final report

Project code: Weed.120

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Date published: May 2006

ISBN: 9781741914542

PUBLISHED BY
Meat & Livestock Australia
Locked Bag 991
NORTH SYDNEY NSW 2059

Feasibility of biological control of solanaceous weeds of temperate Australia

Silverleaf nightshade, *Solanum elaeagnifolium* Cav. and prairie ground cherry, *Physalis viscosa* L.

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Contents

Abstract

The solanaceous weeds, prairie ground cherry and silverleaf nightshade, are significant weeds in the cropping/pasture and perennial pasture zones of temperate Australia. The extensive and deep perennial root systems makes them extremely competitive, and the limited control techniques currently available are uneconomical for the treatment of large, dense infestations. Biological control is therefore considered a highly desirable option to reduce the impact of existing infestations and slow their rates of spread. This study aimed to determine the feasibility of commencing biological control programs for silverleaf nightshade and prairie ground cherry based on a review of natural enemies associated with these plant species in their native ranges and an assessment of the organisms' potential for biological control. A total of 30 species were assessed for silverleaf nightshade but few of these showed much potential for biocontrol because of their apparent lack of specificity. In addition, many of the previous surveys on natural enemies associated with silverleaf nightshade were conducted in regions of the Americas, which have vastly different climates to the regions in Australia where silverleaf nightshade is problematic. No surveys had been conducted in the central regions of Argentina and Chile, where climate analysis indicated more comparable climates with Australia. For prairie ground cherry, no surveys have previously been conducted and therefore little is known about the natural enemies associated with this plant in its native range of South America. Due to this lack of information, combined with uncertainties regarding the origins of Australian populations of these weeds, it is difficult to predict the likelihood of undertaking successful biological control programs for these weeds. However, the reported success of biological control of silverleaf nightshade in South Africa attributed to just one defoliating beetle, provides some promise that the biological control of SLN is possible. The study concluded that investment in biological control of SLN and PGC is warranted and potentially economically viable, however preliminary research is needed to fill key knowledge gaps so that a re-evaluation of the prospects for biological control can be conducted more thoroughly.

Executive Summary

The weeds prairie ground cherry, *Physalis viscosa* L. and silverleaf nightshade*, Solanum elaeagnifolium* Cav. have been identified as Priority Weeds of cropping/pasture zones of temperate rangelands in "Weeds of Significance to the Grazing Industries of Australia" (Grice 2002). The deep and extensive perennial root system of these weeds makes them particularly difficult to control using herbicides and cultivation. As such, biological control is seen as a High Priority Research and Development need for these weeds.

This study investigates the rationale for and feasibility of biological control of prairie ground cherry (PGC) and silverleaf nightshade (SLN) by: (1) reviewing the impact of these weeds, (2) current methods and deficiencies in control techniques, (3) reviewing the literature to identify natural enemies associated with these weed in their native ranges, and (4) discussing their potential as biological control agents. Based on the gaps in knowledge identified through this study, a biological control research project incorporating likely costs and time-lines is proposed for each weed. This information, combined with economic data on the current and projected costs of SLN and PGC to agriculture is used to provide an *ex ante* assessment of the potential economic benefits of an investment in biological control programs for PGC and SLN.

A summary of the major findings is provided for each weed.

SILVERLEAF NIGHTSHADE

Weed impacts. Silverleaf nightshade in Australia is estimated to infest approximately 140,000 ha and is particularly problematic in South Australia, New South Wales and Victoria. The weed risk assessment analysis indicated that SLN is a "highly invasive weed", (scoring 0.668 out of a maximum potential score of 1) and has the potential to invade up to 398 million ha across Australia.

Current methods of control. The extensive and deep root system makes SLN one of the most difficult weeds to control. Cultivation is largely ineffective and exacerbates weed spread, while slashing achieves only short-term control. The three most commonly used herbicides are 2,4-D, picloram and glyphosate, however none of these are selective and some are persistent in the soil. These herbicides can be effective against seedlings as spot-spray treatments for isolated plants, but as yet no effective and affordable treatments are available for the control of large infestations.

Potential biocontrol agents. Extensive surveys by USA, South African and Australian scientists have been made (1960s to 1980s) in the regions of origin of SLN to identify natural enemies with potential for use as biological control agents. The study assessed a total of 30 organisms, (1 fungus, 1 nematode, 3 mites and 25 insect species). Each species was assessed for its potential as a biocontrol agent based on three criteria: (1) its known host range, (2) the nature and level of impact on SLN and (3) the likelihood of the organism becoming established in targeted areas of Australia.

(1) Host range. As there are many Australian native and economically important plant species closely related to SLN, a high degree of host specificity is of upmost importance in considering the potential of organisms for biocontrol. Of the 30 listed organisms, 11 were ranked as having no biocontrol potential because of their known broad host range.

(2) Damage and potential impact on SLN. Organisms that cause repeated defoliation or reduced the vigour of SLN plants were considered promising agents, although the potential of these organisms to cause significant impact if released into Australia is difficult to predict. Disappointingly, no organisms were identified in the literature to attack the SLN root system. Those organisms causing cosmetic or minimal damage were considered a low priority. Of the 30 listed organisms, a further 9 species were ranked as having low potential because their impact on SLN was considered to be minor.

(3) Likelihood of agent establishing in Australia. Theoretically, the better adapted a biological control agent is to its new environment the more abundant and potentially damaging it will become. Organisms from similar climates and the same variety or subspecies of plant are thus more likely to be pre-adapted to conditions in the introduced environment. In this study, a climate analysis of the southern Australian distributions of SLN compared with climates within the native ranges of the weed indicated that the most comparable climates were in the central regions of Argentina and Chile. Organisms originating from the Monterrey region of Mexico, which has a climate similar to the subtropical regions of Northern NSW and Queensland, were considered to be less likely to establish in the summer-drought climates of South Australia, Victoria and Southern NSW. However, some organisms are less influenced by climate, and examples exist where biocontrol agents from dissimilar climates have established and become effective agents. Hence in this study, organisms from dissimilar climates (Mexico, Texas, Arizona) were given lower priority than species from more comparable climates (Argentina). Of the 11 species originating from Argentina, there was little information available on their biology, host range and impact of these organisms, making it difficult to adequately assess their biological control potential. Only one species, *Symmetrischema ardeola*

(Meyr) was ranked Medium-High (the highest ranking given) because preliminary tests in Argentina suggested that this insect might be specific to SLN.

Knowledge gaps. Despite our thorough review of the literature on the natural enemies of SLN, our ability to adequately assess the potential of finding suitable biocontrol agents for use in Australia was limited by insufficient information on:

1. **Origins of SLN populations in Australia compared with the native range.** SLN is native to the Americas, with geographically separate distributions occurring in southwestern/central America and South America (Argentina/Chile). Despite morphological differences existing in SLN populations between these two ranges, little information is available on the taxonomic relationships and genetic variation within and between these populations. In addition, the origins of Australian populations of SLN and the degree of genetic variation within Australian SLN populations is not known. Mismatches between biotypes of the host plant in the native range and the target weed in the introduced range can affect the establishment success or effectiveness of biocontrol agents. Hence, an understanding of the origins of Australian SLN populations is critical to a future biological control program as it will assist in prioritising SLN populations from which potential biocontrol agents might be sourced from in the native range.
2. **Natural enemies associated with SLN in regions of comparable climates.** Preference for the collection of agents is generally given to areas within the native range of comparable climates to the targeted introduced range. In the case of SLN, these areas would be the Buenos Aires and Pampa provinces in Argentina and in the central regions of Chile (around Santiago). However, these areas were never surveyed for potential agents, as previous surveys in South America concentrated mostly in northern Argentina. Therefore the natural enemies associated with SLN within the regions of comparable climates to targeted regions of Australia is not known.

PRAIRIE GROUND CHERRY

Weed impacts. Prairie ground cherry is a summer growing perennial weed with a deep, extensive root system and horizontal rhizomes. It is particularly serious in Victoria where it is estimated to infest over 24,000 ha. Climate and land-use analysis predicts that PGC is still in the early phases of its invasion process and has the potential to invade 409 million ha of Australian agricultural land. PGC was ranked as a “Highly Invasive Weed” in the weed risk assessment, scoring 0.726 out of 1, a higher score than SLN (0.668). In relation to its impact on agriculture, PGC, although rated lower than SLN, was still considered to be of “Medium High” impact.

Current methods of control. Normal cultivation practices are not effective in controlling PGC because it is not deep enough to damage the whole of the root system. Suppression of SLN infestations may be achieved through competition with vigorous summer-growing pasture species (lucerne and white clover) in irrigated situations. Chemical control can be effective particularly when applied in the flowering to fruiting stage. However, chemical control is suitable for the treatment of small infestations but are expensive over large areas.

Potential biocontrol agents. PGC has never been targeted for biological control in Australia or elsewhere in the world. As such, the natural enemies associated with PGC in its native range have never been purposefully surveyed. Few organisms associated with PGC were identified in the available literature. Mites (Acari) causing moderate to severe damage to PGC leaves in Florida are recorded, however little information is available on their identity and host range. The larvae of the moth *Heliothis subflexa* (Guenée) are known to feed on the fruits of *Physalis* species and may be worth investigating further.

A number of generalist fungi are recorded on *Physalis* spp but none are restricted to PGC or to *Physalis* species.

Knowledge gaps. Current literature identified little information on potential biological control agents therefore a thorough survey needs to be conducted in the native range of PGC (South America).

RECOMMENDATIONS ON FUTURE INVESTMENT AND RESEARCH REQUIRED FOR THE BIOLOGICAL CONTROL OF SLN AND PGC

SLN and PGC are difficult and expensive weeds to manage and current technologies do not provide long-term solutions to alleviate ongoing control costs and slow the spread of these weeds. This study has demonstrated that the rationale for considering biological control as a management option for SLN and PGC are justified. Furthermore, *ex ante* benefit cost analyses supports this rationale by indicating that an investment in biological control programs for these weeds would provide significant positive returns, particularly to the Australian grazing industries. For SLN, the analysis estimated that savings of close to $140 million in future control costs would accrue over a 30-year period at a 10% discount rate, providing a benefit to cost ratio of 59 to 1. For PGC, a successful biological control program could potentially result in close to $38 million savings in future control costs and a return of $26.30 for every one dollar investment at 10% discount rate.

