. Firstly, ongoing monitoring of fennel populations already in wild to enter the pristine environment and secondly, consider the fact that in this study only Grasslands vegetation shown to have fennel populations extending to natural areas and it is been long time in the country and naturalised populations are still limited to the Western and Eastern Cape Provinces, fennel populations should be monitored in all identified areas in South Africa until its impacts on biodiversity can be quantified.

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APPENDICES

Appendix I: Locality record of fennel populations with GIS coordinates, elevation, site names, casual/naturalised populations and regions in Sarah Baartman District and Nelson Mandela Bay Municipalities and in South Africa.

Population locality records of fennel distribution within study area (SAPIA, Pretoria National Herbarium and current study field survey)						
Number	**GPS co-ordinates**		**Elevation (m)**	**Site Name**	**Casual/ Naturalised**	**Region**
	Latitude (S)	**Longitude (E)**				**EC**
1	-33.59897	26.11397	323.3	R 72 turnoff to De Mond Farm	Naturalised	EC
2	-33.90120	25.57093	44.4	R 75 Uitenhage Road	Naturalised	EC
3	-33.00000	26.00000	542.0	East Cape Game Farm	Casual	EC
4	-33.59897	26.11396	323.4	Spring mount	Casual	EC
5	-33.59897	26.11391	332.8	Lake Eric to Spring mouth south west of Alexandria	Casual	EC
6	-33.59897	26.11397	323.3	Alexandria	Casual	EC
7	-33.72847	26.57779	10.0	Boknes to Alexandria	Casual	EC
8	-33.72846	26.57738	10.0	Road to Cannon Rock	Casual	EC

9	-32.72187	25.58686	756.7	R 63 Somerset East 1	Naturalised	EC
10	-32.73164	25.59938	713.9	R 63 Somerset East 2	Naturalised	EC
11	-33.43950	25.94030	316.2	R 342 Zand Vlakte	Naturalised	EC
12	-33.43950	25.99903	286.3	R 342 to Addo 1	Casual	EC
13	-33.43950	25.94003	315.7	R 342 to Addo 2	Casual	EC
14	-33.45172	25.75586	165.9	R 342 to Addo 3	Casual	EC
15	-33.94091	25.58432	81.6	Lovemore cres, PE, Diaz Road	Casual	EC
16	-33.55618	25.68410	31.8	R 342 Addo to PE 2	Casual	EC
17	-33.96974	25.61492	39.5	6 Jutland Cres PE	Naturalised	EC
18	-33.95527	25.61039	42.5	55 Sherlock Rd PE	Naturalised	EC
19	-33.93310	25.58865	31.7	2 Fairclough Rd PE	Naturalised	EC
20	-34.06945	24.80059	48.6	R 330 Saint Francis Bay to Humansdorp	Casual	EC
21	-33.91567	25.53400	152.6	Godetia Drive, Port Elizabeth	Naturalised	EC
22	-34.04962	24.92002	32.5	Saint Francis Street Jeffresbay	Naturalised	EC
23	-34.05766	24.91916	15.8	Saint Francis Street, Jeffreysbay	Naturalised	EC

24	-33.78339	25.37585	98.1	R 334 Road From N 2 turn off to Uitenhage Farms	Casual	EC
25	-33.69773	25.45723	143.6	R 75 Road from Utenhage to Jansenville	Casual	EC
26	-33.25818	24.83911	630.4	R 75 Ikwezi to Jansenville	Casual	EC
27	-33.91169	25.54000	135.0	Gail Road Allan Height, Port Elizabeth	Casual	EC
28	-33.92840	25.59545	22.1	Voyle Road Holland Park, Port Elizabeth	Naturalised	EC
29	-33.45540	25.24946	190.0	R 334 Uitenhage to IDZ Coega Road, Port Elizabeth	Naturalised	EC
30	-33.71922	25.49478	127.3	Amanzi Area	Naturalised	EC
31	-33.96648	25.59931	45.9	M 7 Target Kloof Road MillPark, Port Elizabeth	Casual	EC
32	-32.47810	24.06663	748.3	Ziervogel Street, Aberdeen	Casual	EC
33	-33.95091	24.29659	322.2	Baken, Kareedow.	Naturalised	EC

34	-33.85603	24.86754	39.2	R 330 road, Hankey	Casual	EC
35	-33.82663	23.85321	545.2	Strydom Street, Joubertina.	Casual	EC
36	-33.82716	23.85456	547.6	Joubertina	Naturalised	EC
37	-33.83849	23.88978	535.0	Hoof Street, Joubertina	Naturalised	EC
38	-33.81793	23.82652	539.5	R 62 Road, Joubertina	Naturalised	EC
39	-33.82756	23.84965	536.1	Krezinger Street, Joubertina	Casual	EC
40	-33.83060	23.84792	540.1	Plantation field, Joubertina	Naturalised	EC
41	-33.81378	23.73639	569.5	R 62 Road turn off to Gravel Road, Krakeel River	Naturalised	EC
42	-33.76996	23.56897	718.7	R 62 Road, Kou-kamma Municipality	Naturalised	EC
43	-33.74345	23.46713	789.1	R 62 Road, Kou-kamma Municipality	Casual	EC
44	-33.72739	23.20702	867.8	R 62 Road, South Cape DC.	Naturalised	EC
45	-33.72830	23.27151	808.0	R 62 Road to Joubertina	Naturalised	EC
46	-33.95286	25.51319	142.8	M 7 Samantha Way, Port Elizabeth	Casual	EC

