A BIOPHYSICAL AND ECONOMIC EVALUATION OF BIOLOGICAL AND CHEMICAL CONTROL METHODS FOR *SOLANUM ELAEGNIFOLIUM* (SILVERLEAF NIGHTSHADE) IN THE LIMPOPO PROVINCE, SOUTH AFRICA

By

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I hereby declare that the dissertation submitted for the degree MPhil Zoology at the University of Cape Town is my own original work and has not previously been submitted to any other institution of higher education. I further declare that all sources cited and quoted are indicated and acknowledged by means of a comprehensive list of references.

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ABSTRACT

Classical biological control, which entails introducing natural enemies of non-indigenous pests for their control, is considered to be an excellent method to manage alien invasive plants. Other control methods, such as cultural and chemical methods, are often not feasible, while the use of herbicides is economically unsustainable in some cases and, more generally, is unacceptable on environmental and health grounds.

Solanum elaeagnifolium, commonly known as silverleaf nightshade or satansbos, is a solanceous shrub from North America which has become problematic in arable lands and pastures throughout South Africa. It is unpalatable and competes with crops such as lucerne, wheat, maize and sunflowers, reducing yields and causing contamination of the harvest if unchecked.

Several biological control agents have been considered for control of *S. elaeagnifolium* in South Africa, including two leaf-feeding chrysomelid beetles, *Leptinortarsa texana* and *L. defecta*, which were released in 1992. Of the two, *L. texana* has become abundant and is curbing the density and spread of the weed by reducing its growth and fruit production. There is some evidence that the damage caused by the beetles has been effective in limiting the extent of the problems caused by *S. elaeagnifolium*, but there is uncertainty as to how much this has benefited agriculture in areas where the weed occurs, hence the need for further studies.

To assess whether the presence of *L. texana* in an area has measurable benefits for sunflower production, a financial analysis of a private farming system was carried out to compare the production of sunflowers and profitability (control costs) on two adjacent farms near Roedtan in the Waterberg District of the Limpopo Province, one under biological control and the other under chemical control.

To describe whether there were substantial differences in the abundance of *S. elaeagnifolium* on the two farms and whether either of the control options was noticeably better than the other, the density and dimensions (stem diameter and height) of *S. elaeagnifolium* was measured in a plot on each farm. At the same time the population densities of *L. texana* were measured for each life stage (eggs, larvae and adults) to test the hypothesis that the beetles would be scarce where herbicides were being applied and abundant elsewhere and thus suppression of the weed can be attributed to biological control where herbicides were not being used. *Solanum elaeagnifolium* density and height results under chemical control differed slightly with those under biological control method. The financial analysis illustrated the financial benefits of applying biological control as opposed to chemical or no control method on *S. elaeagnifolium* in crop production.

The results showed that the difference in the weed density was insignificant, indicating that biological and chemical control were both effective in the management of *S. elaeagnifolium*. However biological control was shown to be more economically beneficial than chemical control, since there was a net gain as a result of lower costs using *L. texana* beetles. Further research is needed to determine the effectiveness of *L. texana* and damage caused by *S. elaeagnifolium* on expected yield to conduct a full cost-benefit analysis.

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LIST OF ABBREVIATIONS

Acronyms	Names
2, 4-D	2, 4-Dichlorophenoxyacetic acid
AIP	Alien invasive plant
Cav.	Cavanilles
CBA	Cost benefit analysis
Cm	Centimetre
CSIR	Council for Scientific and Industrial Research
NB	Net benefits
PCQM	Point centred quarter model
DEAT	Department of Environmental Affairs and Tourism
EC	Eastern Cape
EPPO	European Plant Protection Organization
GDP	Gross domestic product
Ha	Hectares
HD	High damage
Hr	Hour
ID	Identity
IRR	Internal rate of return
LD	Low damage
M	Meters
MD	Medium damage
R	Returns
SA	South Africa
SAFEX	South African Futures Exchange
SAWS	South African Weather Services
SE	Standard error
SENWES	Sentraalwes
TASS	Texas Agricultural Statistics Services
UCT	University of Cape Town
US	United States
USA	Unites States of America

CHAPTER 1 INTRODUCTION

Invasive alien plants (IAPs) are non-indigenous plants that are introduced outside their natural habitats where they establish, proliferate, spread, cause damage and affect delivery of ecosystem goods and services (Shine, 2007). These species erode natural capital, compromise ecosystem stability and threaten economic productivity (Richardson & Van Wilgen, 2004). Their features include producing reproductive offspring, often in very large numbers at considerable distances from parent plants, growing from seeds and root fragments and forming dense thickets which replace the native vegetation (Kunwar, 2003). These significant economic and environmental impacts frequently make them targets for control (Green *et al.,*1987; Sinden & Thampapillai, 1995; Kostov & Pacanoski, 2007).

Many invasive alien plants are intentionally introduced to new regions for their potentially beneficial characteristics in agriculture, plantation forestry or even horticulture (Shine, 2007). Otherwise, they are accidentally introduced by wind, water, birds, transport vehicles or and machinery between areas within a region.

Past estimates in South Africa reveal that at least 1 000 alien plant species are naturalised in the country and about 20% of those species are regarded as important environmental weeds that invade natural habitats (Henderson, 1998) where they impose significant negative impacts in the agricultural sector by disrupting soil stability, livestock husbandry, natural pastures, water supplies and crop and forest production (Richardson & McKenzie, 1981; Van Wilgen *et al*., 2001). Furthermore, they cause substantial threat to the sustained delivery of a wide range of ecosystem services which are directly and indirectly critical to human survival, including water purification, soil regeneration, waste decomposition, and nutrient cycling (Le Maitre *et al*., 2004). The effect of these losses, in combination with resources spent on controlling alien plants, costs South Africa billions of Rand annually (Van Wilgen *et al*., 2001).

Solanum elaeagnifolium, also commonly referred to as silverleaf nightshade or Satansbos, is one such alien invasive plant (Henderson, 1998). It was declared a weed in South Africa in 1966, with the Highveld and Karoo being the worst affected regions in the country (Henderson, 1998). The presence of *S. elaeagnifolium* is detrimental because it out-competes different crops, both on dry land and under irrigation, thus suppressing yields and affecting the value of crops while increasing production costs (Wassermann *et al*., 1998). For example, more than 10 000 hectares of wheat fields and cultivated pastures were recorded to be heavily infested in New South Wales and Australia. In Morocco more than 100 000 hectares of irrigation land has become infested (Kostov & Pacanoski, 2007). In Texas where *S. elaeagnifolium* is native, it is considered to be a weed when it reaches densities of 100 plants ha^{-1} (Texas Agricultural Statistics Services, 1999). In all these cases infestations resulted in less effective use of land, high control costs and lower economic returns.

To resolve the effect of *S. elaeagnifolium* South Africa launched a four year (1968 to 1972) eradication campaign against the weed, with a budget of more than R300 000 to cover herbicide costs (Wassermann *et al*., 1988; Viljoen, 2003). The campaign did not succeed for several reasons and as a result the weed continued to spread. Research conducted following the initiative showed that *S. elaeagnifolium* is generally very difficult to control with herbicides, including soil sterilants and non-selective chemicals (Wassermann *et al.,* 1988; Heap *et al.,* 1997; Parsons & Cuthbertson, 2001). Reasons for ineffectiveness of these types of control include small leaf area for herbicide absorption relative to well-developed, large root system and the inability of the chemical compounds to translocate in sufficient quantities beyond the root crown (Klein, 2007; Viljoen, pers. comm., 2007).

In addition to its ineffectiveness, chemical control is also regarded as expensive; it dates back to the 1930s. Although investigations at the University of Arizona showed carbon bisulphate as effective against *S. elaeagnifolium* (Davis *et al*., 1945), its control costs were high (Davis *et al*., 2004). Furthermore, by 2004 in South Africa, chemical control costs were estimated to be more than R2000/ha (Marais *et al*., 2004), indicating the high costs associated with such a control method.

Other control options (i.e. mechanical and cultural) are used as primary control techniques against weeds. Mowing *S. elaeagnifolium* has been tried but this tends to encourage multiple shoots which re-sprout vigorously when the weed re-grows (Kidston *et al*., 2007). Removing the above-ground parts every two weeks can prevent seed production but is time consuming and expensive (Richardson & McKenzie, 1981). The lack of success with cultural, mechanical and chemical control methods against *S. elaeagnifolium* has made the weed a prime candidate for biological control in many countries, including South Africa.

The use of biological control against invasive plants has a long history and a generally high rate of success (McFadyen, 1998). Biological control has been practised for 96 years in South Africa, where more than 85 species of biological control agents had been released on to 28 weed species by 1990, making South Africa the third most active country using biological control, after the United States of America and Australia (McFadyen, 1998). It is also a key country in terms of biological control against *S. elaeagnifolium*, since it was the first country worldwide to study the import and release of insects on solanaceous weeds (Sforza & Jones, 2007). Benefits of biological control include self-perpetuating populations, distribution in inaccessible areas and low costs relative to other control methods (Coombs *et al.,* 2004; Culliney, 2005).

1.1 Research problem

Since its introduction into South Africa, *S. elaeagnifolium* has expanded its range considerably and is causing substantial negative impacts on crop and pasture production (Viljoen & Wassermann, 2004). Attempts to control the weed using cultural, mechanical and chemical methods have been largely ineffective in containing ,let alone eradicating, the weed (Wassermann *et al*., 1988; Heap & Carter 1999; Viljoen 2003; Viljoen & Wassermann, 2004).

Two biological control agents, *Leptinotarsa texana* and *Leptinotarsa defecta* were released in South Africa in 1992 to control the weed (Hoffmann *et al*., 1998). *Leptinotarsa defecta* remains localised and scarce around the original release sites, while *L. texana* has proliferated at many sites where it has been released (Hoffmann *et al*., 1998), although there is evidence that *L. texana* is having a major impact on the growth and reproduction of the weed. There is, however, uncertainty as to what this means for productivity of crops in lands where the weed grows and for the associated costs of the weed and the benefits derived from having it under some degree of biological control.

1.2 Objectives

The aim of the study was to determine and compare costs and benefits of controlling *S. elaeagnifolium* using either biological or chemical control. The base-case scenario was sunflower production under no control in the Springbok Flats around Roedtan, Limpopo Province South Africa.

1.4 The study site

Roedtan is situated in the Waterberg district of the Limpopo Province, which is characterised as an agricultural, mining and tourism district. Agriculture is fundamental to the economic and social development of the province. The Waterberg district contributes the largest percentage of total agricultural production in the province, with field crops to a value of R653 million. Agriculture provides significant employment opportunities, particularly on larger farms (Limpopo Provincial Government, 2003). One of the most prominent crops grown in the region is sunflower which is a drought-resistant, dry-land crop predominantly cultivated in the heavy clay soils of the Springbok flats, Dwaalboom and northern regions of the Waterberg District.

Figure 1 Location of the Springbok Flats around Roedtan, Limpopo Province

To conduct the study, field trials were undertaken on two adjacent farms on the Springbok flats around Roedtan (Figure 1). The total study site area was 840 ha with *S. elaeagnifolium* invading sunflower lands, of which 500 ha on one farm was under biological control and 340 ha on the other farm was under chemical control. Rainfall is erratic in the area and severe droughts are experienced about once every eight years (Limpopo Provincial Government, 2003) .