While the rationale for commencing biological control programs for SLN and PGC can be argued, the feasibility of successful biological control in reducing the impact of these weeds is difficult to predict when critical gaps in knowledge exist.

We therefore recommend that for each weed, the first phase of a biological control program be undertaken (approximately 3-years duration) to fill these knowledge gaps, followed by a re-evaluation of the feasibility of biological control. This re-evaluation stage would serve as “go / no go” pathways for making decisions on future investments in biocontrol, should the information gathered in Phase 1 indicate that the potential of finding suitable biocontrol agents is low.

The knowledge gaps for SLN and PGC needing to be addressed in Phase 1 of proposed research programs is outlined in the following table.

Knowledge Gap	Research required for Silverleaf Nightshade	Research required for Prairie Ground Cherry
Determine the precise origins of Australian SLN and PGC populations and characterise the genetic variation within Australian populations. This will assist in matching biotypes of potential agents with biotypes of the weed in Australia.	Molecular studies of SLN populations in Australia compared to populations in USA and South America. Determine the genetic variation of SLN populations within Australia and map these if necessary.	Molecular studies of PGC populations in Australia compared to populations in USA and South America. Determine the genetic variation of PGC populations within Australia and map these if necessary.
Ecology and population dynamics of SLN and PGC. This will improve our understanding of which factors (key	SLN ecology and population dynamic studies.	PGC ecology and population dynamic studies.

population parameters and life stage transitions) are most likely to suppress SLN and PGC populations so as to select potential agents that target vulnerable stages in the weeds' life cycles.		
Natural enemies associated with SLN and PGC in Australia. This is necessary to identify native and exotic arthropods and pathogens associated with the weeds in Australia and to assess their impact and potential as biocontrol agents.	Conduct fauna surveys throughout the SLN distribution in Australia. Examine the biology, impact and host range of identified organisms.	Conduct fauna surveys throughout the PGC distribution in Australia. Examine the biology, impact and host range of identified organisms.
Natural enemies associated with SLN and PGC in the region(s) of origin. This is critical in identifying the fauna associated with SLN and PGC, particularly in regions of most comparable climates to targeted areas in Australia.	Conduct fauna surveys in the Buenos Aires and Pampa provinces of Argentina and possibly central Chile. Conduct preliminary biology, host range and impact studies in the native range. Re-evaluate biocontrol agent priority list.	Conduct overseas surveys for organisms associated with PGC, targeting the regions of origin of Australian accessions of the weed, with climatic similarity to the Australian distribution. Conduct preliminary biology, host range and impact studies in the native range and propose a biocontrol agent priority list.

Given the biological and ecological similarities between the SLN and PGC and the gaps in knowledge related to biological control, it would be highly feasible and advantageous for the Phase 1 research to be undertaken on these weeds concurrently. The benefits of this would be:

- increased efficiencies in combining research activities, particularly weed and fauna surveys and host specificity testing, resulting in overall savings in research costs,
- provision of adequate information being available on each weed to enable informed decisions to be made during the Phase 1 evaluation stage to determine future investment strategies.

Acknowledgments

We gratefully acknowledge the following people for their contribution to the project or information provided: Mr Eligio Bruzzese, Dr Robin Adair, Dr David McLaren, Mr Tom Morley, Mr Greg Lefoe, Mrs Helen Quinn (Department of Primary Industries Victoria), Dr Rachel McFadyen (Weeds CRC, Australia), Dr Chris Preston (University of Adelaide), Mr Iggy Honan (South Australian Animal and Plant Control Board), Ms Vicki Hawker (Department of Water, Land and Biodiversity Conservation), Dr John Heap (SARDI), Mr Royce Holtkamp (Department of Primary Industries NSW), Dr David Symon (Adelaide Botanic Gardens), Dr John Hoffman (University of Cape Town, Republic of South Africa), Dr Helmuth Zimmermann (Helmuth Zimmermann & Associates, Pretoria,South Africa), Dr Michael Nee (New York Botanical Garden, New York, USA), Dr Melanie Bateman (North Carolina State University, Raleigh, North Carolina), Dr Richard Patrock (University of Texas, Austin, USA), Dr

Carlos Villamil (Universidad del Sur, Bahia Blanca, Argentina), Dr Hernan Norambuena (INIA Carillanca, Chile).

Acronyms and Abbreviations

BCA	Benefit-cost analysis
DPI NSW	Department of Primary Industries New South Wales
DPI Vic	Department of Primary Industries Victoria
GRDC	Grains Research and Development Corporation
PGC	Prairie ground cherry
SARDI	South Australian Research and Development Institute
SLN	Silverleaf nightshade
ha	hectare
WRA	Weed Risk Assessment

1 Introduction

1.1 Background

Silverleaf nightshade, *Solanum elaeagnifolium* Cav. (SLN) is a major agronomic weed in Australia and throughout the world (Parsons and Cuthbertson 2001). The spread of SLN in Australia over the past 20 years has grown five-fold (Greenfield 2003). The spread appears to have increased with the advent of aggressive soil applied herbicides in the 1970s, which reduced competition from annual weeds, and the introduction of reduced tillage practices (Boyd *et al.* 1984). SLN currently infests approximately 104,000 ha in Australia and if left unchecked, it has the potential to increase to 398 million ha (Appendix 1).

SLN has a deep and extensive root system enabling it to compete strongly with other vegetation. Cereal yield reductions of up to 77% have been recorded in South Australia (Heap and Carter 1999), where SLN infests over 40,000 ha in cereal growing areas (Hawker unpublished report). In pastures, SLN competes directly with summer-growing pastures such as lucerne, lowering production and leading to reduced carrying capacity. On average, SLN costs affected farmers $1,730 per year in control costs and $7,786 per year in production losses (McLaren *et al.* 2004). In South Australia alone, SLN has been estimated costing producers more that $10 million per year (I. Honan Pers. comm.).

SLN is difficult to control with herbicides as the deep and extensive root system prevents the effective translocation of herbicides. Cultivation is ineffective as it does not kill the deep roots, and may exacerbate the spread of the weed. Currently, there are no effective and affordable treatments for the control of large, dense infestations.

Prairie ground cherry, *Physalis viscosa* L. (PGC) is a summer growing perennial weed with a deep, extensive root system and horizontal rhizomes (Donaldson 1984). It is conservatively estimated to infest 24,000 ha in Victoria and is well established over large areas of the Goulburn Valley in northern Victoria (Parsons and Cuthbertson 2001). Infestations also occur to a lesser degree in southern New South Wales and South Australia. Climate analysis indicates that PGC is still in the early phases of its invasion process and has the potential to invade up to 409 million ha of Australian agricultural land (Appendix 1).

As with SLN, the extensive root system gives PGC a competitive advantage over other vegetation, enabling the plant to withstand drought, shading and trampling. The roots are capable of regeneration and therefore cultivation contributes to the spread of the weed. Other dispersal mechanisms include stock, birds and vermin, which readily consume the fruit, while fruit and seed may be spread by water (irrigation), vehicles and machinery.

Due to the ineffectiveness and expense of managing SLN and PGC using current control methods, attention is turning towards classical biological control as a means of reducing the impact of existing infestations and suppressing the invasion of these weeds into new areas. However, before embarking on a biological control program the rationale and feasibility of a program in Australia requires assessment.

The rationale for considering the commencement of a biocontrol program is generally based on three criteria: (1) the weed has become widespread and causes significant agricultural and/or environmental damage, (2) ongoing costs of control are high enough to warrant the research effort into biological control, and (3) the weed has no or little economic or social value (ie there is not likely to be a conflict of interest).

The feasibility of a biological control program being successful is assessed on a further two criteria: (1) the potential of finding natural enemies that develop upon and damage only the target weed (ie host specific), and (2) the likelihood of selected agents being able to establish in the introduced range and cause sufficient damage to bring about the desired level of weed suppression.

1.2 Obj ectives

The purpose of this study was to examine the rational for considering biological control and to assess the feasibility of initiating classical biological control programs for PGC and SLN in Australia. These objectives were addressed by:

1) documenting the current and predicting the potential distribution of PGC and SLN and their impact on Australian agricultural industries,
2) reviewing current knowledge about the management of these weeds, the deficiencies in the control technologies available and future research needs, and
3) compiling and analysing information on organisms found to be associated with PCG and SLN, reviewing the success of biological control programs against these weeds elsewhere and the possibilities for biological control in Australia.

1.3 Methods

The project involved a desktop review of relevant literature as well as direct communication with key personnel from Australian and overseas scientific organisations.

The literature review for organisms associated with the plants *Solanum elaeagnifolium* and *Physalis viscosa* was conducted utilising electronic databases (CAB Abstracts (1910-2005) and Agricola (1979-2006)) compiling the scientific literature published in the last 95 years. References obtained were examined for their relevance to this study and organisms found to be associated with these plant species were further checked for their host-range or economic status.

A series of small workshops were held throughout the course of the project to discuss methodologies, key findings, to develop recommendations and to periodically assess the progress of the project.

Authors with specialist expertise were engaged to contribute to various sections of the report. The roles and/or contributions of each author are as follows:

Mrs Raelene Kwong	Project Leader, compilation of final report, report sections on weed biology, control methods, discussion and recommendations.
Mr Jean Louis Sagliocco	Review of organisms associated with SLN and PGC.
Mr Trevor Hunt	Climate analysis mapping.
Mr John Weiss	Weed risk assessment, present and potential weed distribution information and maps.
Dr Tereso Morfe and Mr Dailin Kularatne	Benefit-cost analyses.

2 Silverleaf Nightshade, *Solanum elaeagnifolium* Cav.

2.1 Taxonomy

The scientific name of silverleaf nightshade is *Solanum elaeagnifolium* Cavanilles. During this study the spelling *S. eleagnifolium* has also been encountered in a few cases and when found the published spelling was kept for this report. In Australia the common name for *Solanum elaeagnifolium* is silverleaf nightshade while in the USA, besides silverleaf nightshade, several vernacular names are used: bullnettle, silvernettle, silverleaf-nettle, white horse-nettle, prairie berry, sand briar, tomato weed, tomatillo, trompillo, revienta caballo, meloncillo and meloncillo del campo. In South Africa the plant's common names are silverleaf bitter apple, devilbush or its Afrikaans version satansbos.