47	-33.82186	25.64375	42.1	Wells Estate Phase 2, Port Elizabeth	Naturalised	EC
48	-33.64804	25.99002	158.3	Spring mount, Sundays River Valley Municipality	Casual	EC
49	-33.65987	26.01848	178.6	Congo Kraal, Gravel Road, Sundays River Valley Municipality	Casual	EC
50	-33.63502	25.98262	138.5	R 72 Road Side	Naturalised	EC
51	-33.63450	26.20225	149.0	Gravel Road, Sundays River Valley Municipality	Naturalised	EC
52	-33.61438	26.16898	239.1	R 72 Roadside to Alexandria.	Casual	EC
53	-33.62415	26.29594	254.7	R 72 Roadside to Alexandria.	Casual	EC
54	-33.65359	26.41194	177.6	Alexandria Area	Naturalised	EC
55	-33.69104	26.62581	29.5	Unnamed Road, Klip Fontein	Casual	EC
56	-33.69599	25.45816	144.3	Amanzi area	Casual	EC
57	-33.71790	25.49765	115.5	Amanzi area	Naturalised	EC
58	-33.72290	25.50298	138.1	Amanzi area	Naturalised	EC

59	-33.73104	25.50443	129.9	Amanzi area	Casual	EC
60	-33.74861	25.50771	164.7	Amanzi area	Casual	EC
61	-33.74861	25.50940	164.8	Gravel roadside, Uitenhage farm	Naturalised	EC
62	-33.75102	25.50632	155.2	R 334 roadside, Uitenhage farm	Naturalised	EC
63	-33.74897	25.48364	136.5	R 334 roadside, Uitenhage farm	Naturalised	EC
64	-33.77335	25.40885	51.0	Van Riebeeck Hoogte, Uitenhage	Naturalised	EC
65	-33.73386	25.40872	118.9	Van Riebeeck Hoogte, Uitenhage	Naturalised	EC
66	-33.80041	25.43407	51.1	Campher Park off ramp, Dispatch	Casual	EC
67	-33.92338	25.56707	41.6	Stanford Road, Port Elizabeth	Casual	EC
68	-33.92497	25.58405	36.8	Nicoll Road, Port Elizabeth	Casual	EC
69	-33.92621	25.58248	40.4	Lynn Street, Port Elizabeth	Naturalised	EC

70	-33.93800	25.57690	79.4	M 26 Burt Drive, Port Elizabeth	Casual	EC
71	-32.76892	25.72601	635.8	R 63 road, Somerset East	Casual	EC
72	-32.76887	25.66376	674.8	R 63 road, Somerset East	Casual	EC
73	-33.61507	26.17150	182.5	R 72 road, Sundays River Valley Municipality	Casual	EC
74	-34.03257	24.80116	122.0	R 102 Road, Humansdorp	Casual	EC
75	-33.95078	24.30214	317.1	Kanarie Street, Kareedouw	Casual	EC
76	-33.94916	24.30621	297.5	Kanarie Street, Kareedouw	Casual	EC
77	-33.82373	23.85952	582.9	William Steward Street, Joubertina	Naturalised	EC
78	-33.82672	23.87505	586.8	R 62 Road, Joubertina.	Casual	EC
79	-33.81434	23.73126	577.8	R 62 Road.	Casual	EC
80	-33.83478	25.55218	9.5	Swartkop Area, Port Elizabeth.	Naturalised	EC
81	-33.81198	23.73461	570.9	R 62 Krakeel River, Joubertina	Naturalised	EC
82	-33.82244	23.85640	576.7	William Steward Street, Joubertina	Naturalised	EC

83	-33.95749	25.56241	84.9	Glen Hurd Dr, Port Elizabeth	Casual	EC
84	-33.39840	25.42712	112.0	Kirkwood, Sundays River Valleys Municipality	Naturalised	EC
85	-33.92384	25.56658	41	Stanford Road, Port Elizabeth	Casual	EC
86	-33.22300	26.37300	604.1	Belmont Valley, Grahamstown	Casual	EC
Locality records fennel distribution in South Africa outside study area (SAPIA, National Herbarium, Current field survey)						
Number	**GPS co-ordinates**		**Elevation (m)**	**Site Name**	**Casual/Naturalised**	**Region**
	Latitude (S)	Longitude (E)			N/A	
01	-34.14206	18.32680	27.5	23 Dreyer Road, Kommetjie	N/A	WC
02	-34.78041	20.03901	11.9	Struis Bay, Cape Tow	N/A	WC
03	-33.88575	18.65955	104.1	25 Fir Road, Cape Tow	N/A	WC
04	-34.01126	18.43936	62.1	Brommesvlei Trail, Cape Town	N/A	WC
05	-33.98286	18.43663	127.3	13 Cherry Street Newlands Cape Town	N/A	WC

06	-33.95098	18.65793	53.9	R 300 Blue down, Cape Town	N/A	WC
07	-33.00064	18.44923	58.6	ERF 311, Klaasens Road, Alphen Cape Town	N/A	WC
08	-34.36667	20.43333	155.9	Ouplaaas	N/A	WC
09	-33.69806	18.73100	94.0	Slent Road, Malmesbury Farm.	N/A	WC
10	-34.20681	19.14820	297.2	Greater Hermarus N2 South	N/A	WC
11	-34.02508	18.46292	880.9	Contantiaberg	N/A	WC
12	-34.01535	18.41492	135.4	Constantia Glen Wine Farm	N/A	WC
13	-34.02972	18.40694	225.7	Grootboskloof Trail Constantia	N/A	WC
14	-33.92468	18.48314	12.0	McGregor Road to Kingriver	N/A	WC
15	-33.65464	20.30205	854.1	Bayner Klawer Military base	N/A	WC
16	-34.01083	18.35026	220.5	Victoria Drive Hout Bay	N/A	WC
17	-33.95395	18.68437	52.2	Silver Mine, Western Gate	N/A	WC
18	-31.55315	18.34750	49.2	Lutzville	N/A	WC
19	-26.50000	27.75000	1541.2	R 28 Sebokeng	N/A	GP
20	-27.25000	25.92000	1379.0	N 12 Wolmaransstad	N/A	NC
21	-28.67000	20.92000	772.2	Keimoes to Kakamas N 14	N/A	NC