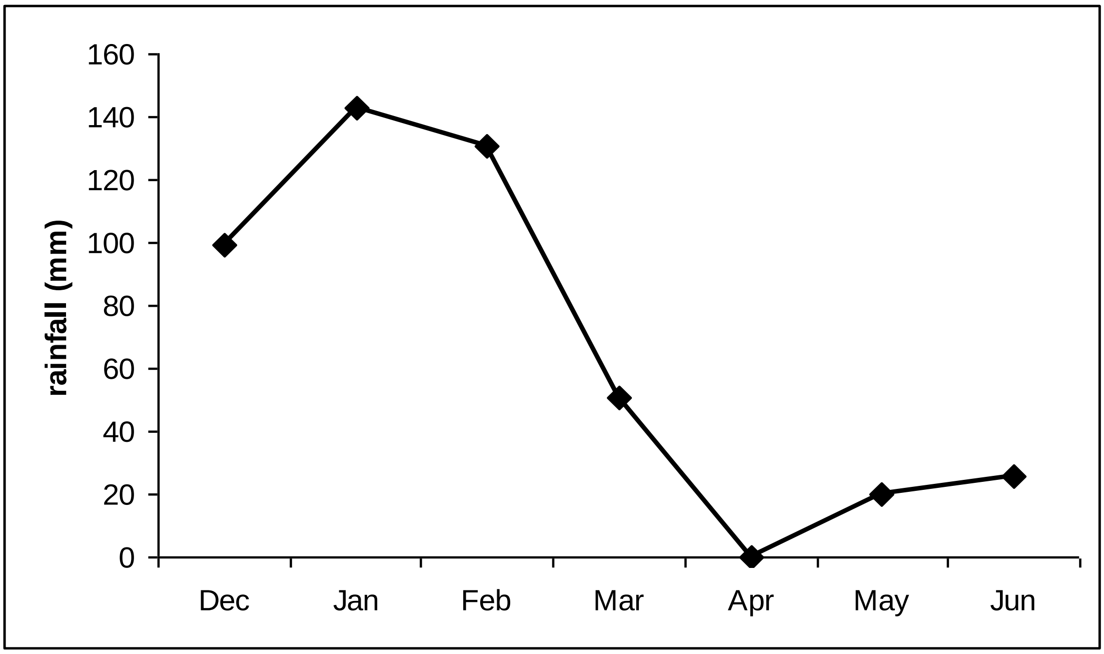


Figure 2 Mean rainfall data for 2008-2009 in Limpopo province (Modimolle data station)

Figure 2 shows monthly rainfalls received at Modimolle in Limpopo Province from December 2008 to July 2009, during the period of this investigation. Rainfall peaked in January and decreased as winter approached with no rain falling in April 2009 and little in May and June 2009 (SAWS, 2009). The rainfall received in the study area is noted because the late peak forced a postponement of normal planting time for sunflower from October 2008 to January 2009, and delayed the start of the monitoring exercise of this study to February 2009.

1.5 Thesis layout

The researched work is presented in four chapters: Chapter One introduces the research work; Chapters Two reviews the biophysical data; Chapters
Three and Four conduct biophysical and economic data analysis. Conclusions are drawn per chapter and suggestions for future work are presented under Recommendations in Chapter Four.

CHAPTER 2 REVIEW OF THE PROBLEM OF *SOLANUM ELAEAGNIFOLIUM*

2.1 Biology, origin, and global distribution

Solanum elaeagnifolium Cavanilles (Cav.) (silverleaf nightshade) is a deep rooted, branched, warm season perennial herb (TASS, 1999; Mekki, 2007; Sforza & Jones, 2007), that grows up to100cm in height (see Figure 3), (Boyd *et al*., 1984; Kidston *et al*., 2007). Its stems are covered with dense fine hairs and numerous slender orange prickles. Its alternating, lance-shaped leaves are three to four times as long as they are broad; with undulating, short, silver-white star shaped trichomes that give the weed a silvery appearance, hence its name (Mkula, 2006; Mekki, 2007). *Solanum elaeagnifolium* plants are able to recover following severe defoliation due to plentiful reserves present in their extensive root system (Figure 3), (Richardson & McKenzie, 1981; Gibbens & Lenz, 2001; EPPO, 2007).

Figure 3 *Solanum elaeagnifolium* plant (Smith & Faithfull, 1998)

Biological traits are important factors in the invasion process of alien plants. These include reproduction, seed dispersal, phenology, physiology, and tolerance to environmental extremes (Roche, 1991; EPPO, 2007; Sforza & Jones, 2007). Dense population of *S. elaeagnifolium* can add over two million seeds per hectare (ha) per year (Boyd *et al*., 1984; Mekki, 2007), indicating the potential threat the weed has when established. In particular, it thrives on disturbed land, particularly arable land.

Its life cycle is composed of four phases: vegetative regeneration and germination during spring; vegetative development, duration depends on the biotope; flowering from spring to the end of summer; and fructification from the end of spring till autumn. *Solanum elaeagnifolium* root system can extend to a depth below 3m, survive up to 15 months under moist conditions and also produce from depths of 20cm or more in loose moist soil (Richardson & McKenzie, 1981; Mkula, 2006; Mekki, 2007). *Solanum elaeagnifolium* has spread in almost all continents and is able to grow under a wide range of environmental conditions and appears to be adapted to a wide range of habitats and soil conditions.

Solanum elaeagnifolium is native to America (Boyd *et al*., 1984; Wassermann *et al.,* 1988; Henderson, 1998; Cuda *et al*., 2002; EPPO, 2007), particularly the south-western United States and northern Mexico, and possibly Argentina. Where it is categorised as one of the most problematic weeds due to serious impacts on crops and pastures (Boyd *et al*., 1984; Mellado *et al*., 2004; Nugent, 2005; Kidston *et al*., 2007; Mekki, 2007; Capinera, 2008). Implying that, *S. elaeagnifolium* is invasive even in its natural environment. Table 1 lists the approximate dates when *S. elaeagnifolium* appeared in different regions around the world.

Table 1 Appearance date of *S. elaeagnifolium* throughout the world (adapted from Boyd *et al.*, 1984)

Region	Approximate date of appearance
Australia	1901
South Africa	1952
India	1955
Egypt	1956
Sicily	1956
Israel	1957
Zimbabwe	1969
Greece	1972
Spain	1975

Solanum elaeagnifolium has made its way into the European Plant Protection Organization (EPPO) region, Asia, Africa, North America, Central America and the Caribbean, and Oceania, including all states in Australia.

Table 2 gives a summary of the weed's global distribution and its status in the country (present, ability to naturalise and invade).

Table 2 ***Solanum elaeagnifolium*** **global distribution**

Country	**Status**	**Country**	**Status**
Algeria	Present in other parts of the country	Mexico	Native
Argentina	Native	Morocco	Noxious weed mainly in the irrigated Tadla plain
Australia	Common weed	New Zealand	Present
Chile	Present	Pakistan	Present
Croatia	Present in other parts of the country	Puerto Rico	Present
Cyprus	Locally naturalised	South Africa	Naturalised
Denmark	Present	Serbia and Montenegro	Present in Vojvodina
Egypt	Present	Switzerland	Present
France	Eradicated in Chateauneuf-les-Lartigues but still present in Vic-la-Gardiole	Spain	Potentially an aggressive weed in Valencia Present in other parts of the country
Greece	Present in other parts of the country	Syria	Noxious weed in the northern region
India	Present in Karanataka	Taiwan	Present
Israel	Naturalised	Tunisia	Noxious weed in irrigated fields in Sbikha
Italy	Present in Sicilia and Sardinia	Zimbabwe	Present

It is incorporated in the top 20 invasive weeds list in the Mediterranean islands, and is declared a major problem in parts of a number of countries, including South Africa, Zimbabwe, India, Australia, Algeria, Greece, Israel, Spain and Italy (Boyd *et al*.,1984; Olckers & Zimmermann, 1991; Nugent, 2005; EPPO, 2007).

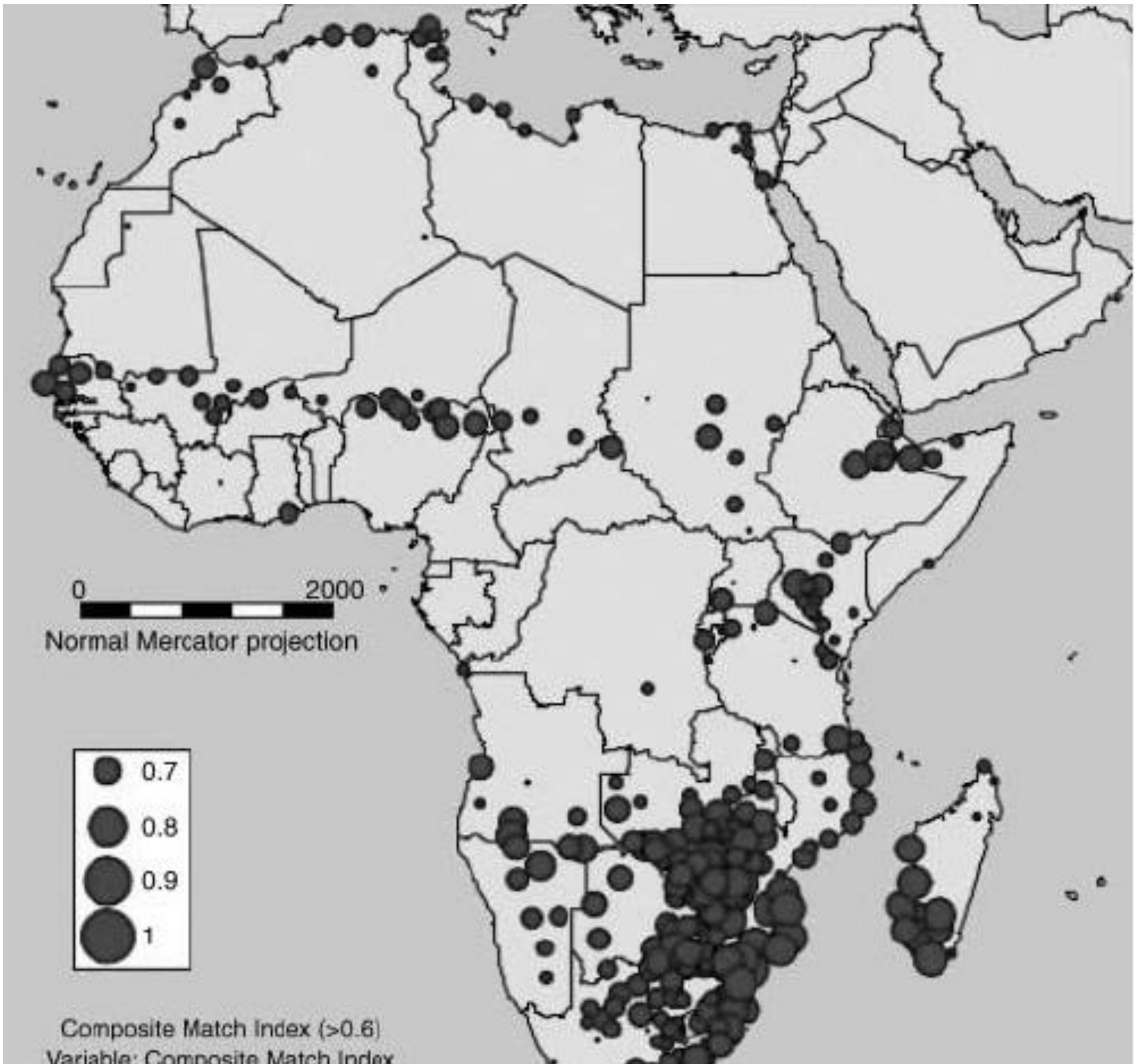


Figure 4 Climate matching between Texas, USA and Africa (Sforza & Jones, 2007)

Figure 4 illustrates the degree of climate matching between areas within a native region to those in destination region. Brownsville (Texas, USA) was considered the home location of *S. elaeagnifolium*, to identify areas in Europe and Africa with the same climate (Sforza & Jones, 2007).

2.2 History of introduction to South Africa, extent and potential range of *S. elaeagnifolium* in the country

Since its introduction into South Africa in 1952, *S. elaeagnifolium* has continuously expanded its range (Boyd *et al*., 1984; Olckers & Zimmermann, 1991), causing substantial negative impacts on crop and pasture production (EPPO, 2007). These negative impacts led to agricultural crops not declared for sale because of contamination (Wassermann *et al*., 1988). Early efforts to control its invasiveness focused on chemical and mechanical control, but these methods proved ineffective at containing, let alone eradicating, the weed (Olckers *et al*., 1991).