The taxonomic position of *Solanum elaeagnifolium* in the plant kingdom is the following:

Kingdom Plantae –Plants

- Subkingdom Tracheobionta – Vascular plants
  - Superdivision Spermatophyta – Seed plants
    - Division Magnoliophyta – Flowering plants
      - Class Magnoliopsida – Dicotyledons
        - Subclass Asteridae
          - Order Solanales
            - Family Solanaceae -- Potato family
              - Genus Solanum L. -- nightshade
                - Species *Solanum elaeagnifolium* Cav. – silverleaf nightshade

Within the family Solanaceae the genus *Solanum* belongs to the sub-family Solanoideae (http://www.mobot.org/MOBOT/Research/APweb/welcome.html) which also includes among other, the genera *Lycianthes*, *Lycium* and *Physalis*. The genus *Solanum* contains about 1,400 species with 117 species present in Australia (Haegi *et al.* 1982). In Australia in the genus *Solanum,* the section *Oliganthes* contains 49 native species and sub-species and the introduced *Solanum elaeagnifolium*, and the section *Melongena* contains 20 native species (Haegi *et al.* 1982).

SLN was described from a cultivated plant grown at Madrid, the seed of which probably originating from Chile (Morton 1976). Morton examined the characteristics of *S. elaeagnifolium* specimens from North and South America populations (Morton 1976). Morton found consistent differences in the pubescence of vegetative parts, especially on peduncles and pedicels. North American plants have generally larger and more entire leaves and more numerous flowers in an inflorescence and the ovary and style are usually more strongly stellate-pubescent, but in Argentine plants are often nearly glabrous. Plants from Argentina and Chile were also found to be more strongly spiny on the stems and leaves. Morton considers *S. elaeagnifolium* in South America as a geographically separated subspecies but has kept Dunal's varietal ranking: *Solanum elaeagnifolium* Cav. var. *leprosum* (Ortega) Dunal. The region of origin of SLN is believed to be Argentina/Chile and perhaps adjacent areas based on the number of close relatives in this region (M. Nee, Solanaceae specialist, New York Botanical Garden, personal communication). The level of morphological variability seems to be higher in the Argentina/Chile region than in the Mexico/USA region, where SLN was probably introduced very early (M. Nee, personal communication).

2.2 Global Distribution

Silverleaf nightshade is native to the Americas, although it is unclear where it originated (http://www.nwcb.wa.gov/weed_info/Written_findings/Solanum_elaeagnifolium.html). It is suggested that the species might have been moved between these continents by Spanish or Portuguese colonisers, however "*from the information available on the distribution of related species, the most likely centre of geographic origin is the southern USA or northern Mexico*" (Boyd *et al.* 1984). This is in contrast to M. Nee's suggestion that SLN's region of origin is Argentina/Chile.

In the USA, SLN is present and invasive at various degrees in thirty-one states, predominantly in the southern states of the USA. SLN is well adapted to semiarid regions with sandy soils and a rainfall comprised between 300 and 600 mm (Boyd *et al.* 1984).

In Argentina, SLN is present in all the provinces north of 41 degrees of latitude (Vigna *et al.* 1981).

Outside of its regions of origin, SLN is established and invasive in Australia, India, Egypt, Israel, Greece, Sicily, Spain, Morocco, Tunisia, Syria, South Africa and Zimbabwe.

2.3 Australian Distribution

In Australia, SLN is a serious weed in New South Wales, South Australia and Victoria (Figure 1). Isolated infestations occur in Queensland, and in Western Australia where it was first recorded in 1950, it is established on more than 50 sites largely between Perth and Albany (Heap and Carter 1999). A 1992 survey indicated that SLN was present over 134,000 ha in New South Wales with dense infestations occuring over 27,000ha (Holtkamp unpublished data). The worst affected areas were in the Murrumbidgee Irrigation area (25,600 ha infested) and the North Western (67,500 ha) and Central West (36,200 ha) areas. In Victoria, SLN was estimated to infest over 145,000 ha in 1980, with the worst affected areas being in the Wimmera, Mallee and North Central regions. In South Australia, it occurs throughout the cereal cropping zones and is causing most concerns in parts of the Upper South East, Mallee and Mid-North and Eastern Eyre Peninsula regions (Heap and Carter 1999).

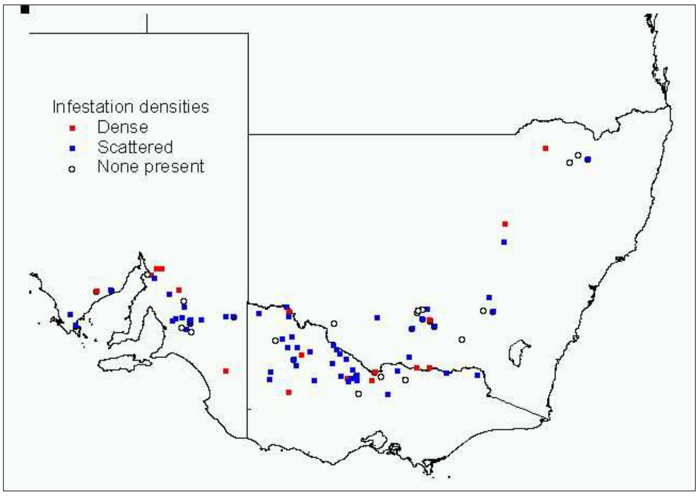


Figure 1. Silverleaf nightshade distribution in southeastern Australia.

2.4 Biolog y

2.4.1 Description

The following description is from Parsons and Cuthbertson (2001).

An erect summer growing perennial herb, to 80cm high, commonly 30 to 45 cm high, reproducing by seed and from roots.

Stem Erect, much branched, densely covered with fine stellate hairs giving a silvery-white appearance, usually armed with numerous slender, yellow to red prickles 2 to 4 mm long.

Leaves Silvery white due to dense covering of stellate hairs, denser on under surface; alternate, lanceolate to oblong, to 15 cm long, usually about 6 to 10 cm, 1 to 2 cm wide, stalked, often with prickles on underside of veins; margins undulate and often scalloped.

Flowers Purple to violet or occasionally white, 3.5 cm diameter; petals 5, fused; anthers 5, prominent, yellow.

Fruit A smooth globular berry, green with dark striations when immature, yellow and orange mottled and becoming wrinkled when ripe; about 1.5 cm diameter; up to 60 per plant.

Seed Light and dark brown, rounded, flattened, 2.5 to 4 mm diameter, smooth, with irregular surface markings, numerous (about 75) in each fruit and surrounded with mucilaginous material.

Root Deep, much branched, vertical and horizontal roots, bearing buds which produce new aerial growth each year.

2.4.2 Habitat

Silverleaf nightshade is adapted to warm-temperate regions and grows well in areas with annual rainfall of 250 to 600 mm (Parsons and Cuthbertson 2001). It is not confined to any particular soil type, although the heaviest infestations occur on sandy soils with low organic matter (Leys and Cuthbertson 1977). In Victoria, SLN grows on the heavy clay soils in the Wimmera and Northern Regions, but appears to prefer the light-textured soils of the Mallee (McKenzie 1980). The largest infestations are found on wheat-growing and grazing land, with smaller infestations being found in irrigated pastures, orchards and vineyards, roadsides, channel banks and stockyards. In its native range, SLN is a problem in areas where the vegetation has been disturbed or removed, such as roadsides, construction sites, overgrazing by livestock and cultivated fields.

2.4.3 Life Cycle

SLN is a summer-growing perennial plant. Seeds germinate in autumn and the young plants produce an extensive root system in the first few months (Parsons and Cuthbertson 2001). Roots can grow over 2 m deep and have been measured to a depth of 4 m in Australia (D. Creeper personal communication cited in Heap and Carter 1999). The root system consists of three main parts: the main or vertical tap root, the portion of the shoot extending from the main tap root to the soil surface, and the lateral roots, which can extend horizontally up to 2 m (Tisdell *et al.* 1961). New shoots are produced from lateral roots each spring from as deep as 50 cm.

In Australia, flowering commences in November and continues through to February or March. Fruit is produced around January and berries ripen and seeds mature about 4-8 weeks after fruit set (Moore *et al*. 1975). Each plant can produce up to 60 berries, each berry containing about 75 seeds. Under favourable conditions, more that 80% of the seeds can germinate (McKenzie 1980). In a dense infestation in northwestern Victoria, over 4,000 seeds per square meter were recorded in the top 10 cm of soil (McKenzie 1980). Seeds are highly viable and can lay dormant in the soil for many years. Most seeds germinate following heavy summer thunderstorms, and survival depends on continued soil moisture during summer (Molnar and McKenzie 1976). Seedlings are able to regenerate following clipping. A study showed that 90% of seedlings recovered when shoots were removed 30 days after emergence (Boyd and Murray 1982b).

Aerial growth dies at the end of summer but the dead stems usually remain standing for several months (Parsons and Cuthbertson 2001).

2.4.4 Dispersal

Seeds are dispersed by water, birds, vehicles, machinery and animal faeces, as well as infested fodder and seed (Parsons and Cuthbertson 2001). When feed is limited, sheep will readily eat the berries and foliage. One study showed that about 10% of the seed fed to sheep were viable after passing through the digestive tract, with most seed being passed within 4 days (McKenzie 1980).

Cultivation is thought to aid in dispersal of SLN as all parts of the root system can regenerate if cut or damaged by cultivation. (Cuthbertson and Leys 1976).