22	-28.17000	23.50000	1491.8	R 31 Danielskuil to Postmasburg	N/A	NC
23	-29.67000	17.83000	941.5	Springbok to Kamieskroon N 7	N/A	NC
24	-30.92000	18.17000	298.8	Garies to Bitterfontein N 7	N/A	NC
25	-31.58000	18.17000	86.3	Lutzville-Strandfontein, Olifants River	N/A	NC
26	-31.50000	18.25000	50.1	Lutzville-Strandfontein, Olifants River Valley	N/A	NC
27	-31.58000	18.25000	54.9	Lutzville- Strandfontein	N/A	NC
28	-31.83000	26.92000	1185.0	R 392 Queenstown – Dordrecht	N/A	EC
29	-31.35000	27.00000	1674.4	R 392 Dordrecht – Jamestown	N/A	EC
30	-32.23000	20.37000	1238.3	Sutherland District, Voelfontein to Oupoort	N/A	NC

31	-32.33000	20.42000	1458.1	Sutherland District; Driefontein to Tweeriviere	N/A	NC
32	-32.30000	20.63000	1378.7	Sutherland district; Kommetjie se Hoogte to Klipplaat	N/A	NC
33	-32.79000	20.71000	1148.0	Sutherland District, Komsberg Pass to Matjiesfontein	N/A	NC
34	-32.80000	20.71000	1154.5	Sutherland District; Komsberg Pass to Matjiesfontein	N/A	NC
35	-32.83000	20.69000	1065.0	Sutherland District; Komsberg Pass to Matjiesfontein	N/A	NC
36	-32.90000	20.63000	995.9	Sutherland District; Komsberg Pass to Matjiesfontein	N/A	NC
37	-32.25000	25.67000	908.1	Cookhouse to Cradock N 10	Casual	EC
38	-32.47000	27.28000	1121.8	Stutterheim	N/A	EC
39	-32.58000	27.42000	804.6	N 6 Stuttrheim	N/A	EC
40	-32.50000	27.92000	306.7	N 2 Butterworth-Komga	N/A	EC
41	-32.32000	28.15000	542.6	N 2 Butterworth	N/A	EC

42	-32.25000	28.17000	723.4	N 2 Idutwa to Butterworth	N/A	EC
43	-33.92000	21.08000	545.6	Duiwenshop River Valley (Plattekloof)	N/A	WC
44	-34.17000	20.83000	178.2	R 322 Witsand to Heidelberg	N/A	WC
45	-34.08000	20.92000	117.3	R 322 Heidelberg to Duiwenhoks/Grootvadesbosch	N/A	WC
46	-34.00000	20.92000	176.6	Heidelberg to Jongersfontein,	N/A	WC
47	-34.25000	20.83000	55.8	Stillbaai to Witsand	N/A	WC
48	-34.17000	21.17000	147.4	Kleinheuwel to Wolwekoppe	N/A	WC
49	-34.17000	21.33000	145.4	R 305 to Stilbaai	N/A	WC
50	-34.17000	21.25000	135.2	N 2 Turnoff to Stillbaai R 305	N/A	WC
51	-34.33000	21.08000	223.6	Stillbaai to Witsand	N/A	WC
52	-34.25000	21.00000	66.9	Stillbaai to Witsand		
53	-34.25000	21.33000	93.9	Hectorskraal to Droevlakte	N/A	WC
54	-34.33000	21.33000	185.4	R 305 Stilbaai to Jongensvontein	N/A	WC
55	-34.25000	21.33000	93.9	R 305 to Stilbaai	N/A	WC

56	-34.00000	21.75000	237.1	Herbertsdale to Mossel Bay R 327	N/A	WC
57	-34.08000	21.75000	23.6	Herbertsdale R 327 turnoff to Melkhoutvlei	N/A	WC
58	-34.08000	21.75000	23.6	Melkhoutvlei-Cooper; N 2 to Albertinia	N/A	WC
59	-34.25000	21.83000	109.3	Johnson`s Post via Vleesbaai to Duinzicht	N/A	WC
60	-34.33000	21.83000	48.3	R 325, Gouritsmond	N/A	WC
61	-34.25000	21.75000	9.5	R 325 to Johnson`s Post	N/A	WC
62	-25.37300	26.37300	1034.9	Zwartruggens	N/A	NW
63	-34.07300	18.39496	464.6	Noorthoek	N/A	WC
64	-34.07300	23.07300	39.1	Knysna	N/A	WC
65	-34.07300	18.46469	4.5	Cape Flats; Dieprivier	N/A	WC
66	-34.07300	21.22300	126.7	Riversdale	N/A	WC
67	-33.37300	19.22300	419.7	Worcester	N/A	WC
68	-33.52300	20.37300	666.8	Zuurbraak, Breede River DC	N/A	WC