In South Africa, several biological control agents have been tested against *S. elaeagnifolium* (Smith & Faithfull, 1998). Two leaf-feeding chrysomelid beetles, *Leptinortarsa texana* and *Leptinortarsa defecta,* were released in 1992 (Hoffmann *et al*., 1998; Olckers *et al*., 1999; EPPO, 2007).

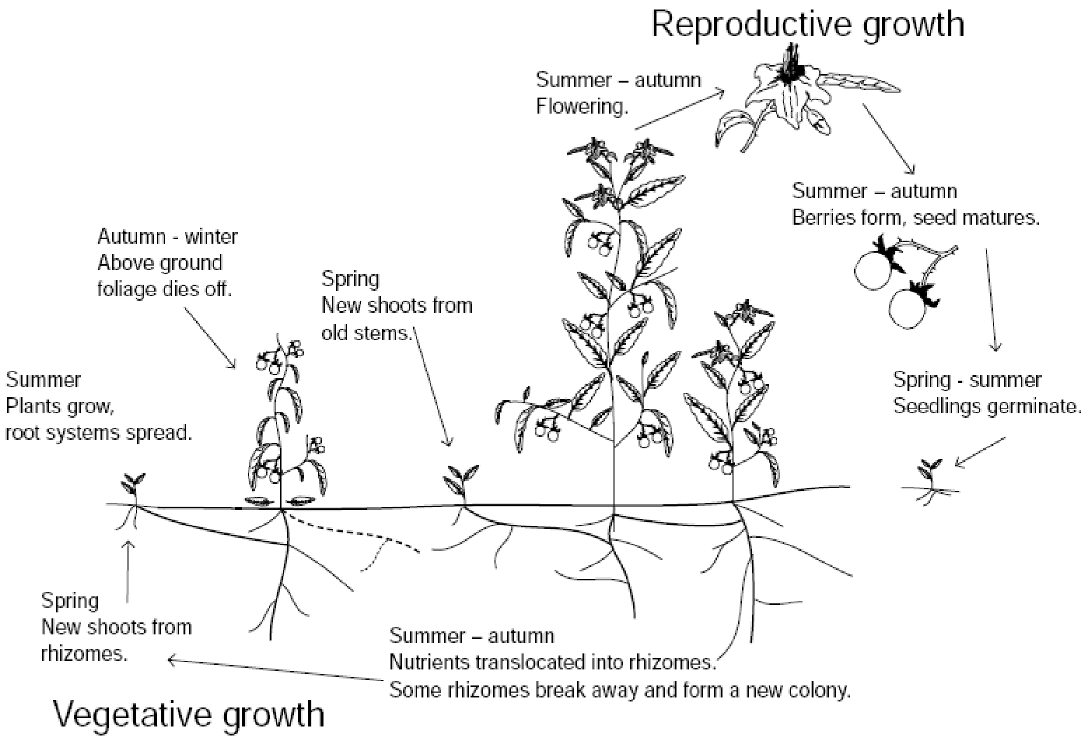


Figure 5 *Solanum elaeagnifolium* life cycle (Kidston *et al*., 2007)

Solanum elaeagnifolium regenerates from seeds or root system (see Figure 5). Seedlings emerge at any time from summer until autumn, depending on rainfall. Germination is greatest at depths of 1 to 3cm, with flowering usually beginning in summer and possible continuation to autumn. Berries are produced during summer till autumn. Berry formation overlaps with carbohydrate translocation to the roots. The colony then produces new shoots in spring (Kidston *et al*., 2007).

2.3 Economic consequences of invasive alien plants on society and the environment

The economic costs of the weed on crop and pasture production are yet to be properly quantified, while the economics of controlling the weed are not adequately known, particularly under different infestation densities and different management regimes. The deleterious and beneficial impacts of invasive alien plants have economic consequences that directly and indirectly affect the use and non-use benefits that societies derive from ecosystems services. For example, invasive alien plants in agricultural areas negatively affect crop/pasture yields (Van Zyl, pers. comm., 2008) and can therefore be classified as affecting the direct use values of ecosystem services. Invasive alien plants invade and transform natural areas with the consequence that the non-use and indirect benefits that individuals derive from biodiversity are lost (Costanza *et al*., 1997; Turpie, 2004; Moran *et al*., 2005). Some of the adverse consequences of alien invasive plants can be estimated in economic (monetary) values (i.e. those that are directly used by society), whereas those that are indirect and non-use in nature cannot be readily estimated in monetary terms (Richardson & Van Wilgen, 2004). In addition negative economic consequences of invasive alien plants are experienced in the form of control costs (Pimentel *et al*., 2005). The decision to invest in a control programme depends on whether the economic costs of control are greater than or less than the avoided economic costs of the impacts of the alien invasive plants.

Solanum elaeagnifolium has direct and indirect impacts on agriculture (Mkula, 2007). Direct impacts include direct competition with summer-growing crops (e.g. sunflower, soybeans, cotton and horticultural crops) and pastures. Indirect impacts include reduced yields of subsequent crops (e.g. winter-growing crops such as cereals) as a result of the depletion of nutrients and moisture in the soil during the dry summer months (Parsons & Cuthbertson, 2001). Because no suitable in-crop herbicide exists exacerbates these problems (Baig *et al*., 1999). For example, corn fields in Texas infested with *S. elaeagnifolium* suffered an estimated yield loss of 8% even with the use of herbicides, and 12% with other forms of control. According to the Texas Agricultural Statistics Service (TASS), *S. elaeagnifolium* affected an estimated 15% of corn land in the South Central, Coastal, and Southern areas, but was recorded to have been rarely seen in other areas (TASS, 1999). In Morocco, an estimated crop loss of 64% in corn and 78% in cotton was recorded as a result of *S. elaeagnifolium* infestations, while Australia experienced crop losses of 12-50% in wheat, 4-10% in sorghum and 5-14% in cotton (EPPO, 2007).

Agriculture is fundamental to the economic and social development of the Limpopo Province as far as employment, food production and exports are concerned (LIMPOPO PROVINCIAL GOVERNMENT, 2009). The Waterberg district contributes the largest percentage of total agricultural production in the province, with field crops worth over R600 million grown in the area. Weeds reduce the quantity and quality of agricultural, horticultural and forestry products, which affects both industry and consumers (LIMPOPO PROVINCIAL GOVERNMENT, 2003). They aggressively compete for water, nutrients and sunlight, resulting in reduced crop yield and poor crop quality (Sinden *et al*., 2004).

Sunflower is one of the main crops contributing to gross agricultural income in Limpopo Province. It is a drought-resistant dry-land crop, almost entirely cultivated in the heavy soils on the Springbok flats (the study site). Its seed is primarily used for the manufacturing of sunflower oil and oilcake, and sunflowers are well adapted to both hot and dry climate in South Africa (DAFF, 2006). The seed can be used for human or animal consumption and is marketed locally. Sunflower is the third largest grain crop produced in South Africa after maize and wheat. Over the past years, production amounted to 700 000 tons on average. South Africa is not a significant role player in the production and trade of oilseeds in the international market since it contributes only 3% to the sunflower seed produced in the world. The gross value of sunflower seed produced in South Africa has been relatively volatile over the past ten years. A report by the Department of Agriculture Forestry and Fisheries stated the existence of a correlation between area planted to sunflower, total production and gross value of agricultural production. For example, during the 2006/07 production year, there was a decrease in total area planted to sunflower and in total production of sunflower; this resulted in a decrease in the gross value of agricultural production for that seasonal year (DAFF, 2009).

2.3.2 The costs and benefits of control

In crop production weed control is often the most important crop protection activity undertaken on farms (Hillocks, 1998). Uncontrolled weed growth, particularly in the early stages of crop establishment, can reduce final crop yield as a result of competition between crops and weed populations. The economic benefits and costs of controlling weeds in agricultural systems are relatively easy to identify and quantify. The benefits of control are realised in increased yields and returns to the land; the costs of control are the direct costs of the herbicides and labour. Additional benefits of control in agricultural systems that are more difficult to identify and quantify are those that impact on the quality of the environment (e.g.

better conservation of soil and water, and reduction in soil erosion), on the non-use benefits that societies derive from these systems (e.g. aesthetic values), and the avoided future costs (Bowles & Webster, 1995; Wiles, 2004). These benefits are often not included in an economic assessment of a control programme and so these values tend to be conservative, under-estimates of the benefits of control.

2.4 Control methods

The benefits of controlling the weed in terms of agricultural gains are relatively well documented, but defensible economic information on the environmental and social gains resulting from control is scarce. Therefore, further investigation is needed with respect to the variation and consequent differential abilities of benefits to cover the costs of controlling the weed.

2.4.1 Mechanical control

Mechanical control of weeds includes hand-pulling, hoeing, tillage, mowing, grubbing, chaining, bulldozing, harvesting, and draining (Culliney, 2005). Soil disturbance caused during the control often stimulates the seeds of the invasive plant to germinate after clearing. However, regular tillage during the growing season and in winter weakens *S. elaeagnifolium* due to its lack of growth then (David *et al*., 1945; EPPO, 2007). This method is considered expensive, energy and labor intensive, and requires repeated effort. Furthermore, it is uneconomical where weed infestations are wide spread and land values low, or in areas that are difficult to access. Additional disadvantages include disrupting habitats and contributing significantly to soil compaction and erosion.

2.4.2 Chemical control

2.4.2.1 History

Chemical control on *S. elaeagnifolium* dates back to a field trial at the University of Arizona in the late 1930s. Spray applications of sodium chlorate and arsenic salts were compared with fumigation by carbon bisulphate, and the results suggested that carbon bisulphate was the more effective herbicide. The results of the spray application, however, could not be put into practice because it was not cost-effective (Davis *et al*., 1945).

Broadleaf herbicides such as phenoxy-acetic acid and phenoxy-propionic acid compounds, and most importantly 2,4-D amine, do not control the weed effectively. These herbicides only control the top growth but do not reduce competition and formation of seeds; they fail to translocate throughout the root fragments in order to prevent regeneration (Leys & Cuthbertson, 1977).

In order to achieve satisfactory control, it is recommended that new shoots are sprayed with 2,4-D amine. With follow up treatments with glyphosphate or 2, 4-D amine applied during the early berry formation stage and when the viable seeds begin to mature (Viljoen, 2007). Sorghum, corn and millet compete for moisture with *S. elaeagnifolium*; as a result these crops tend to have an ability to suppress the weed.

It is beneficial to treat small infestations with Tordon 75D, or registered glyphosphate herbicides, since these prevent the weed from expanding in density (Kidston *et al*., 2007). There is usually movement of carbohydrates and nutrients in the root system during early berry formation, and herbicides such as glyphosphate can then be translocated from the leaves to the roots, which enhance the control effect of spraying herbicides (EPPO, 2007).

Herbicides can have negative impacts on people and the environment (Pimentel *et al*., 1992). For example, high rates of nitrogen and phosphorus released from agricultural fields as a result of herbicide use often result in pollution of water resources and ecosystems (Babu, 1992; Jeong & Forster, 2003). Furthermore, persistent organic pollutants (POPs) resulting from spraying can poison non-target organisms in the environment. In humans, herbicides could increase the probability of disruption to the endocrine system and cause cancer, infertility and mutagenic effects, although little is known about these long-term chronic effects as yet.

Herbicides can also impact negatively on biological control agents (natural enemies that have been released as a form of controlling the weeds), resulting in resurgence. Unaware of how to deal with this problem, farmers often increase their use of herbicides, causing further problems. Moreover, increasing rates of resistance have resulted in many pesticides having shorter market lives than in the past (www.ipm.tamu.edu). All of these factors result in higher costs and potentially lower profits for chemical companies and farmers.

On the other hand, when resistance is not a problem, and taking into account the other disadvantages, herbicides in general are highly effective for controlling pests. However, when the disadvantages of chemical control outweigh the advantages, farmers look to alternative methods of pest control, the most common being biological control (Viljoen, pers. comm., 2007b).