2.5 Economi c Importance

2.5.1 Detrimental Properties

SLN is a highly competitive plant. It competes with crops and pastures, interferes with animal husbandry and harvesting practices, and is an alternative host for pest insect and plant diseases (Heap and Carter 1999). SLN does not severely affect orchards or vineyards, but competes with cover crops grown in these situations (Parsons and Cuthbertson 2001).

i) Impact in crops

SLN competes directly with summer growing crops and reduces production of winter crops such as cereals because of the depletion of nutrients and moisture from the soil in the previous summer (Parsons and Cuthbertson 2001). To obtain the same cereal yield as in unifested crops, extra expenditure on herbicides, cultivation and fertilisers is necessary (McKenzie 1980). In some seasons when SLN produces seeds early, there is a danger that berries may be harvested with the crop. Studies conducted in Victoria in 1977 and 1978 indicated that SLN may reduce wheat yields by up to 50% (McKenzie 1980). Allelopathic effects of SLN have been demonstrated in cotton (Parsons and Cuthbertson 2001).

ii) Impact in pastures

SLN competes strongly with summer-growing pastures such as lucerne. Perennial pastures do not check its growth. In annual pastures, there is evidence of delayed autumn pasture growth and lower pasture production, leading to reduced stock carrying capacity (McKenzie 1980). In dense infestations, SLN may restrict stock gaining access to pasture growing underneath (Heap and Carter 1999). The plant's spiny leaves and course stems may contaminate and lower the quality of hay taken from infested fields (Boyd *et al.* 1984).

SLN is toxic to stock and feeding trials have confirmed that all parts of the plant, particularly the fruit, are toxic. Symptoms of poisoning include salivation, nasal discharge, difficult breathing, bloating, trembling and loose faeces (McKenzie and Douglas 1974). Cattle are more susceptible than sheep, whilst goats appear to be tolerant. Stock losses have been recorded overseas, for example cattle in Texas and horses in Argentina, and are sometimes suspected in Australia (McKenzie 1980).

2.5.2 Beneficial Properties

Plants in the genus *Solanum* contain the glycoalkaloid solasodine, a chemical used in the manufacture of pharmaceutical corticosteroidal hormones (Bradley *et al.* 1978). Research has been underway since the 1950s to determine which *Solanum* species have commercial potential, and over 87 Australian native *Solanum* species have been assayed for their solasodine content (Bradley *et al.* 1978). SLN berries yield 3.2% dry weight solasodine and of 28 *Solanum* species studied, SLN was considered to be the most promising source of the solasodine alkaloid (Chiale *et al.* 1991, Heap and Carter 1999, Maiti and Mathew 1967). Should a pharmochemical industry develop in Australia utilising SLN, potential conflicts of interest may arise if the weed is also the target for biocontrol. In this event, the resolution of a conflict of interest may need to be pursued through the Biological Control Act (Commonwealth of Australia 1984).

It has been observed that SLN survives within areas polluted with heavy metals. Recent research has assessed the potential for using SLN as a bioremediation tool to bind heavy metals in contaminated arid areas (Tiemann *et al.* 2002).

2.5.3 Weed Risk Assessment

An Australia-wide weed risk assessment (WRA) of SLN was conducted as part of this study to determine the relative importance and potential impact of this weed. The WRA used a Decision Support System based on the Analytical Hierarchal Process using multi-criteria methodology. The weed's overall Assessment was based on a combination of its invasiveness and a "ratio" of its present and potential distribution. The full details of this process and the findings of the WRA of SLN is provided in Appendix 1. The major findings of the WRA are summarised as follows:

- SLN was assessed as being a "Highly Invasive" weed, scoring 0.668 out of a maximum score of 1.
- In relation to its impact on agricultural values, SLN was assessed as being of "High Agricultural Impact", scoring 0.538 out of 1.
- The predictive potential distribution of SLN in Australia is 398 million ha (Figure 2), with over 90% of this total susceptible area being grazing land.
- The overall final assessment of SLN is illustrated in the risk matrix below (Table 1). In comparison to six other significant temperate pasture weeds for invasiveness and impact, SLN ranked second. The rank order (from highest to lowest priority) was: (1) serrated tussock, (2) silverleaf nightshade, (3) prairie ground cherry and cape tulip, (4) spear thistle, (5) St John's wort and (6) Bathurst burr.

Table 1. Risk matrix of Weed Impact versus Invasiveness and Potential Distribution for SLN, PGC, Cape tulip, spear thistle, St John's wort and Bathurst burr.

		IMPACT		
		High Impact	Moderate Impact	Low Impact
Invasive Potential & Potential Distribution	V Highly Inv & High Potential	**Level 4**	**Level 3**	Level 2
	High Inv and High Potential	Level 3 **SLN**	Level 2 **PGC** Cape tulip	Level 2 Spear thistle St John's wort
	Mod Inv and Potential	Level 2	Level 2	Level 1 Bathurst burr
	Mod Inv and Low Pot (or vice versa)	Level 2	Level 1	Level 1
	Low Inv and Potential	Level 1	Level 1	Level 1

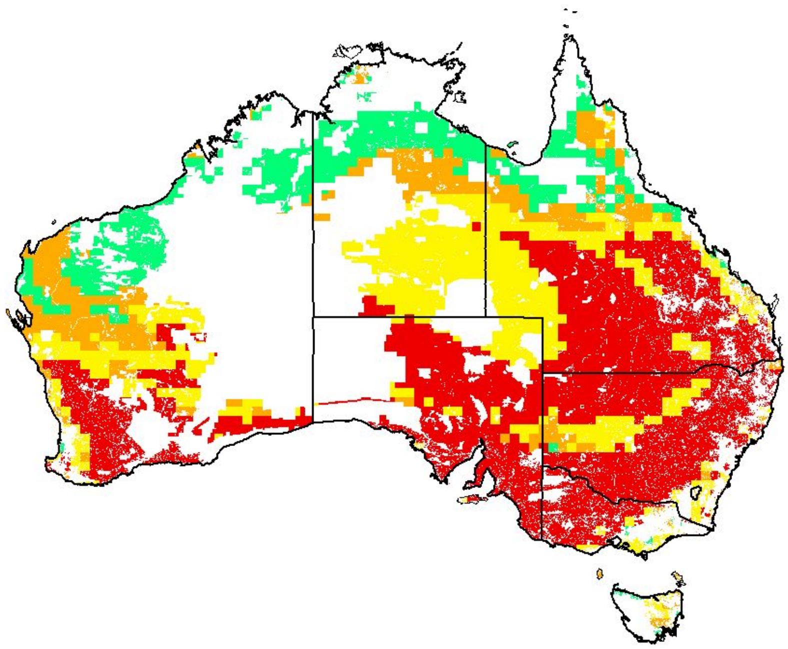


Figure 2. Potential distribution of silverleaf nightshade in Australia. Areas in red indicate a very high probability that Silverleaf nightshade could establish in suitable vegetation and landuse within this region, yellow a high and orange a medium probability of establishment.

2.6 Current Control Methods

Silverleaf nightshade is one of the most difficult weeds to control requiring repeated application of herbicides. Picloram + 2,4-D amine, 2,4-D ester, Bromacil and glyphosate are the commonly used herbicides. Mechanical control such as slashing achieves only short-term control.

2.6.1 Herbicides

Considerable research into herbicide control of SLN has been conducted in many countries since the 1930s, and Heap and Carter (1999) provide an overview of past research. Some herbicides are effective against seedlings and as spot-spray treatments for isolated plants, but as yet, no effective and affordable treatments for the control of large infestations are available.

The extensive and deep root system makes SLN a difficult weed to control by herbicides. Richardson and McKenzie (1981) note that a herbicide that is easily absorbed and very effectively translocated is required to kill the whole root system. The three most significant herbicides arising to date are 2,4-D, picloram and glyphosate, however none of these are selective and some are persistent in the soil.

Picloram is most commonly used to treat small infestations because it remains active in the spoil for several years and is moved down the soil profile with wetting fronts. It is often used in a mixture with 2,4-D, which gives rapid control of shoot growth and residual control of regrowth. Field experiments suggested that picloram/2,4-D was effective but one application of herbicide, even at a very high rate, was not sufficient to eradicate colonies, and that successive applications were required to kill the root system. Picloram is not suitable for treating large areas due to cost and the detrimental effect on following broad-leaf crop and pasture species (Heap and Carter 1999).

Ester or amine formulations of 2,4-D are used to suppress shoot growth and to reduce flowering and seed set in large SLN infestations but it does not affect the perennial roots. McKenzie (1980) recommended that 2,4-D ester be applied 2 to 4 times during the 6-month growing season. He also noted that the combination of slashing or cultivation with 2,4-D did not improve the level of control.

Glyphosate gives variable control, and its efficacy is probably determined by factors such as drought stress, dustiness of leaves and air humidity (Heap and Carter 1999). McKenzie (1980) noted that glyphosate, although initially promising, failed to control plants under dryland Mallee conditions, with plants recovering and setting seed in the same season. Lemerle (1982) found that glyphosate applied with a rope wick wiper was equally effective as boom-spray applications, while in Texas, the use of a rope-wick applicator in cotton gave over 95% control (Abernathy and Keeling 1979). The use of a rope-wick applicator enables herbicides to be applied selectively to weeds that are taller than the crop or meadow and may provide cheaper control of SLN in the long term (Smith and Faithfull 1998).

In glasshouse trials conducted in South Australia, the major factor influencing glyphosate absorption and translocation to the roots was found to be season (Greenfield 2003). Plants sprayed in October and November 2002 absorbed up to 58% and translocated 50% of the absorbed herbicide to the roots. Plants treated in December and January had the lowest absorption (10–40%) and translocation (0-10%) rates, while glyphosate sprayed in February recorded absorption of 70% and translocation of 60% of the herbicide. In the same project, drought stress did not affect absorption nor the subsequent translocation compared to well-watered plants. In a further experiment, the application of 2,4-D to plants before treating with glyphosate did not affect absorption of glyphosate but significantly reduced the amount of glyphosate translocated to the root system. The addition of an organosilicate penetrant (Freeway™) did not affect the absorption or translocation rates of glyphosate. Greenfield (2003) notes that further studies under field conditions would be required to confirm her initial conclusions that glyphosate applied at the wrong time of year or in conjunction with 2,4-D would give poorer translocation of the herbicide to the roots.

Other herbicides listed by Heap and Carter (1999) with reported efficacy against SLN include bromacil, clopyralid, ethidimuron, fluoroxypyr, hexazinone, imazapyr, karbutilate, tebuthiuron and terbacil.

2.6.2 Cultivation and slashing

Cultivation is reported to be ineffective in Australia because most of the roots are below the depth of cultivation and new plants may re-shoot from severed fragments. However, under dry conditions, deep cultivation may reduce but not eradicate an infestation (Parsons and Cuthbertson 2001).