69	-34.07300	18.39277	465.7	Orange Kloof	N/A	WC
70	-25.52300	29.22300	1246.7	Middelburg	N/A	MP
71	-33.22300	22.07300	616.5	Cango Valley	N/A	N/A
72	-26.07300	27.52300	1628.0	Furrow East of Kleinjukskei	N/A	GP
73	-34.07300	18.52300	9.3	Gordon Bay	N/A	WC
74	-27.22000	30.07000	1885.1	Wakkerstroom	N/A	MP
75	-33.59130	18.46560	134.6	Annandale Road	N/A	WC
76	-26.10380	27.59040	1567.2	Johannesburg	N/A	GP
77	-33.57530	18.55330	149.9	Jonkershoek	N/A	WC
78	-33.46220	18.55170	103.6	R 315 Stellenbosch	N/A	WC
79	-31.31390	18.17190	239.7	Koekenaap	N/A	WC
80	-26.42440	27.03490	1473.3	Potchestroom	N/A	NW
81	-29.52300	30.37300	907.5	Umbumbulu area	N/A	KZN
82	-30.17040	30.20530	914.0	Ixobho	N/A	KZN
83	-34.13320	21.07280	167.0	Between Riversdale and Vermaaklikheid	N/A	WC
84	-31.07300	30.07300	368.0	Umtamvuna Nature Reserve	N/A	KZN

85	-30.37300	29.37300	1567.2	Ngele, East of Dakota Kop	N/A	KZN
86	-25.36010	27.59210	1016.6	Ga-Rankuma, Molatlhoa Street	N/A	GP
87	-32.38300	27.16330	1246.7	Road R 345	N/A	EC

Days	November 2016	December 2016	January 2017	February 2017	March 2017	April 2017
	Emergence phase	**Flowering phase**		**Grain fill phase**		**Maturity phase**
	Daily PDD (Tmax+Tmin)/2-Tbase	Daily PDD (Tmax+Tmin)/2-Tbase	Daily PDD (Tmax+Tmin)/2-Tbase	Daily PDD (Tmax+Tmin)/2-Tbase	Daily PDD (Tmax+Tmin)/2-Tbase	Daily PDD (Tmax+Tmin)/2-Tbase
	PDD	PDD	PDD	PDD	PDD	PDD
1	14.05	15.15	18.9	15.6	18.9	16.7
2	15.3	15.7	20.7	15.8	17.95	18.2
3	15.6	17.35	15.4	15.15	16.8	17.25
4	13.8	17.2	16.15	17.8	17.05	15.65
5	12.4	15.3	20.35	17.3	17.05	15.9
6	11.5	19.85	16.6	17.4	18.05	12.1
7	11.65	17.65	15.9	21.4	17.9	15.45

8	14. 75	17.7	15.5	17.7	17.85	17.3
9	15.55	15.4	16.55	16.8	15.35	18.65
10	13.2	13.25	16.95	18.55	16	15.8
11	11.45	13.8	20.55	23.2	21	15.6
12	12.95	17.45	18.8	18.05	14.95	20.9
13	11.15	16	15.4	16.3	14.45	11.55
14	10.8	15.55	15.75	16.8	16.15	8.85
15	10.7	17.45	16.85	18.5	15.25	9.4
16	12.8	17.15	16.05	21.25	14.5	12.85
17	12.95	16.5	15.4	19.35	17.1	13.35
18	12.5	18.3	18.25	17.1	16.25	14.1
19	14.05	19	17.15	15.2	15.45	12.2
20	14.6	17.9	15.85	16.45	15.95	14.2
21	14.05	17.1	14.95	15.5	17.15	12.45
22	14.85	18.2	18.5	16.4	24	11.7
23	16.1	18.8	18.5	17.8	16.05	14.6
24	15.65	13.9	19.85	19.5	11.75	13.5

25	14.4	14	15.85	15.8	12.1	12.25
26	15.35	16.95	14.2	14.65	12.9	13.2
27	16.6	18.9	16.85	14.75	13.9	18.9
28	16.15	16.5	15.15	21.25	14.3	18.85
29	15.7	16.8	16.5	-	13.7	15.5
30	15.3	17.95	16.2	-	22.75	13.4
31	-	17.8	15.75	-	16.6	-
	Total 415.9	Total 520.55	Total 525.35	Total 491.35	Total 509.15	Total 440.35
181	PDD 2 902.65					

Appendix II: Fennel degree-days per generation calculated daily from 01/November /2017 to 30/April/ 2017.

Appendix III. Estimation of area covered by fennel on vegetation types and other habitation with GPS co-ordinates, number of plants, extent of infestation and quantitative estimate as dense, medium or scattered occur in the study area.

Number	Vegetation types	GPS coordinates		Number of plants 1, 2-5, 6-20, 20-50 and > 50.	Extent of infestation from <1m², 1-10m², 10-100m², 100-1000m² and >1ha.	Dense, Medium or Scattered.
		Latitude	Longitude			
1	Woodland/Open bush	-33.59897	26.11397	>50	> 1 ha	Medium
2	Thicket/Dense bush	-33.90120	25.57093	>50	>1 ha	Dense
3	Thicket/Dense bush	-33.00000	26.00000	2-5	1-10m²	scattered

4	Thicket/Dense bush	-33.59896	26.11396	6-20	10-100m²	scattered
5	Thicket/Dense bush	-33.59891	26.91397	1	<1m²	scattered
6	Settlement	-33.59897	26.11397	20-50	10-100m²	scattered
7	Woodland/Open bush	-33.72847	26.57779	20-50	10-100m²	scattered
8	Settlements	-33.72846	26.57738	20-50	10-100m²	Scattered
9	Settlements	-32.72187	25.58686	>50	100-1000m²	Medium
10	Settlements	-32.73164	25.59938	>50	100-1000m²	Medium
11	Cultivated commercial annual crops non-pivot	-33.43950	25.94030	>50	100-1000m²	Medium