2.4.3 Biological control of alien invasive plants

Biological control, involves the importation, colonisation, and establishment of exotic natural enemies (predators, parasites, and pathogens) to reduce exotic pest populations to, and maintain them at, densities that are economically insignificant (Klein, 2007). Classical biological control is considered by many to be the best method to control alien invasive plants. Many argue that instead of waiting until other control methods have failed, biological control should be used in the initial control stages (Simberloff, 1996).

2.4.3.1 Advantages and disadvantages of biological control

If correct management practices are applied, biological control agents can remain present on the weed until completely defoliated (with reference to *L. texana* beetles), and can substitute for herbicides at a lower cost without ever having to be re-applied, since control agents increase in number and spread (Klein, 2007). Further benefits of biological control result from increased revenue from improved lands, decreased health risks from exposure to weed allergens, reduced use of herbicides, and avoidance of biodiversity losses. More specifically, advantages include (Culliney, 2005):

- Low cost once established (proves to be successful in a cost-effective way)
- Effective in low return ecosystems
- Non-disruptive to the ecosystem
- Selectivity does not intensify to create new pest problems
- Control agents will increase in number and spread
- Control is self-perpetuating,
- Free of side effects
- Safe to handle or use
- High degree of host specificity (suitable biological control organisms do not attack other species)
- Searching ability - meaning that the agent is able to move in search of food (i.e. the host plant)
- Usually a large proportion of the host population is destroyed
- Suitable biological control organisms do not attack other species.

It is for these reasons that biological control of invasive weeds is often argued to be the only strategy that can provide permanent management of invasive weeds in an ecologically sustainable and cost effective way (Culliney, 2005). Furthermore biological control is recognised as being more effective against weeds that are tolerable enough to only need to be suppressed, not destroyed entirely.

2.4.3.3 Risks in biological control

Pemberton in 2000 assessed the risk to native plants posed by insects introduced for biological control. The assessment was the first of its kind, and was conducted on 55 weed species that had been introduced into Hawaii since 1902. One of the risks involved in biological control is that the agent may use an indigenous plant as its host, and in the process potentially destroy it (Pemberton, 2000).

Biological control is also considered risky when an introduced agent disperses from its initial site of introduction to other areas where it threatens endemic species with extinction. In risk assessment it is important to consider the dispersal and host specificity of the potential biological control agent. The outcomes of introducing biological control agents are inherently unpredictable and potentially irreversible

(Simberloff, 1996 and McFadyen, 1998). In addition, different farming systems, crop varieties and environmental conditions contribute further to the unpredictability of outcomes. Other disadvantages of biological control include:

- It needs time to achieve results, making it difficult to assess effectiveness in the short term
- The impact is often not dramatic
- It will not exterminate the pest (partial success)
- It is often unpredictable
- It is difficult and expensive to develop and apply
- It requires expert supervision
- It can be complex
- It disrupts food chains.

According to Hoffmann *et al*. (1998), biological control has not been a general option chosen when weed species are closely related to important economic crops in the country of introduction. In South Africa, biological control of *S. elaeagnifolium* was found to target the following crops: tomatoes (*Solanum lycopersicon*), potatoes (*Solanum tuberosum*), eggplant (*Solanum melongena* L.), tobacco (*Nicotiana Tabacum*) and chilli (*Capsicum annum*). Therefore, the process of host-specificity-testing and clearing of *L. texana* and *L. defecta* was delicate and prolonged (Hoffmann *et al*., 1998).

Table 3 lists the main natural enemies of Solanum species used in Mexico sorted into groups and species, field host range, parts attacked and damage caused, and whether or not those species were used for biological control in South Africa. Out of ten species on the list, three species were used in South Africa and those included *Frumenta nephalomicta*, *Leptinotarsa texana and defecta*, which led to the release of two species *L. texana and defecta* in the country in 1992.

Table 3 List of main natural enemies of *S. elaeagnifolium* in Northern Mexico used in South Africa (Sforza & Jones, 2007)

Natural enemies		**Part attacked and damage**	**Field host range**	**Used in South Africa as biological control**
Group	**Species**			
Chrysomelidae	*Leptinotarsa texana*	Leaf-defoliation	*Solanum elaeagnifolium* and *S. rostratum*	Yes
	Leptinotarsa defecta	Leaf-defoliation	*Solanum elaeagnifolium* and *S. dimidatium*	Yes
	Grtiana pallidula	Leaf-defoliation	Solanum spp.	No
Tingidae	*Gargaphia arixonica*	Leaf-defoliation	*Solanum elaeagnifolium*	No
	Gargaphia opacula	Leaf-defoliation	Solanaceae	No
Cecidomyidae	Undetermined	Stem galling	*Solanum elaeagnifolium*	No
Gelechiidae	*Frumenta nephalomicta*	Fruit & seed feeding	*Solanum elaeagnifolium*	Yes
Tephritidae	*Zonosemata vitiigera*	Fruit & seed feeding	*Solanum elaeagnifolium*	No
Curculionidae	*Trichobaris texana*	Stem boring	*Solanum elaeagnifolium* and other *Solanum* spp.	No
Nematoda	*Orrina phyllobia*	Leaf galling	*Solanum elaeagnifolium*	No

2.4.4 History of control in South Africa

This section discusses the history of control against *Solanum elaeagnifolium* in South Africa. Methods discussed include chemical and biological control. Although other methods were used against the weed, the scope is based on chemical and biological control and the status of the weed under these control methods is compared in the biophysical analysis (Chapter 3).

2.4.4.1 Effective herbicides

In 1988 Tordon (picloram) was considered the most effective herbicide to control *S. elaeagnifolium*, but in order for it to give acceptable results, follow-up applications are necessary. Picloram is expensive to use and many farmers partially replaced it with 2, 4-D amine without loss of efficacy. In spite of the effectiveness of combining these herbicides, such herbicides are not promoted, because of their residual effects that can have negative impact on other plant growth in crop growing areas. Therefore, no herbicide was registered against *S. elaeagnifolium*, making control of the weed limited, especially on arable land such as the Springbok Flats in Limpopo Province and at Kendrew in the Eastern Cape (Olckers *et al*., 1991; Viljoen, 2003). As a result, there was a need for a herbicide that could be translocated within the plant more efficiently and not be excreted by the root system (Viljoen, pers. comm., 2007b). Roundup® was therefore considered, since its gives promising results, although it is too costly under intensive farming conditions.

The Agricultural Research Council – Plant Protection Research Institute (ARC-PPRI) launched a root-absorbed herbicide investigation from 1968 to 1972 (Viljoen, 2007a). Herbicides such as Arsenal, Bushwhacker, Savanna and Molopo were investigated. Results revealed reduction in shoot densities of *S. elaeagnifolium* infestation in shallow soils and alluvial sandy soils 36 months after the initiation of the treatments. The measures in shoot reduction effectiveness increased to 90% over three years. Results also indicated that chemical control is more effective in shallow soils than in deep arable soils, and different application levels of chemical control are suggested to maximise effectiveness (Heap & Carter, 1999; Viljoen, 2007). Treating S*. elaeagnifolium* with chemical control and harrowing early in the season when planting sunflower can reduce the infestation densities to some extent.

2.4.4.2 History of biological control of *S. elaeagnifolium* in South Africa

Several biological control agents have been tested in South Africa against *S. elaeagnifolium*. Two leaf-feeding chrysomelid beetles, *Leptinotarsa texana and Leptinotarsa defecta,* were released in 1992 (Hoffmann, *et al*., 1998)and established successfully in six provinces (Free State, Eastern Cape, North West, Limpopo, Western Cape and Gauteng) (Zimmermann & Olckers, 1991). These beetles have caused sufficient damage to be considered reasonably effective for control of *S. elaeagnifolium* (Hoffman *et al*., 1998; Olckers *et al*., 1999). Significant events in the history of biological control of *S. elaeagnifolium* in South Africa are:

Surveys were undertaken to determine insects with potential to control the weed.
1973: *Gratiana lutensces* and *Gratiana pallidula* tortoise beetles (of the Chrysomelidae family) from Texas and Argentina were introduced for biological control purposes.
1974: *Arvelius albopunctatus* (Penatomidae) a bug feeding on seeds was introduced from Argentina.
1976 &1989: *Frumenta nephalomicta* (Gelechiidae) a moth from North Mexico was introduced from Mexico in 1976 and Texas in 1989.
1984: *Ditylenchus phyllobius* (Nematoda), a gall forming nematode from Texas was also introduced for biological control purposes.
1992: *Leptinotarsa defecta* and *Leptinotarsa texana*, as well as anthonomus species (spp), were introduced.

2.4.4.3 Biology of *Leptinotarsa defecta* and *Leptinotarsa texana*

Leptinotarsa texana and *Leptinotarsa defecta* inflict foliar damage on *S. elaeagnifolium*. They attack leaves, flowers, young fruits, and stems, during their larvae and adult stages, causing considerable damage and defoliation. These leaf beetles are indigenous to North America and have a similar biology (Hoffmann, 1985; Zimmermann & Olckers, 1991). An adult female lays clusters of about 20 to 40 eggs, which become attached to the lower (abaxial) surface of *S. elaeagnifolium* leaves. Eggs of *L. texana* are pale yellow and rather bigger in size than the bright yellow eggs of *L. defecta*. The larvae hatch from the eggs after about four days and the neonates feed on the eggshell. The larvae of *L. texana* feed on the leaves, flowers and buds of their host plant, but they do not affect the fruit of the weed. The larvae feed in groups, and pass through four instars stages in 10-14 days. Mature larvae burrow into the soil to pupate, and adults emerge 10-14 days later (Cuda *et al*., 2002; Klein, 2007). *Leptinotarsa texana* is distinguishable from *L. defecta* as the former's larvae have orange heads, whereas the latter have black heads. *Leptinotarsa defecta* adults have two elytral stripes, while the *L. texana* adults have four black elytral stripes. Adults of both species diapause before winter, burrowing into the soil, and emerge in spring (Olckers *et al*., 1995; Hoffmann *et al*., 1998; Klein, 2007).

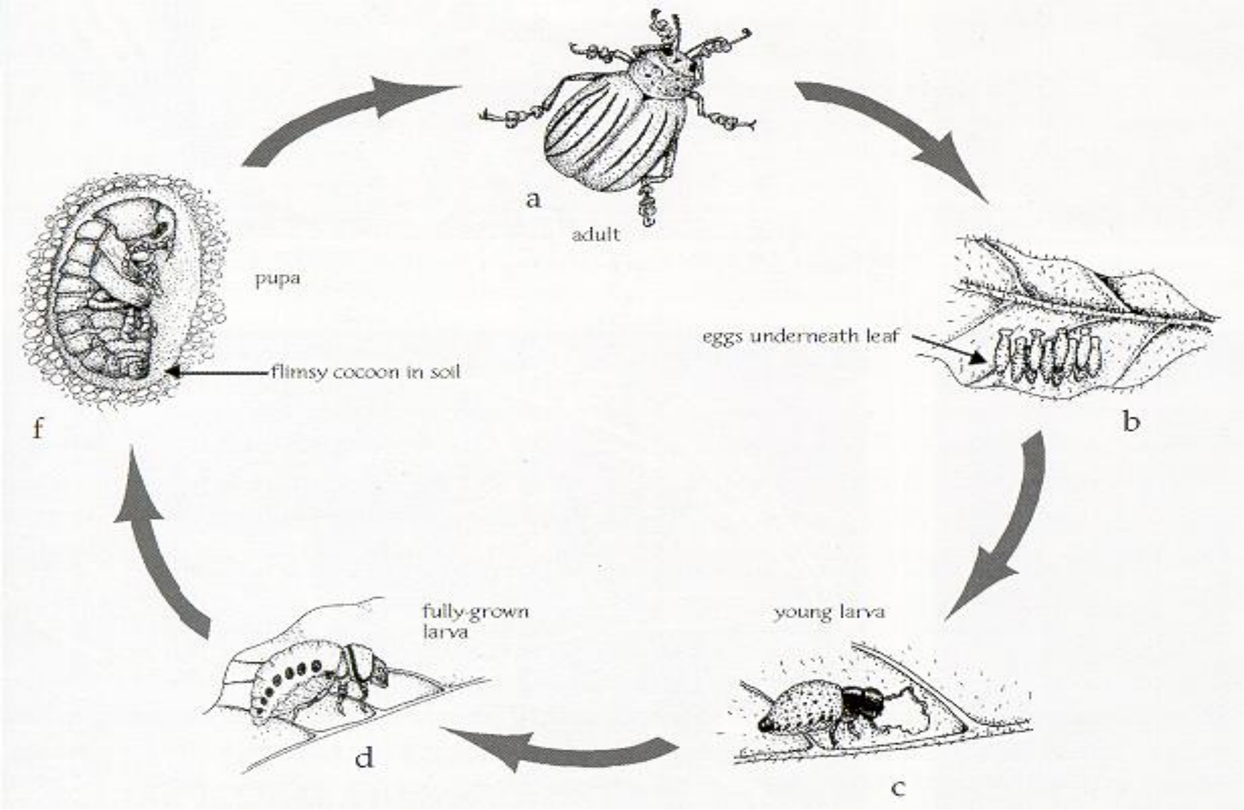


Figure 6 Life cycle of *S. elaeagnifolium* leaf-feeding beetle *Leptinotarsa* agents (Klein, 2007)