Cultivation every 3-5 weeks was required to obtain acceptable control, however this frequency of cultivation is expensive and damaging to the soil structure. Cultivation increases shoot density, as the wounded roots produce multiple shoots. Slashing was proven in trials to be ineffective as the SLN plants recovered rapidly and still produced flowers even when the plants were slashed every 2-3 weeks (Heap and Carter 1999). The combination of slashing or cultivation and herbicide application did not improve control above the level of 2,4-D or picloram/2,4-D treatments alone (McKenzie 1980).

2.6.3 Other control measures

Crop competition is largely ineffective against SLN. Davis *et al.* (1945) showed that shading by cotton crops contributed to the success of SLN control when used in conjunction with repeated cultivation, however shade alone was ineffective. In South Africa in regions of sufficient summer rainfall, dense crops were able to effectively suppress SLN (Wassermann *et al.* 1988). Boyd and Murray (1982a) showed that shade levels between 63% and 92% are needed to prevent seed production. In a further trial in South Africa, Viljoen and Wassermann (2004) studied the suppression of SLN in cultivated pastures under dry-land conditions over a four-year period. They concluded that under conditions of limited soil moisture, oats and lucerne provided no suppressive effect, while smuts finger grass (*Digitaria eriantha*) was effective in reducing SLN shoot density and biomass.

A 3-year study has recently been conducted in South Australia to determine the efficacy of grazing, alone and in conjunction with herbicides in controlling SLN (Hawker unpublished report). Sub-lethal doses of 2,4-D amine were applied to make the weed more palatable, and livestock were introduced at relatively high stocking rates for short durations to maximise grazing pressure and minimise paddock degradation. The preliminary results obtained after one year of the trial indicated that both grazing and spray grazing reduced the size and number of SLN shoots as well as suppressing flowering and seed set. Plants recovered slightly following rain after livestock were removed, however reduction in shoot density and suppression of seed set were maintained. The statistical analysis of data collected over the 3-year period had yet to be analysed and thus could not be included in this report. However, if this trial proves that repeated defoliation of SLN plants depletes the extensive root reserves, grazing and spray grazing may provide landholders with an affordable control method.

2.7 Silverleaf Nightshade National Workshop

A national workshop was held in Adelaide, 19th June 2002 jointly funded by the South Australian Animal and Plant Control Commission and GRDC (Anon, 2002). The aims of the workshop were to bring researchers and effected landholders together to determine the current status and management of the weed and to identify gaps and priorities for research. Twenty-two participants from three states attended the workshop, including weed researchers, landholders, extension workers, authorised weed officers, policy makers and the CRC for Weed Management.

2.7.1 Priorities for Further Action

The workshop conducted a gap analysis to identify priorities for further research and action (Appendix 2). Possible actions were listed within four broad areas of Biological Control, Herbicide Control, Containment or Eradication and Integrated Weed Management. Table 2 summarises the priority actions and the progress achieved towards addressing these actions, since the National Workshop.

In addition to the activities summarised in Table 2, other research conducted in Australia since 2002 are summarised in Table 3.

Table 3. SLN research conducted in Australia since 2002.

Topic	Research activity
Understanding herbicide behaviour in SLN	• One-year, greenhouse study conducted in 2003 by the University of Adelaide (Greenfield 2003) investigated the fate of glyphosate and its behaviour in SLN. The project studies herbicide absorption and translocation through the roots and the effect of environmental stress of herbicide behaviour. These studies need to be repeated under field conditions.
SLN dispersal mechanisms	• 2005/06 study of dispersal mechanisms of SLN based on genetic analysis of populations at a local (paddock) and regional scale. (University of Adelaide). This study will provide an indication of the relative importance of dispersal mechanisms within and between sites.
SLN management through grazing	• A 3-year study established in South Australia in 2002 conducted to determine the efficacy of grazing alone or in conjunction with herbicides in controlling SLN. Trial results are currently being analysed.

2.8 Victorian Farmer Experiences with Silverleaf Nightshade Management

A workshop facilitated by the DPI-Victoria was conducted on 6 August 2003 in Bendigo, Victoria. The 'Integrated Management of Silverleaf Nightshade' workshop, which involved farmers from central and northern Victoria, developed what they considered the best management practices for the (1) eradication of small SLN infestations, and (2) containment of widespread SLN infestations.

A summary of best practice management options is provided in Appendix 3, as is a summary of research priorities identified by workshop participants.

Table 2. Progress against priority actions identified from the National SLN Workshop.

Priority Actions	Activity since 2002	Further work required
1. Biological control		
• Determine whether the beetle *Leptinotarsa texana* attacks eggplant in South Africa.	• The University of Cape Town, South Africa was contracted to undertake field studies to determine if *L. texana* would attack eggplant and African native solanums. Due to technical difficulties experienced during the trials, the study did not yield any conclusive results.	• This study needs to be repeated to adequately assess the risk of *L. texana* to eggplant.
• Conduct host specificity testing of Australian native Solanum spp. and Australian biotypes of silverleaf nightshade in South Africa	• The host specificity testing of native Solanum species and Australian biotypes of SLN has not been conducted.	• It is unlikely that permits for the importation of Australian plants species into South Africa will be obtained, hence if such testing were to proceed, it would need to be done under quarantine conditions in Australia.
2. Herbicide control		
• Enhance herbicide translocation in the root system	• Preliminary glasshouse studies conducted at the University of Adelaide (Greenfield 2003) to understand glyphosate absorption and translocation in the roots.	• Field trials required to confirm results. No studies have yet determined methods for improving herbicide translocation.
• Conduct trials on Graslan® with a view to obtaining registration or an off-label use permit as a spot treatment.	• Trials conducted in South Australia with results indicating an excess of 6-year residual effect in the soil.	• Registration of Graslan for SLN is unlikely to be pursued.
3. Containment or eradication?		
• Risk assessment of not doing anything to control the weed	• A risk assessment of the impact of SLN compared to other noxious weeds was conducted for Victoria as part of the Victorian pest plant prioritisation process. • The benefit:cost analysis conducted as part of the feasibility of biocontrol of SLN and PGC report includes the potential costs to industry if biological control is not implemented.	• More accurate information is required on weed distribution, densities and impact (control costs and lost production). The current assessment of SLN impact is highly underestimated.
• Education and publicity program to raise awareness of silverleaf nightshade.	• A farmer workshop was held in Victoria in 2003 to develop best practice management options for SLN. • Extension programs continue in Vic, SA, and NSW.	• Results of the farmer workshop need to be tested and promoted through the establishment of SLN best practice management demonstration plots.
4. Integrated weed management		
• Documenting the true costs and potential costs of the weed.	• Mail surveys conducted with 254 land managers across Vic, SA and NSW to determine the distribution, economic impact and attitudes towards SLN (McLaren *et al.* 2004)	• Surveys to determine the impact of SLN on production.
• Produce a best-practice control guide.	• No guide has been produced.	

3 Feasibility of Biological Control of Silverleaf Nightshade

3.1 History of surveys for natural enemies of silverleaf nightshade

The use of natural enemies to control the invasive SLN has been considered for some time, and since the 1960s, several surveys have been conducted to identify the arthropod fauna associated with SLN populations in the Americas. Although surveys for natural enemies of the invasive SLN have involved American (Goeden 1971) or Australian scientists (Wapshere 1988), South Africa is the only country which has surveyed, imported, tested and released biological control agents on *Solanum* weeds (Olckers 1996a). The results of the surveys conducted in the different regions have been published: USA (Goeden 1971), Mexico (Wapshere 1988), Argentina (Olckers *et al.* 2002; Zimmermann 1974) and are summarised in Appendix 4. Several organisms identified in these surveys are either generalist or polyphagous, or listed as pests of economic importance. As such, we did not consider these organisms as having potential as biological control agents and were subsequently not listed in this report.

3.2 Analysis of potential agents for biological control of SLN

3.2.1 Natural enemies associated with SLN in the regions of origin

The study assessed a total of 30 organisms, (1 fungus, 1 nematode, 3 mites and 25 insect species). Each species was assessed for its potential as a biocontrol agent based on three criteria: (1) its known host range, (2) the nature and level of impact on SLN and (3) the likelihood of the organism becoming established in targeted areas of Australia. A summary of each organism and its potential for the biological control of SLN is provided in Table 4.

1. Host range. As there are many Australian native and economically important plant species closely related to SLN, a high degree of host specificity is of upmost importance in considering the potential of organisms for biocontrol. Of the 30 listed organisms, 11 were ranked as having no biocontrol potential because of their known broad host range (Table 4).

2. Damage and potential impact on SLN. Organisms that cause repeated defoliation or reduced the vigour of SLN plants were considered promising agents, although the potential of these organisms to cause significant impact if released into Australia was impossible to predict. Disappointingly, no organisms were found in the literature to attack the SLN root system. Those organisms causing cosmetic or minimal damage were considered a low priority. Of the 30 listed organisms, a further 9 species were ranked as having **Low** potential because their impact on SLN was considered to be minor.

3. Likelihood of agent establishing in Australia. Theoretically, the better adapted a biological control agent is to its new environment the more abundant and potentially damaging it will become. Organisms from similar climates and the same variety or subspecies of plant are thus more likely to be pre-adapted to conditions in the introduced environment.

In this study, a climate analysis of the southern Australian distributions of SLN compared with climates within the native ranges of the weed indicated that the most comparable climates were in the central regions of Argentina and Chile (Figure 3).

Many of the previous surveys for potential SLN biocontrol agents concentrated in central and southern USA, where the greatest diversity of herbivorous insects was found to exist on SLN. Wapshere (1988) summised on the basis of greatest arthropod diversity, that the Monterrey region in central Mexico was the centre of origin and evolution of SLN. However, Monterrey has a tropical climate with summer rains and therefore its climate is very different from the climate in regions of southern Australia affected by SLN (Figure 4).

Wapshere concluded that the summer drought conditions occurring throughout the Adelaide, Swan Hill and the Leeton regions of South Australia, Victoria and New South Wales (Figure 5) respectively would make these locations unlikely to support agents from the Monterrey region.