12	Cultivated commercial annual crops non-pivot	-33.43950	25.99903	20-50	10-100m²	Scattered
13	Grasslands	-33.43950	25.94003	20-50	10-100m²	scattered
14	Thicket/Dense bush	-33.45172	25.75586	1	<1m²	Scattered
15	Grasslands	-33.55618	25.99410	6-20	10-100m²	Scattered
16	Woodland/Open bush	-33.55618	25.68410	6-20	10-100m²	Scattered
17	Thicket/Dense bush	-33.96974	25.61492	>50	100-1000m²	Medium
18	Thicket/Dense bush	-33.95527	25.61039	>50	100-1000m²	Dense
19	Settlements	-33.93310	25.58865	>50	>1 ha	Dense

20	Cultivated commercial annual crops non-pivot	-34.06945	24.80059	1	<1m²	scattered
21	Thicket/Dense bush	-33.91567	25.53400	>50	>1 ha	Dense
22	Settlements	-34.04962	24.92002	>50	100-1000m²	Dense
23	Settlements	-34.05766	24.91916	>50	>1 ha	Dense
24	Settlements	-33.78339	25.37585	2-5	<1m²	Scattered
25	Wetlands	-33.69773	25.45723	20-50	10-100m²	Scattered
26	Low Shrubland	-33.25818	24.83911	20-50	10-100m²	Scattered
27	Low Shrubland	-33.91169	25.54000	20-50	100-1000m²	Scattered
28	Settlements	-33.92840	25.59545	>50	>1 ha	Dense
29	Grasslands	-33.45540	25.24946	>50	100-1000m²	Dense

30	Wetlands	-33.71922	25.49478	>50	>1 ha	Dense
31	Thicket/Dense bush	-33.96648	25.59931	20-50	100-1000m²	Scattered
32	Thicket/Dense bush	-32.47810	24.06663	1	<1m²	Scattered
33	Settlements	-33.95091	24.29659	>50	10-100m²	Dense
34	Cultivated commercial annual crops non-pivot	-33.85603	24.86754	20-50	10-100m²	Medium
35	Settlements	-33.82663	23.85321	6-20	10-100m²	Scattered
36	Settlements	-33.82716	23.85456	>50	100-1000m²	Dense
37	Settlements	-33.83849	23.88978	>50	100-1000m²	Dense
38	Thicket/Dense bush	-33.81793	23.82652	>50	>1 ha	Dense

39	Settlements	-33.82756	23.84965	6-20	1-10m²	Scattered
40	Thicket/Dense bush	-33.83060	23.84792	>50	>1 ha	Dense
41	Settlements	-33.81378	23.73639	>50	>1 ha	Dense
42	Settlements	-33.76996	23.56897	>50	10-100m²	Dense
43	Low shrubland	-33.74345	23.46713	2-5	<1m²	Scattered
44	Low Shrubland	-33.72739	23.20702	>50	100-1000m²	Dense
45	Plantations/Woodlots	-33.72830	23.27151	>50	100-1000m²	Dense
46	Settlements	-33.95286	25.51319	6-20	10-100m²	Scattered
47	Settlements	-33.82186	25.64375	>50	100-1000m²	Dense
48	Woodland/Open bush	-33.64804	2599002	20-50	10-100m²	Medium
49	Grasslands	-33.65987	26.01848	6-20	10-100m²	Scattered

50	Thicket/Dense bush	-33.63502	25.98262	>50	100-1000m²	Dense
51	Woodland/open bush	-33.63450	26.20225	>50	>1 ha	Dense
52	Cultivated commercial annual crops non-pivot	-33.61438	26.16898	20-50	10-100m²	Medium
53	Cultivated commercial annual crops non-pivot	-33.62415	26.29594	20-50	10-100m²	Medium
54	Woodland/open bush	-33.65359	26.41194	>50	100-1000m²	Medium
55	Settlements	-33.69104	26.62581	2-5	<1m²	Scattered

56	Wetlands	-33.69599	25.45816	20-50	10-100m²	Medium
57	Woodland/open bush	-33.71790	25.49765	>50	100-1000m²	Dense
58	Cultivated commercial annual crops non-pivot	-33.72290	25.50298	>50	100-1000m²	Dense
59	Thicket/Dense bush	-33.73104	25.50443	20-50	100-1000m²	Medium
60	Thicket/Dense bush	-33.74861	25.50771	2-5	1-10m²	Scattered
61	Grasslands	-33.74861	25.50940	>50	100-1000m²	Dense
62	Thicket/Dense bush	-33.75102	25.50632	>50	100-1000m²	Medium

63	Thicket/Dense bush	-33.74897	25.48364	>50	>1 ha	Dense
64	Settlements	-33.77335	25.40885	>50	100-1000m²	Dense
65	Settlements	-33.73386	25.40872	>50	>1 ha	Dense
66	Wetlands	-33.80041	25.43407	6-20	10-100m²	Scattered
67	Settlements	-33.92338	25.56707	20-50	10-100m²	Medium
68	Thicket/Dense bush	-33.92497	25.58405	20-50	10-100m²	Medium
69	Woodland/open bush	-33.92621	25.58248	>50	>1 ha	Dense
70	Cultivated commercial annual crops non-pivot	-33.93800	25.57690	20-50	10-100m²	Medium
71	Grasslands	-32.76892	25.72601	6-20	10-100m²	Scattered