With *Leptinotarsa texana* the beetles are show to disperse, and although they have well-developed wings, the adults are reported to be incapable of flying or, at least, are reluctant to do so (Hoffmann *et al*., 1998). Although the beetles do not damage the fruit or the root system, damaged plants of *S. elaeagnifolium* that have been defoliated repeatedly by the beetles are usually stunted and produce fewer fruit. This reduces the abundance of *S. elaeagnifolium* and alleviates some of the problems related to competition with crops, while not impacting negatively on the crops being grown. Figure 7 illustrates the weed after being defoliated and stripped (leave defoliation) by *Leptinotarsa texana* larvae and adults, indicating the parts attacked and damage caused which is the basis of determining and categorising damage levels in Chapter 3 (section 3.2).

Figure 7 A *S. elaeagnifolium* plant that has been defoliated by larvae and adults of the leaf beetles (Klein, 2002)

CHAPTER 3 BIOPHYSICAL ANALYSIS TO DETERMINE THE NET EFFECT OF USING CHEMICAL AND BIOLOGICAL CONTROL ON *SOLANUM ELAEAGNIFOLIUM*

3.1 Introduction

Initially a biophysical survey was carried out to describe the status of *S. elaeagnifolium* Cavanilles on the two identified study areas (farms). In the past both farms relied on chemical control against the weed. The release of *L. texana* around 2001, led to one farm adopting biological control (e.g. *Leptinotarsa texana*), whilst the other continued the usage of chemical control (e.g. Roundup®) to curb weed invasion. In addition to measuring the abundance of the weed under the two management practices (biological and chemical control), the effect of *L. texana* on the weed when herbicides were used was also determined. This chapter presents the materials and methods used in the study, and their biophysical analysis.

3.2 Materials and methods

On each farm, a plot of land under sunflower cultivation was selected for the surveys. Each plot was monitored monthly from February to June 2009. The monitoring was conducted on field measurements and on samples returned to the laboratory.

The field study used a Point Centred Quarter Method (PCQM), to collect measurements on plant density. The PCQM date back at least 150 years, were it was used by surveyors in the mid-nineteenth century making the first surveys of government land (Stearns, 1949). The advantages of this method are that it is relatively quick, efficient, and inexpensive in terms of equipment and manpower (Mitchell, 2007). For this study, transects were established within the selected research plots and were used to establish sample points at 5 metre intervals. An imaginary horizontal line crossed transects at right angles at each sample point. This process demarcated four indeterminate quadrants, two on either side of each transect. At each site (biological and chemical control), three permanent 100 metre parallel transects, spaced 30 metres apart were demarcated and sampled, giving 60 sample points for each plot. The distance from the central sample point to the nearest plant in each quadrant was recorded to provide a measure of the relative density of the plants per transect. The reciprocal of these values was calculated to show relative densities of the plants in a visually-meaningful format (i.e. higher plant densities have low mean distance measurements which result in greater reciprocal values).

Thereafter, at each 5 metre sample point per transect, the plant closest to a point at least 1 metre from the right of the transect was harvested, by cutting its stem 10mm above the soil surface. The harvested plants were placed in a plastic bag and stored in a freezer at -18ºC for further inspection in the laboratory. Stem diameter, amount of leaf damage, fruits, eggs, larvae and adult beetles per plant were recorded.

In terms of biological control, the extent of leave damage was categorised according to the following three categories: Low damage (LD), medium damage (MD) and high damage (HD).

HD was found on plants with most, if not all, of their leaves missing and with high levels of feeding damage by *L. texana* adults and larvae on the few remaining leaves; medium damage (MD) was observed on plants with all or most of their leaves *in situ* but with obvious signs of feeding damage by *L. texana* adults and larvae; and low damage (LD) was found on plants with either no signs, or with only superficial levels, of feeding damage by *L. texana* adults and larvae. In terms of chemical control, damage was assessed as follows: High damage (HD) = leaves that had turned brown and brittle; medium damage (MD) = leaves that had turned yellow but were still pliable; and low damage (LD) = leaves that had no visible signs of colour change. The combination of measured data provided information on the population density of *S. elaeagnifolium* plants, as well as a description of the state of the plants and their insect herbivores.

3.2.1 Statistical analysis

It must be noted that two sets of data need to be analysed when using analysis of variance (ANOVA), Statistica® Version7. The two sets of data were field and laboratory data, respectively. Laboratory data were subjected to comparisons for the months of March and April only, when plants were present in both the biological and chemical control plots. Field comparisons were carried out during February and June. For relative density, the actual distances between sample points and plants were used in the analysis, although reciprocal values are presented.

3.3 Results and discussion

3.3.1 *Solanum elaegnifolium* field measurements

Illustrated in Figure 8 is the mean relative density of *S. elaeagnifolium* at two control sites. The distance from the central sample point to the nearest plant in each quadrant was recorded to provide a measure of the relative density of the plants per transect. Higher plant densities indicate low mean distance measurements which result in greater reciprocal values.

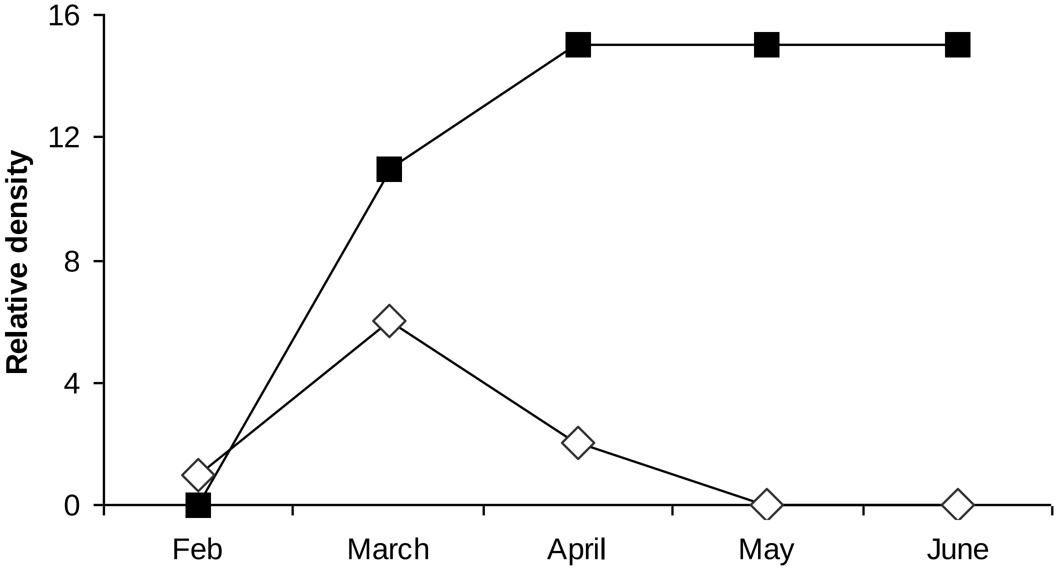


Figure 8 Mean relative density of *S. elaeagnifolium* at two sites, one under biological control (open diamond) and the other under chemical control (closed squares), during February to June 2009

There was a statistically significant difference in the density of the plants between sites ($F_{(1,\ 1917)\ site}$ =114.8; $p << 0.0001$) and between sample dates ($F_{(1,\ 1917)\ date}$ =51.0; $p << 0.0001$). The density of the plants was routinely greater in the chemical controlled plot than in the biological controlled plot, indicating that biological control was key in suppressing the density of the weed. There was significant difference in the mean relative density between biological and chemical control. Biological control proved to have a positive effect in reducing weed density.

Figure 9 shows the mean standard error of *S. elaegnifolium* plant height at biological and chemical controlled sites. The height in this case represents the length of the weed.

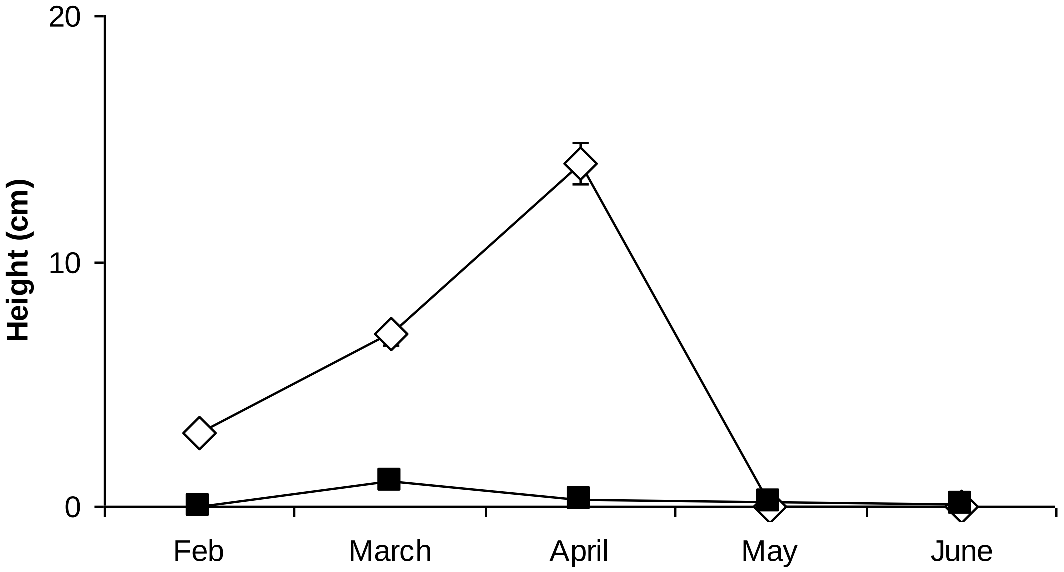


Figure 9 Mean±SE of *S. elaegnifolium* plant height at two sites, one under biological control (open diamonds) and the other under chemical control (closed squares), during February to June 2009

There was statistical difference in the mean height of the weed in both sites ($F_{(1,\ 1917)\ site}$ =314.1; $p<<0.0001$) regardless of sample dates ($F_{(1,\ 1917)\ date}$ =35; $p<<0.0001$). The possible benefits of lower densities may have been offset because plant heights were significantly greater in the biological controlled plot than in the chemical controlled plot.

3.3.2 *Solanum elaeagnifolium* laboratory measurements

Figure 10 shows the stem diameters of *S. elaeagnifolium* plants harvested in the biological controlled and chemical controlled sites.