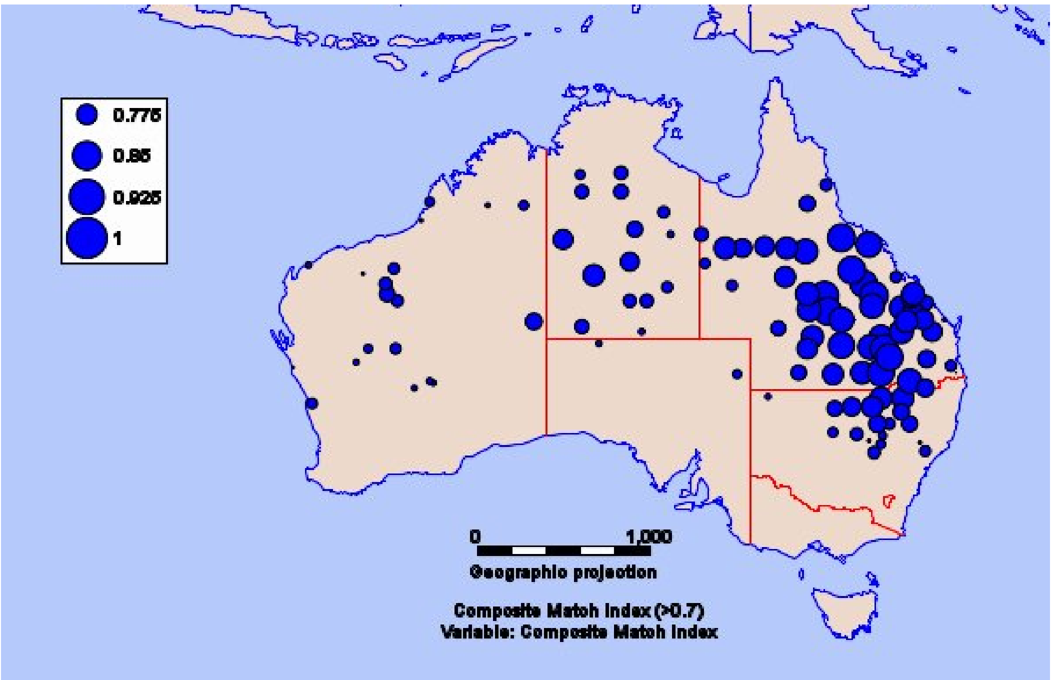
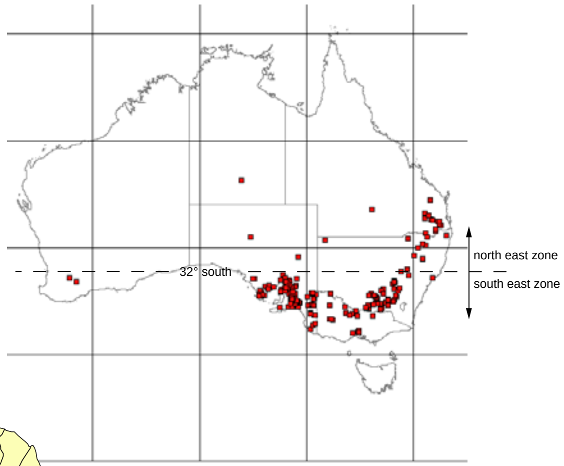


Figure 4. Locations in Australia matching Monterrey (Mexico) climate (Matching Index 0.7)

The map (right) shows silverleaf nightshade locations in Australia used for climate match predictions. Due to the broad distribution of SLN and the variation in climate across this range, it was decided to refine the climate match predictions by separating the Australian locations into two zones (north east and south east).



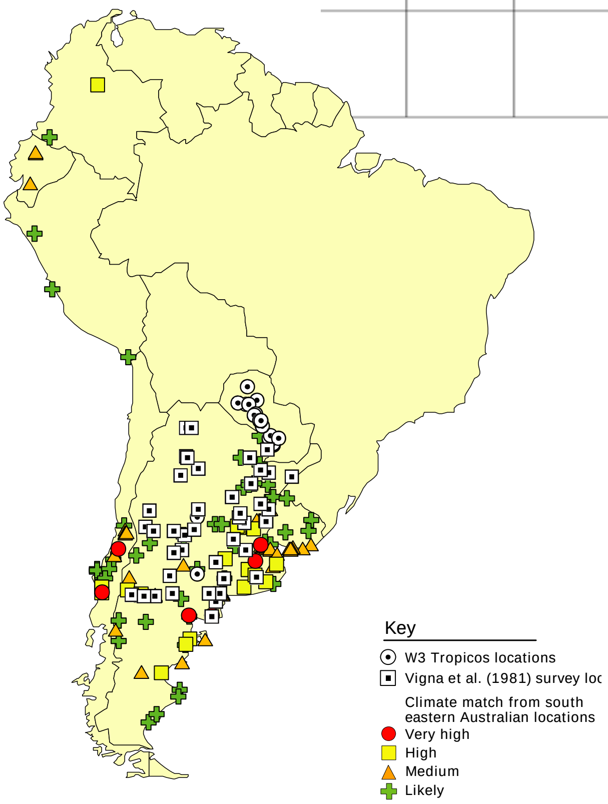


Figure 3. Climate match predicition of SLN infestations in southeastern Australia to South America, overlayed with known SLN locations in Argentina. CLIMATE software was used to generate climate predictions. The closed circles indicate locations with a very high climate match comparable to SLN locations in southeastern Australia (occurring south of 32^{O}). Data source for SLN locations (W3 Tropicos) from http://mobot.mobot.org/W3T/Search/vast.html

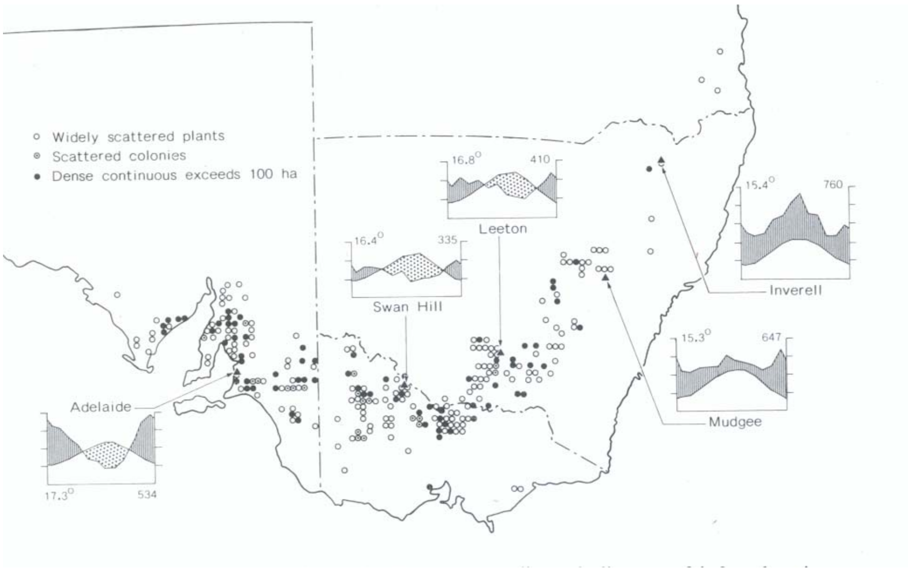


Figure 5. Climatic charts of the main regions infested by SLN in eastern Australia (reproduced from Wapshere 1988).

The influence of climate and other environmental factors varies amongst organisms, and examples exist where biocontrol agents from dissimilar climates have established and become effective agents. Hence in this study, organisms from dissimilar climates (eg Mexico, Texas, Arizona) were given lower priority than species from more comparable climates (Argentina).

In Argentina, populations of SLN have been identified between 41° and 23° latitude South (Vigna *et al.* 1981) while in Chile SLN is distributed between 18° and 34° latitude South (H. Norambuena, personal communication) and possibly even further north in regions with marked summer drought. Specialist opinion indicates that South America and not Mexico is the suitable region to investigate for natural enemies of SLN. On the basis of the number of close relative species in this region, it seems probable that SLN originates from Argentina and Chile (M. Nee, Solanaceae specialist, New York Botanical Garden, personal communication). In regard to the confirmation of the origin of SLN, this important question can only be answered by studying populations of different origins (Argentina, Chile, Mexico, USA and Australia) to determine their genetic similarities and to identify the origin of the species and the source(s) of introduction in Australia. In terms of climate, the regions in South America comprised between 30° and 45° of latitude are more similar to Victoria and South Australia than any other region in the SLN native range.

During surveys for natural enemies of cactus weeds, Zimmermann surveyed SLN populations in the northern half of Argentina (north of 32° latitude). However, Zimmermann did not survey the Buenos Aires and Pampa provinces more climatically suitable to southern Australia (Figure 3) and where SLN populations have been identified (Vigna *et al.* 1981).

Of the 11 species from Argentina that were assessed in this report, little information was available on the biology, host range and impact of these organisms, making it difficult to adequately assess their biological control potential. Organisms associated with SLN in Argentina with some potential for biological control in Australia are the gelichiid moth *Symmetrischema ardeola* and *Gnorimoschema* sp. The larvae of *S. ardeola* feed on flower buds, stamens and pistils and thus can greatly limit seed production. Preliminary tests in Argentina suggest that this insect might be specific to SLN. There is little information on *Gnorimoschema* sp. who cause stem galls on SLN, and therefore this species requires taxonomic and biology investigations and impact evaluation.

Because SLN populations were surveyed only in certain regions in Argentina and no survey occurred in Chile, it can be considered that a knowledge gap still exists on SLN and its associated fauna. These regions are of major interest for Australia in terms of climate similarities and possible origins of the weed.

In South Africa, a number of candidate biological control agents were rejected on the basis of damage to eggplant and native African *Solanum* species during choice tests in cage conditions, including the two leaf beetles *L. texana* and *L. defecta*. A comprehensive risk assessment process was used to re-evaluate the risks posed by these insects. This risk assessment concluded that the effective risks posed to eggplant cultivations were minimal and mitigated by the existing cultural and insecticidal control measures. This process led to the release of *L. texana* and *L. defecta* in South Africa in 1992. Both insects have established with *L. texana* populations having increased more than those of *L. defecta*. The impact of *L. texana* on SLN is substantial (Hoffman *et al.* 1998) to such extent that, in the summer rainfall infestations many farmers and landholders do not see SLN as a real problem any longer (John Hoffmann, pers. comm. 2006). Despite the lack of quantitative data to support this, it appears that the beetles impact negatively on the regenerative capacity of the plants, possibly due to the insect attack on the aerial parts depleting root reserves. Unfortunately, the lack of funds did not allow scientists to quantify the impact of the beetles on the root reserves and the regenerative potential of the weed.