72	Grasslands	-32.76887	25.66376	6-20	10-100m^2	Scattered
73	Woodland/Open bush	-33.61507	26.17150	20-50	10-100m^2	Medium
74	Settlements	-34.03257	24.80116	1	<1m^2	Scattered
75	Settlements	-33.95078	24.30214	6-20	1-10m^2	Medium
76	Settlements	-33.94916	24.30621	20-50	100-1000m^2	Medium
77	Settlements	-33.82373	23.85952	>50	100-1000m^2	Dense
78	Settlements	-33.82672	23.87505	1	<1m^2	Scattered
79	Settlements	-33.81434	23.73126	20-50	10-100m^2	Medium
80	Wetlands	-33.83478	25.55218	>50	>1 ha	Scattered
81	Settlements	-33.81198	23.73461	>50	100-1000m^2	Dense
82	Settlements	-33.82244	23.85640	>50	>1 ha	Dense
83	Thicket/Dense bush	-33.95749	25.56241	20-50	100-1000m^2	Medium

84	Cultivated commercial annual crops non-pivot	-33.39840	25.42712	>50	100-1000m²	Dense
85	Thicket/Dense bush	-33.92384	25.56658	20-50	100-1000m²	Scattered
86	Cultivated commercial annual crops non-pivot	-33.22300	26.37300	2-5	1-10m²	Scattered

Appendix IV. Summary of vegetation types with number of locality records, GPS coordinates, estimate number of plants and extent of infestation where fennel occurred in Sarah Baartman District and Nelson Mandela Bay Municipalities.

Vegetation types	Number of Locality Records	GPS Coordinates		Number of Plants	Extent of infestation
		Longitude	Latitude		
Grasslands	06	-33.43950	25.94003	20-50	10-100m²
		-33.45540	25.24946	>50	100-1000m²

		-33.55618 -33.74861 -33.65987 -32.76892	25.99410 25.50940 25.72601 26.01848	6-20 >50 6-20 6-20	10-100m² 100-1000m² 10-100m² 10-100m²
Low Shrubland	04	-33.25818 -33.91169 -33.74345 -33.72739	24.83911 25.54000 23.46713 23.20702	20-50 20-50 2-5 >50	10-100m² 100-1000m² <1m² > 1 ha
Thicket/Dense bush	20	-33.90120 -33.00000 -33.59896 -33.59891 -33.45172 -33.96974 -33.95527 -33.91567 -33.96648	25.57093 26.00000 26.11396 26.91397 25.75586 25.61492 25.61039 25.53400 25.59931	>50 2-5 6-20 1 1 >50 >50 >50 20-50	> 1 ha 1-10m² 10-100m² <1m² < 1m² 100-1000m² 100-1000m² >1 ha 100-1000 m²

		-32.47810	24.06663	1	< 1 m²
		-33.81793	23.82652	>50	>1 ha
		-33.83060	23.84792	>50	>1 ha
		-33.63502	25.98262	>50	100-1000m²
		-33.73104	25.50443	20-50	100-1000m²
		-33.74861	25.50771	2-5	1-10 m²
		-33.75102	25.50632	>50;	100-1000m²
		-33.92497	25.58405	20-50	10-100m²
		-33.95749	25.56241	20-50	100-1000m²
		-33.92384	25.56658	20-50	100-1000m²
		-33.74897	25.48364	>50	>1 ha
Wetlands	04	-33.71922	25.49478	>50	> 1 ha
		-33.69599	25.45816	20-50	10-100m²
		-33.80041	25.43407	6-20	10-100m²
		-33.83478	25.55218	>50	> 1 ha
Woodland/Open bush	09	-33.59897	26.11397	>50	>1 ha
		-33.72847	26.57779	20-50	10-100m²

		-33.55618	25.68410	6-20	10-100m²
		-33.64804	25.99002	20-50	10-100m²
		-33.63450	26.20225	>50	> 1 ha
		-33.65359	26.41194	>50	100-1000m²
		-33.71790	25.49765	>50	100-1000m²
		-33.92621	25.58248	>50	> 1 ha
		-33.61507	26.17150	20-50	10-100m²

Appendix V: Fennel risk assessment as Pheloung *et al*. (1999) and Gordon *et al*. (2010).

History of the species	Questions	Rating	Answer	Score
Domestication/ Cultivation	1.1 Is the species highly domesticated?	y=-3, n=0	Yes	-3
	1.2 Has the species become naturalized where grown in South Africa?	y=1, n=-1	Yes	1

	1.3 Does the species have weedy races?	**y**=-1, n=-1	Unknown	?
Climate and Distribution	2.1 Species suited to South African climate (0-low;1-intermediate;2-high)	intermediate		1
	2.2 Quality of climate match data (0-low; 1-intermediate; 2-High)	intermediate		1
	2.3 Broad climatic suitability (environmental versatility)	y=1, n=0	Yes	1
	2.4 Native or naturalised in regions with extended dry periods (areas with rainfall in the driest quarter less than 50 mm).	y=1, n=0	Yes	1
	2.5 Does the species have a history of repeated introductions outside its natural range?	n=0 y= -2, ?= -1	Yes	-2

Weed elsewhere	3.1 Naturalised beyond native range	y=1, n=0	Yes	1
	3.2 Garden/amenity/disturbance weed	y=1, n=0	No	0
	3.3 Weed of agriculture/horticulture/ Forestry	Y=2*, n=0	No	0
	3.4 Weed of disturbance	Y=2*, n=0	Yes	4
	3.5 Congeneric weed	y=1*, n=0	No	0
Undesirable Traits	4.1 Produces spines, thorns or burrs	y=1, n=0	No	0
	4.2 Allelopathic	y=1, n=0	No	0
	4.3 Parasitic	y=1, n=0	No	0
	4.4 Unpalatable to grazing animals	y=1, n=-1	No	-1
	4.5 Toxic to animals	y=1, n=0	No	0
	4.6 Host for recognized pests and pathogens	y=1, n=0	Unknown	?
	4.7 Causes allergies or is otherwise toxic to humans	y=1, n=0	Unknown	?