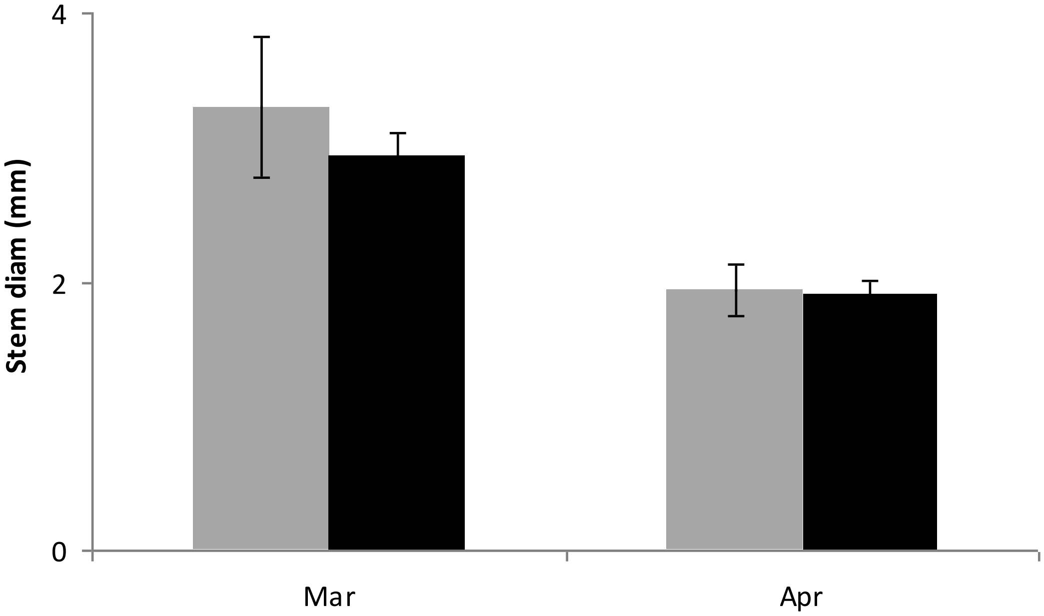


Figure 10 Mean±SE of *S. elaeagnifolium* stem diameter at two sites, one under biological control (grey bar) and the other under chemical control black bar), during March and April 2009

The stem diameter decreased from March to April at both sites ($F_{(1,\ 113)\ date}$ =24.6; p<<0.0001) but there was no significant difference between sites ($F_{(1,113)\ site}$ =0.5; p=NS) showing that the plants harvested from the two situations were of comparable size.

Figure 11 presents mean number of fruits on *S. elaeagnifolium* plants from a biological controlled and a chemical controlled plot.

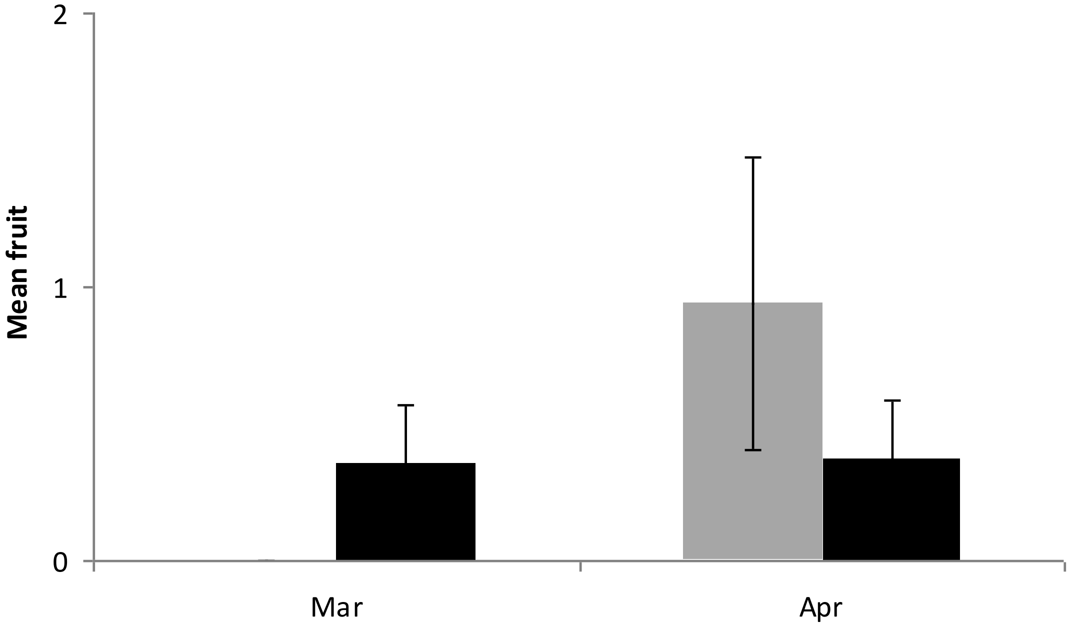


Figure 11 Mean±SE number of fruits on *S. elaeagnifolium* plants from a biological control plot (grey bar) and a chemical control plot (black bar), during March and April 2009

Although the plants from the biological controlled plot only had fruit present in April (Figure 11) and the numbers were higher than in the chemical controlled plot, the difference was not significant (t = 0.987, df = 20), indicating that levels of fruiting were consistent under the two control treatments.

Illustrated in table 4 is the mean number of *L. texana* with associated standard errors in different life stages.

Table 4 Numbers (Mean±SE per plant) of different life stages of *L. texana* on *S. elaegnifolium* plants at two sites, one under biological control and the other under chemical control during March and April 2009

	March		**April**	
Life stage	**Biological control**	**Chemical**	**Biological control**	**Chemical**
Eggs	2.2 ±0.8	0± 0	0.8± 0.4	0± 0
Immature larvae	5.6± 2.5	0.1± 0.1	5.3± 1.9	0± 0
Mature larvae	7.6± 2.9	0± 0	1± 0.8	0± 0
Adults	1.5± 0.5	0.1± 0.1	1.1± 0.6	0± 0

Although low numbers (i.e. 0-0.1) of *L. texana* eggs, larvae and adults were found in the chemical controlled plot during March, in general the beetles were absent from this plot, indicating that herbicide spraying was having either a direct (toxic or deterrant) or indirect (unpalatable host plant) effect on *L. texana*. The numbers of each life stage on the plants were higher in March than in April in the biological controlled plot but only the numbers of mature larvae were significantly different between the two months (t = 2.23, df =10, p=0.05).

Table 5 shows damage levels on *S. elaeagnifolium* plants at the biological and chemical controlled sites caused by *L. texana* and by herbicides. In the biological controlled plot there was much more damage by *L. texana* in April (100% of the plants extensively damaged) than in March, when 60% of the plants were in this category. Levels of herbicide damage in the chemical controlled plot were the same in both March and April.

Table 5 Percentage of *S. elaeagnifolium* plants with different types and levels of damage at two sites, one under biological control and the other under chemical control during March and April 2009

Type and extent of damage		**Biological controlled plot**		**Chemical controlled plot**	
		March	**April**	**March**	**April**
L. texana	Low	10	0	0	0
L. texana	Medium	30	0	0	0
L. texana	High	60	100	0	0
Herbicide	Low	0	0	12	6
Herbicide	Medium	0	0	33	47
Herbicide	High	0	0	55	47

3.4 Conclusion

The results of the one-off survey described in this chapter indicate that there was no major distinction between the levels and status of *S. elaeagnifolium* on the two farms under consideration. It would seem that biological control and chemical control were both having a substantial impact on the weed and that the two situations did not exhibit many differences except for the negative effect that herbicides had on the biological control agent (see Table 4).

CHAPTER 4 FINANCIAL ANALYSIS

4.1 Introduction

Agriculture is fundamental in the economic and social development of the Limpopo Province as far as employment, food production and exports are concerned. The main economic sectors and employers in the district are agriculture (26.98%), mining (16.17%) and tourism (21.3%) (Waterberg District Municipality, 2009; Lehohla, 2004). The Waterberg district in particular contributes the largest percentage of total agricultural production in the province, with field crops contributing R653 million (Limpopo Provincial Government, 2003). Sunflower is one of the main crops, contributing approximately 10.7% to gross agricultural income in the Limpopo Province. Sunflower is a drought-resistant, dry-land crop and so it does particularly well in this region where the average temperature and rainfall are 2.5-40ºC and 380-700mm, respectively.

An attempt was made to determine the economic value of negative impacts such as loss of yield and weed control costs associated with *S. elaeagnifolium*. The rationale behind the research was to quantify benefits, if any, of biological control in financial terms in order to justify expenditure on biological control research and its use as a method to manage alien plants in agricultural situations.

To determine effectively and comprehensively the net economic effects of *S. elaeagnifolium* and its control in sunflower cropping systems, both a farm-level financial analysis and a regional-scale financial analysis were undertaken. The farm results were extrapolated to regional level, based on the assumption that the farms represent typical farms in the region. The extrapolation was achieved by determining the costs and benefits of two control methods, where the weed is causing substantial damage. It must be emphasised that this study focused on private benefits and costs; in other words, a financial analysis (at both farm and regional scale) was conducted, and externalities were ignored.

As a result of insufficient data on the economic impacts of the weed and the effectiveness of control methods, it was necessary to develop scenarios of all possible combinations for each control method using damage and effectiveness estimates from farmers' personal records and estimations. The choice of 'no control' was included as one of the control options. The economic effectiveness of each control method was then utilised relative to the base-case land-use practice, which was defined by each of the three control options available to farmers.

4.2 The economic equation

The formula for financial benefits (income) is:

i. $$Income_{control-method} = (P.Y.r) - c$$

Where

CP = Crop price which indicates value of harvest (crop produce),

Y = Yield (output),

r = Percentage damage (expressed as a proportion) on crop produce caused by *S. elaeagnifolium* presence under a control method,

c = Total costs (management and control costs)

Control method = no control; chemical control or bio-control.

The financial model was made of total costs (management and control costs), yield, returns (yield by crop price) and profit (returns less total costs). While the financial equation was derived from returns which equal CP (crop price) by Y (output) by damage (r) minus c (total cost associated with the control scenario in question).

4.3 Calibrating the financial framework

Variables for the financial model included the following:

- Range of crop yields experienced in the region

- Range of prices received for the crop outputs
- Range of direct costs incurred cultivating sunflower
- Range of costs incurred by controlling the weed
- Upper and lower estimates of the impact of the weed without control
- The effectiveness of the two other control methods.

These values were obtained from various sources including: personal communication with the farmers; 2003 and 2009 reports from Limpopo Department of Agriculture Fisheries and Forestry; private and public agricultural and financial services companies; and departments such as the South African Futures Exchange (SAFEX, 2009); Sentraalwes (SENWES, 2009); Grain South Africa (GrainSA, 2009). Values used to parameterise the model are summarised in Table 6. Since *S. elaeagnifolium* affects quality and quantity of expected output (Van Zyl, pers. comm., 2008; Wassermann *et al*., 1988), the study assumed that quality of output was homogeneous.

Table 6 gives a summary of parameter values in the financial framework. According to the farmers, under the worst case scenario in the absence of control, one loses 90% of the crop, loses 85% of the crop on average or loses 75% of the crop.

Table 6 Summary table of the upper, average, and lower values used for all variables in the financial framework

Parameter values	**Value**			**Units**	**Source**
	High	**Expected (average)**	**Low**		
Crop price	3685	3217.5	2750	R/tonne	SAFEX (2009); GrainSA (2009); SENWES (2009)
Management costs	1602	1426.5	1251	R/ha	Van Zyl & Roos (2009):personal communication
Average yield	1.5	1.3	1.1	tonnes/ha	SENWES (2009)
Effect of *S. elaeagnifolium* on yield	1.35	1.1	0.82	tonnes/ha	Van Zyl & Roos (2009):personal communication
No control cost	0	0	0	R/ha	Van Zyl & Roos (2009):personal communication
Expected yield on no control	0.34	0.19	0.08	tonnes/ha	Van Zyl & Roos (2009):personal communication
Bio-control cost	0	0	0	R/ha	Van Zyl & Roos (2009):personal communication
Expected yield on bio-control	1.35	1.05	0.74	tonnes/ha	Van Zyl & Roos (2009):personal communication
Chemical costs	150	92.5	35	R/ha	Van Zyl & Roos (2009):personal communication
Expected yield on chemical control	1.08	0.82	0.57	tonnes/ha	Van Zyl & Roos (2009):personal communication

The cost of the research and development (R&D) involved in introducing *L. texana* and *L. defecta* in the Springbok Flats was a public cost incurred by government. No private financial costs were incurred by the individual farmers. As a result, the study undertook a private financial analysis, which means the costs of the bio-logical control agent were zero. The highest level of effectiveness of the beetles was estimated to be 100% (i.e. no damage on crops), with the expected average at 95% (5% crop damage) and the lowest at 90% (or 10% crop damage).