The *L. texana* population introduced into South Africa was collected in the Monterrey region, characterised by the occurrence of a summer rainfall period. In South Africa *L. texana* has successfully contributed to SLN control in regions with the same rainfall pattern, chiefly in the Pretoria area. It is not known if *L. texana* populations have dispersed outside of the Monterrey region and adapted to winter rainfall regions such as California. In any case the host-specificity of the insect, especially regarding potential damage to eggplant, would remain the major obstacle for its release in Australia.

The gall-forming moths of the genus *Frumenta* (Gelechiidae) were the only agents that proved host specific to SLN in quarantine tests in South Africa (Olkers *et al.* 1999). *Frumenta nephelomicta* Meyrick was observed by Zimmermann (1974) to destroy a high proportion of SLN fruit in Mexico. However females lay eggs on the litter around plants and this characteristic seems to limit the species performance and potential. The impact of *F. nephelomicta* on SLN in South Africa has been greatly affected by native parasitoids limiting its populations (Olckers 1995). Two related species, *Frumenta* (Sp. A) from Texas and *F. solanophaga* from Mexico also appear to have good potential to limit production of fruits and seeds. Ultimately, climatic considerations remain the major obstacle against the use of agents from the Monterrey region in Mexico, as establishment in Australia might be impossible.

Fungi All surveys for natural enemies of SLN have targeted arthropods and none have specifically identified fungal pathogens of substantial importance to the plant. From the available literature and databases, a number of non-specific fungi were recorded as being known from SLN, most of them having an extended host-range. The only fungus with a relatively limited host-range identified during this study was *Pseudocercospora atromarginalis* (Atk.) Deighton (Dothideomycetidae: Mycosphaerellaceae) causing leaf-spot symptoms. The host-plants of this fungus include *Solanum elaeagnifolium*, *S. biflorum*, *S. carolinense*, *S. gracile*, *S. nigrum*, *Solanum* spp., *Capsicum* sp.

(Appendix 4.3). Due to its host-range outside of SLN this agent cannot be seen as having any potential for the biological control of silverleaf nightshade.

As the literature revealed little information on the fungal pathogens of SLN, surveys for fungi in the native range of SLN are appropriate to identify pathogens with potential for the biological control of SLN in Australia.

3.2.2 Fauna associated with SLN in Australia

The invertebrate and pathogen fauna (native and exotic) associated with SLN in Australia is poorly understood. As such we were unable to discuss the impact of these organisms on SLN populations in Australia and assess their potential for biological control. Reports of native organisms attacking SLN in Victoria and New South Wales have been made as well as reports of viruses suppressing flowering (Heap and Carter 1999). Apparent insect-feeding on SLN roots in South Australia has also been reported (Heap and Carter 1999) and to our knowledge, no additional information has been published confirming the identity of this insect. It is important to mention that surveys in Australia on the introduced *Solanum chenopodioides* Lam. and *S. physalifolium* Rusby var. *nitidibaccatum* (Bitter) Edmonds led to the discovery of three new species of native *Asphondylia* spp. from five native *Solanum* species (Kolesik *et al.* 2000).

3.3 Benefit-Cost Analysis of a biological control program for SLN

A standard benefit-cost analysis (BCA) was conducted to estimate the impact of a hypothetical biological control program against SLN to Australian agricultural industries (mainly cropping and grazing).

This analysis examined the benefits and costs that may accrue to graziers and growers, due to the reduced need for current control technology for SLN, with biological control. The net economic benefit was calculated by comparing the benefits and costs of the current control technology with the benefits and costs associated with the development and implementation of biological control, estimated to cost a total of $4.97 million over a 15 year period. The benefits estimated were limited to agriculture alone, and was based on the expected control cost savings to grazing and cropping industries following the release of biological control agents in three states (Victoria, New South Wales and South Australia). A full report providing details on the methodology, results and conclusions is provided in Appendix 5.

Positive returns on investment were estimated at all discount rates applied (8, 10, & 12%) with close to $140 million savings in future control costs over a 30-year period and a benefit cost ratio of $58.60 to one dollar investment, at 10% discount rate. During the first seven years from the commencement of a biological control program, no positive benefits would accrue due to the additional costs of the research program to industry, and the absence of any measurable benefits resulting from the project (Figure 6.). However by the eighth year, positive benefits would commence and continue to accrue exponentially as the biological control agents dispersed across the range of the weed.

Sensitivity analysis of results was performed to address uncertainties about the data and assumptions applied in the study. The parameters tested included probability of success of the research program, discount rate and the adoption rate of the technology.

The BCA did not include lost production costs caused by SLN, therefore it underestimates the full costs of SLN to the agricultural industries. Nevertheless, the overall findings indicate that the proposed research investment in the biological control program for SLN is economically viable. Based on proportion of future costs to graziers and growers, at least 80% of the expected benefits is likely to be captured by grazing industries in Victoria, New South Wales and South Australia.

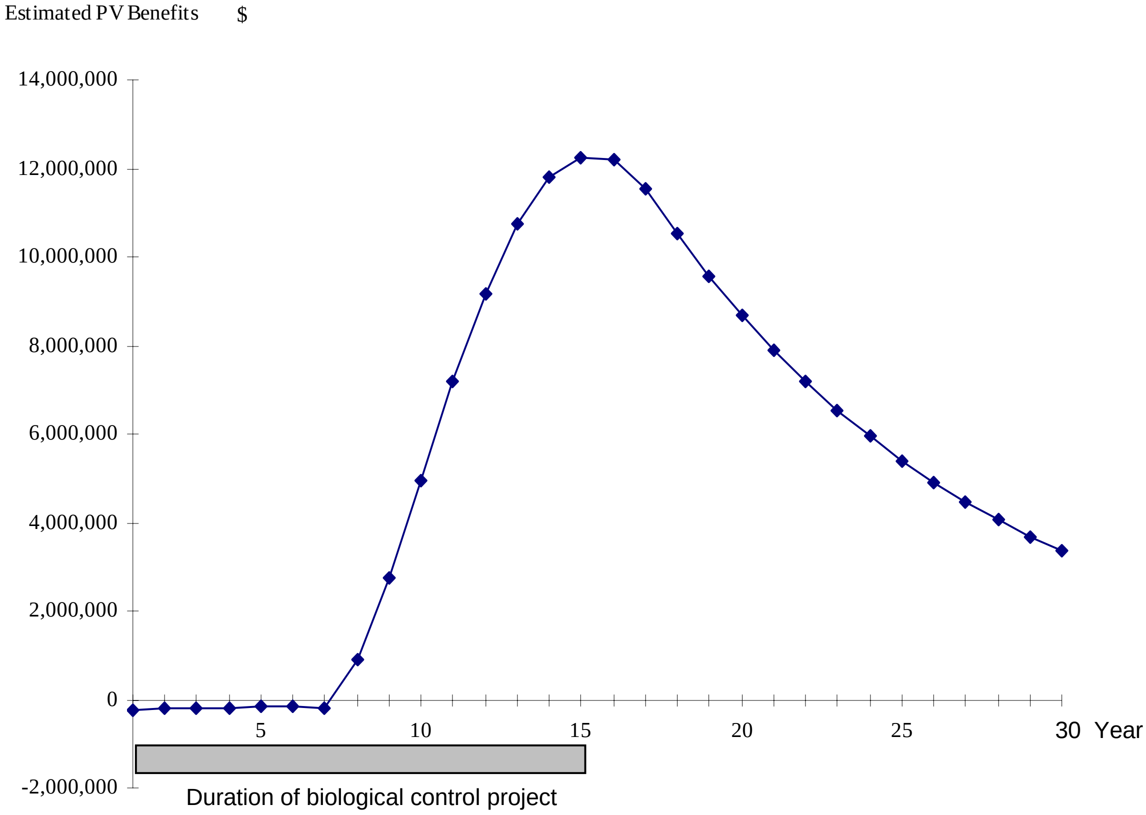


Figure 6. Estimated distribution of present value of benefits of biological control of SLN over a 30-year period, based on a 15-year biological control program costing $4.97 million.

Table 4. Organisms associated with silverleaf nightshade and their biological control potential.

Order Family Species	Host-plants	Plant association	Host range	Distribution	Status as potential as biocontrol agent	Potential for biocontrol in Australia
Ascomycetes, Dothideomycetidae, Mycosphaerellales, Mycosphaerellaceae						
Pseudocercospora atromarginalis (Atk.) Deighton	*Solanum elaeagnifolium, S. biflorum, S. carolinense, S. gracile, S. nigrum, Solanum spp., Capsicum sp.*	Leafspot disease	Wide host range	Florida, Brazil, Venezuela, Asia, New Zealand (Subtropical and tropical regions)	Due to its host-range outside of SLN this pathogen cannot be seen as having any potential for the biological control of silverleaf nightshade.	None
Nematoda Tylenchida: Anguinidae						
Ditylenchus phyllobius (Thorne) Filipjev	*Solanum elaeagnifolium*	leaf galling nematode	*S. elaeagnifolium, S. viarum*, *S. tampicense*	Mexico, Texas, Arizona	Attacked eggplant and 13 Australian native *Solanum* species in host specificity tests. Rejected as potential agent for introduction in Australia.	None
Acarina Eriophyidae						
Getrapodili sp.	*Solanum elaeagnifolium*?	leaf galls	unknown	Argentina	Little information on biology, host range and impact.	Low-Medium
Aceria bicornis Trotter *(=Eriophyes bicornis)*	*Solanum elaeagnifolium*	leaves erinea	possibly restricted to SLN	Argentina	Little information on biology, host range and impact.	Low-Medium
Eriophyes ? sp.	*Solanum elaeagnifolium*	deformed leaves	possibly restricted to SLN	Argentina	Little information on biology, host range and impact.	Low-Medium
Hemiptera Cicadellidae						
Tapajosa rubromarginata (Signoret)	*Solanum elaeagnifolium*?	leaves	Generalist pest	Argentina	None (a pest of sugar cane, *Saccharum officinale*)	None

Table 4. Organisms associated with silverleaf nightshade and their biological control potential (cont'd).