	4.8 Creates fire hazard in natural ecosystems	y=1, n=0	Yes	1
	4.9 Is a shade tolerant plant at some stage of its life cycle	y=1, n=0	No	0
	4.10 Grows on infertility soils	y=1, n=0	Yes	1
	4.11 Climbing or smothering growth habit	y=1, n=0	Yes	1
	4.12 Forms dense thickets	y=1, n=0	Yes	1
Plant type	5.1 Aquatic	y=5, n=0	No	0
	5.2 Grass	y=1, n=0	No	0
	5.3 Nitrogen fixing woody plant	y=1, n=0	No	0
	5.4 Geophyte	y=1, n=0	No	0
Reproduction	6.1 Evidence of substantial reproductive failure in native habitat	y=1, n=0	No	0
	6.2 Produce viable seed	y=1, n=-1	Yes	1
	6.3 Hybridises naturally	y=1, n=-1	No	-1
	6.4 Self-fertilisation	y=1, n=-1	Yes	1
	6.5 Requires specialist pollinators	y= -1, n=0	No	0

	6.6 Reproductive by vegetation propagation	y=1, n=-1	No	-1
	6.7 Minimum generating time (years)	1 year =1, 2 or 3 yrs=0, 4+ years = -1	2 yrs	0
Dispersal Mechanisms	7.1 Propagules likely to be dispersed unintentional	y=1, n=-1	Yes	1
	7.2 Propagules dispersed intentionally by people	y=1, n=-1	Yes	1
	7.3 Propagules likely to be disperse as a produce contaminant	y=1, n=-1	No	-1
	7.4 Propagules adapted to wind dispersal	y=1, n=-1	No	-1
	7.5 Propagules water dispersed	y=1, n=-1	Yes	1
	7.6 Propagules bird dispersed	y=1, n=-1	Unknown	?
	7.7 Propagules dispersed by other animals (externally)	y=1, n=-1	Yes	1
	7.8 Propagules dispersed by other animals (internally)	y=1, n=-1	unknown	?
Persistence Attributes	8.1 Prolific seed production	y=1, n=-1	Yes	1
	8.2 Evidence that a persistent propagule bank is formed (> 1 yr)	y=1, n=-1	Yes	1

8.3 Well controlled by herbicides.	y=-1, n=1	Yes	-1
8.4 Tolerates or benefits from mutilation, cultivation or fire	y=1, n=-1	Yes	1
8.5 Effective natural enemies in South Africa	y=-1, n=1	Unknown	?
Total score			11

Appendix VI: Supporting information and literatures on fennel risk assessment questions on appendix V.

Questions	Literature and field observation information	References
1. Domestication/ cultivation		
1.1	According to the literature fennel is used for medicinal purposes and widely used in gardens.	Kling *et al*., 1923; City of Cape Town Biannual Environmental newsletter, 2012

1.2	In South Africa, the fennel population has been reported as being naturalised in most parts of the country.	Henderson, 2007; Baard and Kraaij, 2014. Current study.
1.3	Not known to South Africa.	?
2. Climate and Distribution		
2.1	According to data from literature, SAPIA and National Herbarium fennel are widely distributed in South Africa, except in the Free State and Limpopo provinces. CLIMEX results indicated that fennel has wide potential distribution in South Africa.	SAPIA, Henderson, 2007 and Herbarium records and CLIMEX results in this study.
2.2	CLIMEX results indicate that fennel have an intermediate match range as the EI values range from 40 < 50, 50 < 60, 60 < 70; 80 to < 90 and 80 to < 100 along the coastal provinces of the Western Cape and Eastern Cape and 0 to < 10 and 10 to < 20 in other provinces (Fig. 10).	CLIMEX results on this study.
2.3	Current distribution results indicate that fennel has been found in a variety of climates in South Africa. CLIMEX results indicated that fennel could occur in some climates	Henderson, 2007; field observation from the current study and CLIMEX model results on this study.

	region in South Africa, except in the arid and desert areas of South Africa.	
2.4	Current studies indicated that fennel populations have been naturalised in dry places such as Cradock area in the Eastern Cape Province.	Field observation.
2.5	Literature found that fennel has been introduced in many countries including California, Fiji, Hawaii, Australia, New Zealand, French Polynesia, Guam and Niue.	Van Driesche, 2000; Junak *et al*., 1995; PIER, 2013.
3. Weed elsewhere		
3.1	Fennel is naturalised outside its native range, for example, in countries such as South Africa, California, New Zealand, Australia and Hawaii.	Henderson, 2007; Baard and Kraaij, 2014; Current study; Wagner *et al*., 1999; CAL-IPC, 2005.
3.2	Fennel is used for culinary and medicinal purposes.	Kling *et al*., 1923; Baard and Kraaij, 2014; Parsons and Cuthbertson, 2001; USDA-ARS, 2013.
3.3	It is an agricultural crop.	Brown, 2001
3.4	Fennel invades all types of environment, natural and disturbed.	Beatty and Licari, 1992; Queensland Government, 2013.