The highest level of effectiveness of chemical control on *S. elaeagnifolium* was 80% (i.e. 20% crop damage), with an average of 75% (i.e. 25% crop damage) and a lowest effectiveness of 70% (i.e. 30% crop damage). Costs associated with applying chemical control per ha were estimated at a high R150, with expected average cost at R92.50 and the lowest cost R35.00. Spraying contributed largely to non-existence of the beetles in the chemical controlled plot, and as a result no biological control benefits were attributed in this plot. The optimistic approach under the no control scenario refers to minimum damage, low management costs, high crop yield and high crop price, while the pessimistic approach refers to maximum damage, high management costs, low crop yield and low crop price.

4.4 Scenarios

Table 7 lists control options, their benefits and net damage levels (i.e. high and low) caused by the presence of *S. elaeagnifolium*.

Table 7 Net benefits and damage of control options included in the study

Control option	**Net damage**	**Income (*Yield *price - cost*)**		
		High	**Average**	**Low**
No control	Low	B_1	B_2	B_3
	High	B_4	B_5	B_6
Chemical	Low	B_7	B_8	B_9
	High	B_{10}	B_{11}	B_{12}
Bio-control	Low	B_{13}	B_{14}	B_{15}
	High	B_{16}	B_{17}	B_{18}

Benefits recorded were categorised as high, average and low at each control method. They were used in the different base case scenarios (i.e. no control; chemical control and bio-control) and in comparing the three scenarios to determine the cost-effective control option.

The base case scenarios were then summarised to reflect the intervention undertaken at each base case scenario. With the no control base case, chemical control was introduced as the first intervention followed by bio-control. With chemical control base case, biological control was introduced as the last intervention (see Table 8).

Table 8 Summation of financial evaluation of control options

Intervention	**Base case**		
	No control	**Chemical control**	**Bio-control**
No control	-	-	-
Chemical control	Yes	-	-
Bio-control	Yes	Yes	-

4.4.1 Base case scenario

This scenario represents a situation where farmers with *S. elaeagnifolium* in their lands are either practising biological control, chemical control or not practising any control for the management of *S. elaeagnifolium*.

4.4.1.1 No control scenario

With the no control, base case scenario farmers plough the field only for planting purposes, and thereafter leave the field without doing anything further to control/eradicate the weed. The no control scenario included benefits from the management strategy (no control, chemical and biological control) categorised as high, average or low. The optimistic approach refers to minimum damage, low management costs, high crop yield and high crop price, while the pessimistic approach refers to maximum damage, high management costs, low crop yield and low crop price.

4.4.1.2 Biological and chemical control scenarios

Biological and chemical control scenarios represented the adoption of a control strategy against *S. elaeagnifolium* when cultivating sunflower. This was selected in order to determine the benefits of introducing control methods, and to identify opportunity costs (which are measured by the value of goods and services forgone for other purposes, i.e. control methods). Benefit scenarios for biological and chemical control were as follows:

- High benefits (high crop price, average yield and average management cost)
- Average benefits (average crop price, average yield and average management cost) and
- Low benefits (average yield, average management cost and low crop price).

Low effectiveness was defined as high levels of damage on the crop caused by the weed, while high effectiveness referred to low damage caused. There is therefore a linear, negative relationship between the effectiveness of control and the damage level caused by the weed, i.e. as effectiveness of control increases, damage caused by the weed decreases. Values of damage were gauged from estimates made by farmers. Biological and chemical control was then compared to determine the most cost-effective control method to adopt.

4.5 Results and discussion

4.5.1 Farm-scale analysis

Figure 12 shows the net financial returns to sunflower farmers for each of the three control options available to them, for all combinations of the range of possible values for yield, crop price, input costs, and weed impact (damage).

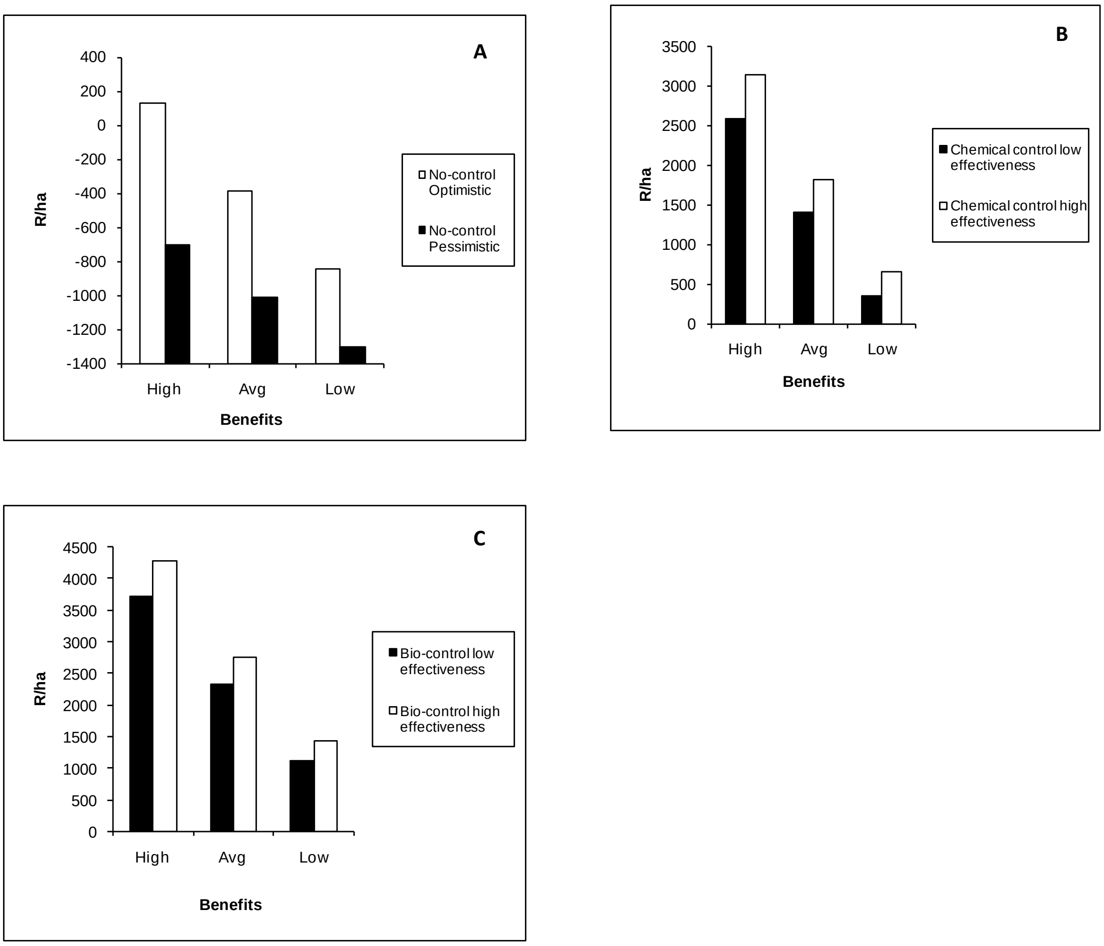


Figure 12 Base case scenarios showing benefits at each control method (A) no control, (B) chemical control) and (C) bio-control

In situations where farmers choose not to control the weed (no control scenario), in all cases but the most optimistic case (i.e., where weed impact is low, crop yield and prices are high, and input costs are low), it is uneconomical to cultivate sunflower when *S. elaeagnifolium* is present. The decision to introduce a control method for *S. elaeagnifolium* leads to positive net financial returns for all the scenarios, irrespective of whether bio-control or chemical control is used (Figure 12). Since there are benefits from using both control methods, they were compared with the no-control strategy to determine which one was the most cost-effective.

4.5.2 Evaluation of intervention strategies

4.5.2.1 Chemical control at low and high effectiveness compared with no control

Figure 13 gives the comparison between chemical controlled plots and plots where no control of the weed was used. Because the introduction of a control method led to financial benefits for the farmers, a comparison was undertaken to show financial benefits obtained from changing from one control option to the other.

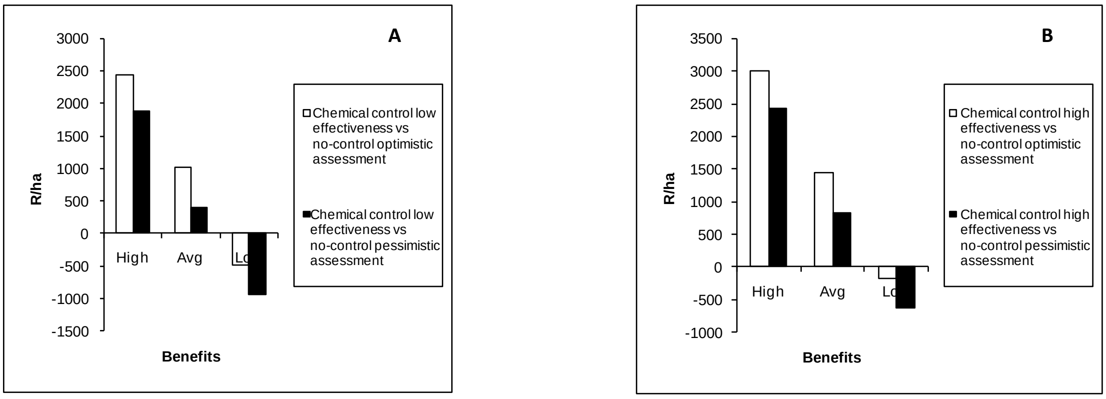


Figure 13 Benefits of chemical control at (A) low and (B) high effectiveness compared with benefits of no control scenario under optimistic and pessimistic assessment

Benefits realised from the chemical control scenario were then compared with the no control, base case scenario. The analysis showed that introducing chemical control, both low effectiveness level (70%) and high effectiveness level (80%), provided farmers with higher net financial returns. Losses occurred where no method to control *S. elaeagnifolium* was practised. However, those losses were reduced by chemical control at a high effectiveness level. The benefits received from introducing chemical control are therefore regarded profitable in a financial sense.

4.5.2.2 Bio-control benefits at low and high effectiveness compared with benefits of chemical control at low and high effectiveness

Figure 14 shows the benefits derived from introducing biological control against *S. elaeagnifolium* when chemical control is the base case.

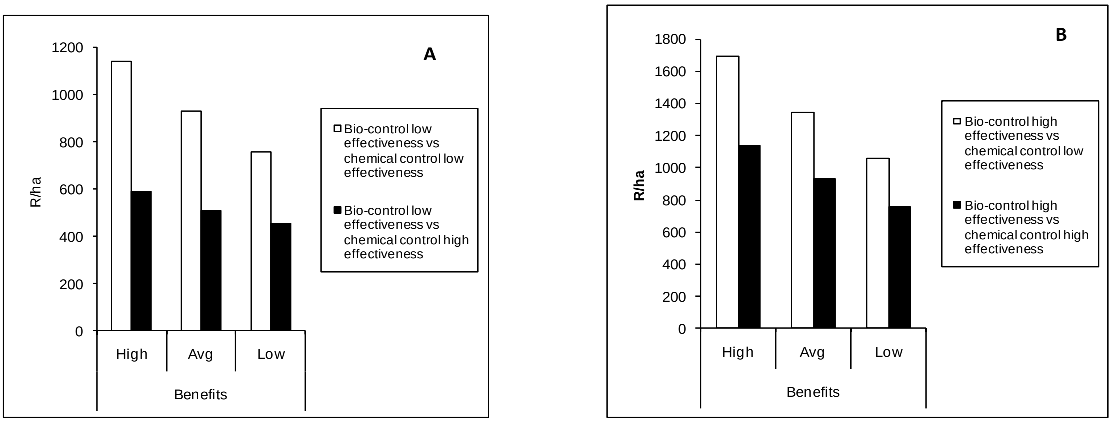


Figure 14 Biological control at (A) low and (B) high effectiveness compared with chemical control as a base case at low and high effectiveness

Since chemical and biological control treatments were beneficial compared with the no control base case scenario, a comparison analysis was conducted on benefits derived from both control methods at different effectiveness levels. Biological control at high effectiveness resulted in higher financial benefits than chemical control at low and high effectiveness. It was shown that, even at a low level of effectiveness in controlling the invasion of *S. elaeagnifolium*, biological control provides higher financial returns than chemical control.

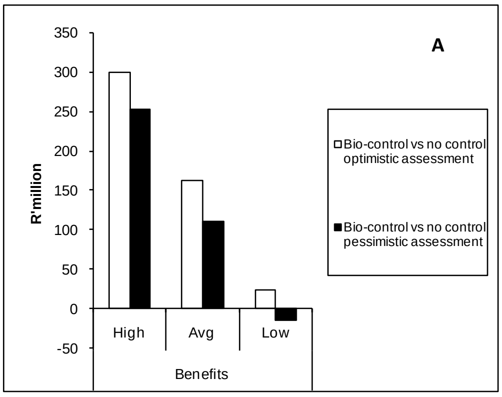
The results show that financial benefits realised by farmers from introducing biological control were much greater than those of the no control and chemical control.

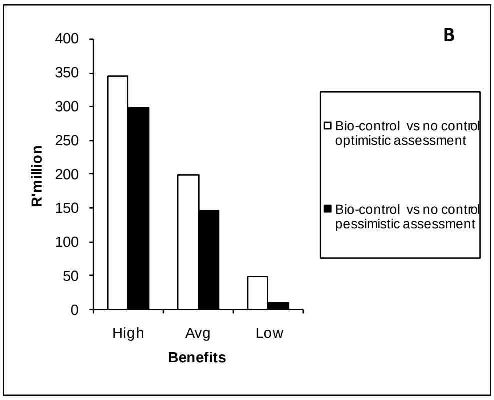
4.5.3 Large scale regional analysis

The large scale regional analysis was conducted based on interesting financial benefits from the private farm scale analysis described in section 4.4.1. The three scenarios (no control, chemical and biological control) were treated in the same manner as in the private farm scale analysis. In this section the financial benefits of introducing a control method (chemical or biological control) at regional level are estimated. This analysis was made on the assumption that the farms in the private farm analysis were representative of farms in the region.

The private farm analysis indicated that farmers practising chemical control were able to control the weed, and were receiving higher profits than they would have received had there been no control. On the regional scale, the additional benefits to farmers in the Springbok Flats associated with making use of biological control as opposed to no-control and chemical control to suppress *S. elaeagnifolium* were compared.

Figure 15 illustrates a biological control scenario, compared with chemical control and no control options at a regional scale which was undertaken to determine the regional benefits of introducing biological control against *S. elaeagnifolium*.





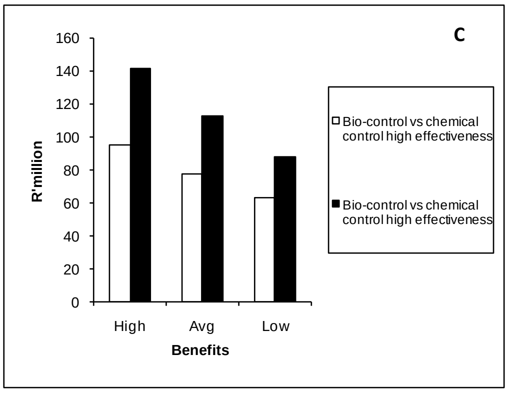


Figure 15 Biological control at low effectiveness (A) and high effectiveness (B) compared with no control (optimistic and pessimistic assessment) and chemical control at low and high effectiveness (C) at regional level

At regional scale, biological control continued to result in higher financial benefits than no control and chemical control.

The region will therefore benefit from biological control of *S. elaeagnifolium* and avoided externalities associated with chemical control at high quantity. Resulting in higher income, which in turn could lead to better wages for farm labourers, increased investment in machinery and equipment and higher yields with a better quality of oil seed produced. All this would contribute to an overall increase in the province's sunflower production and enhance the standard of living.

When applying chemical control, an average of 3ℓ per ha is used to control *S. elaeagnifolium*. This translates into a total of some 25 044 600ℓ of herbicides used over an area of 8 348 200ha. The environmental and social costs associated with using herbicides include degraded soil quality which results in a low crop yield; increased health concerns; translocation in groundwater; biodiversity losses and higher production costs. Drift during application causes loss of herbicides and detrimental affects for beneficial and non-target organisms, including in this case the biological control agents. In addition, there is slow translocation to the root system which reduces the overall effectiveness of the herbicides. If it is assumed that all farmers are aware of the effectiveness of biological control, and that they all use the biological control agents (and that these agents are as effective across the entire region as they were in our case study farm), then the net economic effects in the region are positive relative to no control, and chemical control.

4.5.4 Sensitivity analysis

Since the parameter values elicited from farmers were based on their observations and past experience, the findings in section 4.5 were therefore subjected to a brief sensitivity analysis, in order to test their sensitivity to changes in parameters. A 5% change in effectiveness showed an increase in financial benefits in no control, chemical control and bio-control. However, under the optimistic assessment, the no control base case resulted in lower benefits, than those of chemical control at high effectiveness level. Nevertheless, biological control at 100% control provides the farmer with higher benefits, as it improves land, reduces health risks and avoids loss of biodiversity.

Table 9 Summation of a brief sensitivity analysis

	Effectiveness Values				
Parameter	**100%**	**95%**	**85%**	**70%**	**50%**
No control (optimistic assessment)	3723	3171	2618	2065	1512
Chemical control	3776	3222.8	2670	2117.3	1011.8
Bio-control	3925.5	3372.8	2820	2267.25	1161

4.6 Conclusion

The results of the financial analysis on private farms show that it is uneconomical not to control *S. elaeagnifolium* under cultivation in all cases but the most optimistic case (i.e. where weed impact is low, crop yield and prices are high, and input costs are low). While introducing a control method on *S. elaeagnifolium* provides the farmer with net financial benefits, the chemical control method proved to require high management and control costs. Spraying herbicides necessitates re-application and greater use of fuel, whereas with biological control individual farmers incur no private financial cost, since the cost of the research and development (R&D) involved in introducing the biological control agent was a public cost through government services.

Although it is recognised that a private financial analysis was undertaken, and the private costs of *L. texana* were zero, it is of importance to consider social costs associated with chemical control at large quantities. Literature indicates that chemical control (application of herbicides) can negatively impact people in the surrounding areas through: loss of food, water and soil poison, and biodiversity threat. These possible social costs were not quantified in this study.

Results from both the farm scale and regional analyses indicated that introducing a control method offers financial returns to farmers. The regional analysis provided some indication as to the total expected benefits associated with introducing chemical control and biological control treatments on a larger scale. The potential gain from implementing biological control throughout the region was estimated to be high. These seem to provide justification for the adoption of biological control on a regional scale in order to suppress and control *S. elaeagnifolium* infestations in an efficient and cost-effective way.

4.7 Recommendations

- Since only two sites were surveyed in the current study, further investigation of control methods aimed at reducing the negative impacts of *S. elaeagnifolium* on both crop and pasture production at a large scale is required.
- Exclusion trials should be undertaken to investigate the effectiveness of *L. texana* and levels of damage caused by *S. elaeagnifolium* on expected crop yields, in order to conduct a full cost-benefit analysis of this method of control.
- Findings from this and other similar studies should be presented to farmers in the region, in order to raise awareness regarding alternative methods for controlling agricultural pests, most importantly *S. elaeagnifolium*.
- Further investigation is needed into farmers’ responses to the findings and into their willingness to pay for the release of biological control agents by the Agricultural Research Council-Plant Protection Research Institute.

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APPENDIX 1: Pictures taken during the survey

1. ***Solanum elaeagnifolium* prior to planting under biological control**

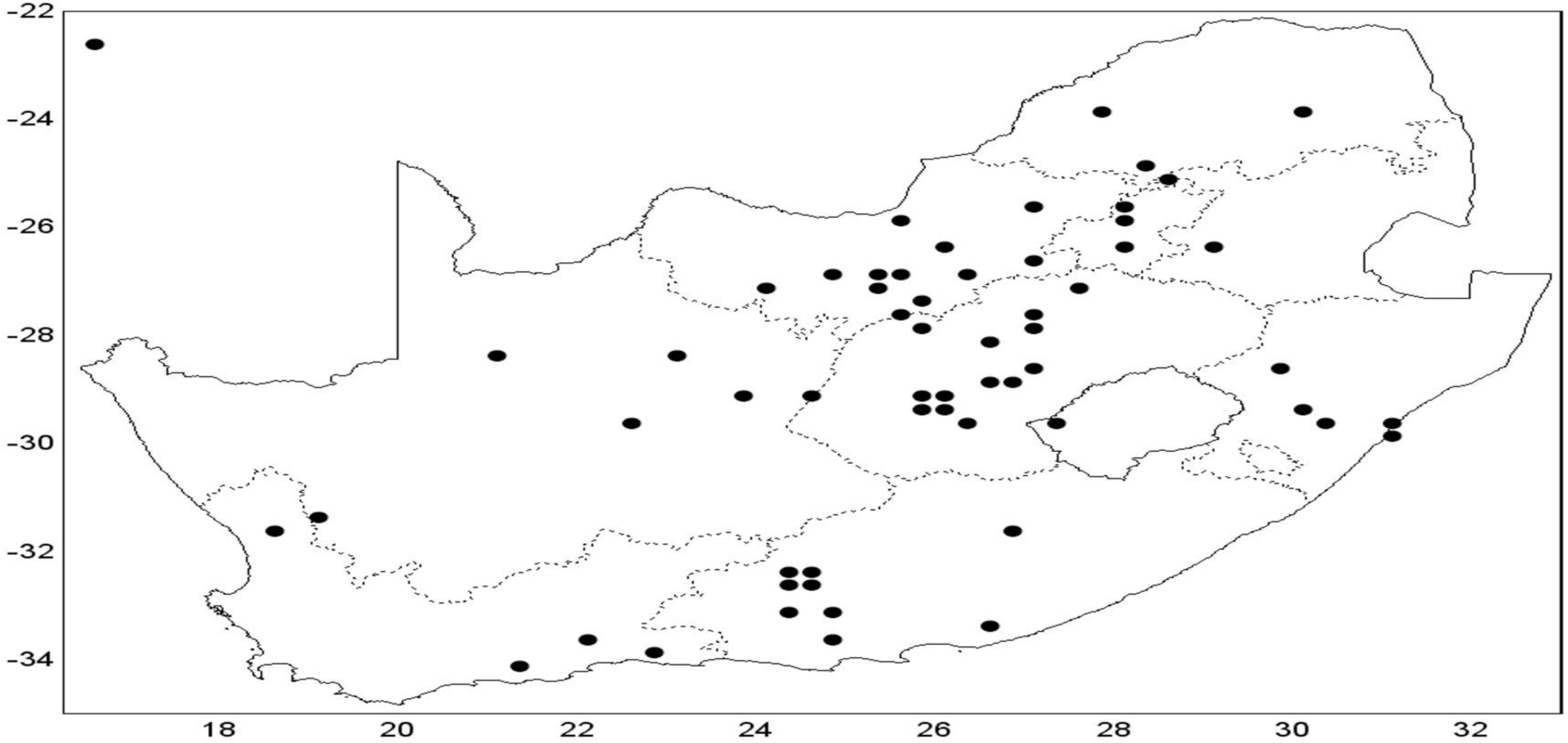
2. ***Solanum elaeagnifolium* before spraying under chemical control**

3. ***Solanum elaeagnifolium*** **with two weeks sunflower plants**

4. ***Solanum elaeagnifolium*** **invasion**

5. ***Leptinotarsa texana*** **agents feeding on *S. elaeagnifolium***

6. Distribution of *Solanum elaeagnifolium* in South Africa



(Drawn by L. Henderson; data source: SAPIA database, ARC-Plant Protection Research Institute, Pretoria)