3.5	Only fennel is documented as a weed from its genus.	Mabberley, 1997.
4. Undesirable traits		
4.1	Fennel does not have spines, thorns or burrs.	Current study field observation.
4.2	Fennel competes with surrounding plant species for resources.	Weber, 2003 and CAL IPC, 2005.
4.3	Fennel growth is not independent from other species.	Current study field observation.
4.4	Grazers can feed on fennel while it is still young, but as it grows, it becomes unfavourable to them, because of its strong smell. In three different places in the study area, namely, Addo, De mond Farm and Cannon Rocks, where cattle farming takes place, fennel is shown to be eaten by grazers when it grows inside the grazing fields, but it grows well in places where cattle are restricted to enter.	Bossard *et al*., 2000; Parsons, 1973; field observation current study.
4.5	Fennel is not toxic to grazing animals.	Parsons and Cuthbertson, 1992.
4.6	Unknown in South Africa and not mentioned in literature.	?
4.7	Unknown in South Africa and not enough evidence from literature.	?

4.8	It is a fire hazard, because of its dense growth leading to high fuel loads.	Elser, 1988; Brown and Bettink, 2016; Current study field observation.
4.9	Fennel's natural habitat include places exposed to sunlight. All fennel populations visited indicated no growth in the shade; all populations were fully exposed to light.	Beatty and Licari, 1992; Purwaningsih and Brink, 1999; Parsons and Cuthbertson, 2001; current study field observation.
4.10	Fennel grows in all soil types, both infertile and fertile. Based on its wide pH range of 4.8 to 8.3, it is indicated that it can grow well in many soil types.	Current study field observation; Bossard *et al*. 2000 and Purwaningsih, H and Brink, M. 1999.
4.11	*Foeniculum vulgare* (fennel) is a perennial member of the Apiaceae family.	He and Huang, 2011.
4.12	It grows densely, which obstructs and limits the passage of humans and domestic and wild animals.	Esler, 1988; Current study field observation.
5. Plant type		
5.1	Fennel is not an aquatic plant.	Current study field observation.
5.2	Fennel is a perennial member of the Apiaceae family.	He and Huang, 2011; Current study field observation.
5.3	It is not a woody plant or a nitrogen fixing plant.	Current study field observation.
5.4	All the reproductive activity of fennel is above the ground.	Current study field observation.

6. Reproduction		
6.1	No evidence exists of fennel's reproductive failure in its native habitat.	Bossard *et al*., 2000.
6.2	Fennel seeds can remain viable and dormant in the field over a long period.	DiTomaso *et al*., 2013 and Beatty and Licari, 1992.
6.3	No history of fennel hybridization is found in literature.	
6.4	Fennel flowers are bisexual and mainly pollinated by insects.	Brown and Bettink, 2016.
6.5	Field observation confirmed through fieldwork that fennel is pollinated by a variety of insects.	Brown and Bettink, 2016; field observation.
6.6	Each spring, fennel can produce flowers from the perennial crown.	Bossard *et al*., 2000 and Parsons and Cuthbertson, 2001.
6.7	Fennel can start to produce seeds when it is 18 to 24 months of age.	Bossard *et al*., 2000.
7. Dispersal mechanisms		
7.1	Habitats dominate along the roadsides in South Africa. Fennel is found mostly at off-ramps and intersections on	Current study field observation; Literature: Bossard *et al*., 2000.

	major freeways. It is highly possible that it spreads by being trapped on car tires.	
7.2	Fennel is intentionally introduced in many countries as edible plants and for herbal purposes. Its spread to other countries is caused mostly by human activities.	Baard and Kraaij, 2014; Parsons and Cuthbertson, 2001; Brown, 2001.
7.3	Fennel is cultivated commercially in many countries for the production of Anethole and it is widely used in medicine for many diseases. In South Africa, fennel seeds are still sold in food markets and both as seeds and seedlings in nurseries.	Parsons and Cuthbertson, 2001 and current study field observation.
7.4	The only seed dispersal range mentioned in literature is about 200m from the sprouting plants.	Blood, 2001.
7.5	Fennel seeds are spread by water. Fieldwork observations confirmed this where fennel grows in slope areas and further growth was noticed in low-lying areas along rivers.	Bossard *et al*., 2000 and current study field observation.
7.6	In other countries and unknown to South Africa.	Bossard *et al*., 2000.
7.7	Fennel seeds' dispersal include animals' skin.	Parsons, 1973.

7.8	Dispersal through propagules from the gut of birds and small mammals is well documented outside South Africa and unknown in the country.	Bossard *et al*., 2000.
8. Persistence attributes		
8.1	Individual plants have high reproductive seed output.	Beatty and Licari, 1992; Erskine-Orden, 2004; Thomlison, 2013; Brown and Bettink, 2016; current study field observation.
8.2	Fennel seed banks have a long life and success in seed viability.	Beatty and Licari, 1992; CAL-IPC, 2006; DiTomaso *et al*. 2013.
8.3	It is possible to control fennel by integrated methods, including a combination of herbicides.	Brenton and Klinger, 1994.
8.4	The control of fennel by fire was found to not be successful on several occasions, as burning causes the plant to recover quickly by stimulating the dormant seeds to germinate, leading to re-infestations.	DiTomaso *et al*. 2013.
8.5	Natural enemies in South Africa are not known.	Current study field observation.