Order Family Species	Host-plants	Plant association	Host range	Distribution	Status as potential as biocontrol agent	Potential for biocontrol in Australia
Hemiptera Tingidae						
Gargaphia arizonica Drake and Carvalho	*Solanum elaeagnifolium*	leaves, cell sucking	*S. elaeagnifolium* only host known	Mexico	Little biological data. Host specificity unknown, but suspected to be restricted to SLN. Climatic adaptability may be an issue.	Medium
Hemiptera Pentatomidae						
Arvelius albopunctatus (De Geer)	*Solanum elaeagnifolium*	Fruits and seeds	Polyphagous within *Solanum*	Texas	Rejected – not host specific, attacks cultivated Solanaceae and soybeans.	None
Arvelius albopunctatus (De Geer)	*Solanum elaeagnifolium*	Fruits and seeds	Polyphagous within *Solanum*	Mexico		
Arvelius albopunctatus (De Geer)	*Solanum elaeagnifolium*	Fruits and seeds	Polyphagous within *Solanum*	Argentina		
Lepidoptera Gelechiidae						
Frumenta nephelomicta Meyrick as *Asapharca nephelomicta* Meyrick	*Solanum elaeagnifolium*	fruits and seeds larval feeding	*S. elaeagnifolium* only host known	Mexico, Central and North America	High percentage (up to 100%) of berries destroyed by larvae but high parasitism also occurs. Climatic adaptability may be an issue, should be considered.	Medium

Table 4. Organisms associated with silverleaf nightshade and their biological control potential (cont'd).

Order Family Species	**Host-plants**	**Plant association**	**Host range**	**Distribution**	**Status as potential as biocontrol agent**	**Potential for biocontrol in Australia**
Frumenta (Sp.A)	*Solanum elaeagnifolium*	fruits and seeds	*S. elaeagnifolium*	Texas	Host specific, but releases in South Africa failed to establish, probably due to parasitism. No further releases made due to success of *L. texana*, negating the need for fruit-feeding agents. Climatic adaptability may be an issue.	Medium
Frumenta solanophaga Adamski and Brown	*Solanum elaeagnifolium*	fruits and seeds	*S. elaeagnifolium* only host known	Mexico	Little biological data known, may be host specific. Climatic adaptability may be an issue, parasitism and climatic adaptation might be limiting factors, should be considered.	Medium
Symmetrischema ardeola (Meyr)	*Solanum elaeagnifolium*	flowers and flower buds, stamens and pistils	*S. elaeagnifolium*	Argentina (Tucuman)	Tests in Argentina showed no attack of crops. Considered as potential agent for South Africa but was not introduced. Good potential to limit fruit formation. Should be considered.	Medium-High
Keiferia glochinella (Zell.)	*Solanum melongena, S. elaeagnifolium*	leaf miner	Egg-plant (*S. melongena*)	California	Pest of eggplant.	None

Table 4. Organisms associated with silverleaf nightshade and their biological control potential (cont'd).

Order Family Species	**Host-plants**	**Plant association**	**Host range**	**Distribution**	**Status as potential as biocontrol agent**	**Potential for biocontrol in Australia**
Keiferia sp.	*Solanum elaeagnifolium*?	leaf miner	unknown	Argentina	Relatively abundant in host range. Impact possibly low.	Low
Gnorimoschema sp.	*Solanum elaeagnifolium*?	stem galls	unknown	Argentina	Little information on biology, host range and impact, does not appear to have economic importance, investigation on taxonomy required.	Medium
Lepidoptera Carposinidae						
unidentified species	*Solanum eleagnifolium*	fruits and seeds	unknown	USA (Texas, Arizona)	No information on biology, host range and impact, probably *Frumenta* (Sp.A) (Olckers 1995).	Unknown
Coleoptera Nitidulidae						
Carpophilus sp.	*Solanum elaeagnifolium*	flowers and flower buds	*S. elaeagnifolium*	Argentina	Tests in Argentina showed no attack on crops. However, its impact on SLN fruit production is considered low.	Low-Medium

Table 4. Organisms associated with silverleaf nightshade and their biological control potential (cont'd).

Order Family Species	Host-plants	Plant association	Host range	Distribution	Status as potential as biocontrol agent	Potential for biocontrol in Australia
Coleoptera Chrysomelidae						
Gratiana pallidula (Boh.)	*Solanum elaeagnifolium*	leaves, defoliator	*Solanum* spp.	Mexico, USA	Attacks eggplant.	None
Gratiana lutescens (Boh.)	*Solanum elaeagnifolium*	leaves, petioles and flower buds	*S. elaeagnifolium* and possibly *S. melongena*	Argentina	Attacks eggplant.	None
Leptinotarsa defecta Stahl	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium* and *S. dimidatium*	Mexico, Texas, Florida	Attacks eggplant. Released in South Africa but establishment low. May not be climatically suited to Australian SLN distribution.	Low
Leptinotarsa texana (Schaeffer)	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium*, possibly *S. rostratum*	Mexico, Texas	Introduced in South Africa ex Texas in 1992. Established and reaches damaging populations. May not be climatically suited to Australian SLN distribution. Threat to eggplant and other native Solanaceae needs to be determined.	Low
Metriona elatior (Klug)	*S. elaeagnifolium, S. sisymbriifolium, S. aculeatissimum*	Leaves, defoliator	also *Ipomea batatas* (Convolvulaceae)	Uruguay	Not specific to SLN.	None

Table 4. Organisms associated with silverleaf nightshade and their biological control potential (cont'd).

Order Family Species	Host-plants	Plant association	Host range	Distribution	Status as potential as biocontrol agent	Potential for biocontrol in Australia
Coleoptera Curculionidae						
Anthonomus aeneolus Dietz (= *Anthonomus brevirostris* Linell)	*Solanum elaeagnifolium*	flower buds or as inquiline in galls of *N. phyllobia*	*S. elaeagnifolium*	USA	Are associated with the galls caused by *N. phyllobia*, rather than with SLN.	None
Trichobaris texana LeConte	*Solanum elaeagnifolium*	stems, borer	*S. elaeagnifolium* and three closely related *Solanum* spp.	Mexico, Texas	Has narrow host range in *Solanum*. Introduced to South Africa but did not survive in quarantine. Does not cause significant damage to SLN in Mexico.	None
Conotrachelus bisignatus Boh.	*Solanum elaeagnifolium*	fruits, seeds	*S. elaeagnifolium*, *S. hyeronimii*	Argentina	Non specific.	None
Diptera Cecidomyiidae						
Asphondylia sp.	*Solanum eleagnifolium*	flowers, galls	unknown	USA (Texas)	No information on biology, host range and impact. Climate adaptability may be an issue.	Low
unknown species gall midge	*Solanum eleagnifolium*	stem galls	unknown	Mexico (Monterrey)	No information on biology, host range and impact. Climate adaptability may be an issue.	Low
Unnamed gall midge species	*Solanum elaeagnifolium*	Stems, distortion by galling	***S. elaeagnifolium***	Mexico	No information on biology, host range and impact. May be host specific. Climate adaptability may be an issue.	Low

Table 4. Organisms associated with silverleaf nightshade and their biological control potential (cont'd).

Order Family Species	**Host-plants**	**Plant association**	**Host range**	**Distribution**	**Status as potential as biocontrol agent**	**Potential for biocontrol in Australia**
Diptera Agromyzidae						
Haplomyza sp.	*Solanum elaeagnifolium*	leaves	unknown	Argentina	No information on biology, host range and impact.	Low at this stage
Diptera Tephritidae						
Zonosemata vittigera (Coquillett)	*Solanum elaeagnifolium*	fruits and seeds	*S. elaeagnifolium*	Texas, New Mexico, California, Arizona	Apparently host specific but seems to cause little seed damage.	Low

3.4 Discussio n

Through the analysis of previous SLN fauna surveys, it appears that very few of the organisms identified would be worth considering as potential agents for the biocontrol of SLN in Australia. Two major factors (host specificity and climate) have contributed to our assessment of the biological control potential of the organisms identified in the literature. A third factor (origins of SLN) further limits our ability to adequately assess these organisms.

Host specificity. The major factor limiting the selection of potential agents is the apparent oligophagous habit (lack of specificity to SLN) of many of the species. This problem is compounded by the large number of agronomic crops in the Solanaceae family cultivated in Australia, two of which (potato and eggplant) also belong to the genus *Solanum.* In addition, there are 117 *Solanum* species indigenous to Australia, with 49 native species belonging to the *Oliganthes* section, of which *Solanum elaeagnifolium* belongs.

Previous attempts at the biological control of SLN in Australia during the 1980s were hampered by the lack of specificity of the potential agent. The leaf-galling nematode, *Ditylenchus phyllobius* (= *Orrina phyllobia*), during host specificity tests attacked eggplant and 13 of the 15 Australian native species tested, demonstrating that the host range of the nematode was larger than initially thought (Field unpublished results). Due to the risk posed to native Australian *Solanum* species, the nematode was considered unsuitable for release.

Early attempts to initiate a biological control program against SLN in South Africa in the 1970s were also hampered by insufficient host specificity of potential agents. Almost all of the agents tested displayed expanded host ranges under confined experimental conditions, feeding on closely related *Solanum* species that were never reported to be attacked under natural conditions (Neser *et al.* 1990; Olkers and Zimmermann 1991; Olkers 1996). It was concluded that under the confined conditions of host-specificity tests in quarantine, very few solanaceous insects were likely to demonstrate their actual host specificity (Olkers *et al.* 1999). Hence, through a risk assessment process, the two leaf-feeding beetles *L. texana* and *L. defecta* were released based on the argument that under field conditions, the risks of these insects to eggplant and native *Solanum* species were minimal and tolerable.

The difficulties experienced by earlier attempts to initiate a biological control program for SLN in Australia and South Africa suggest that a renewed attempt at biological control may also be difficult. However, many of these earlier problems can possibly be overcome. For instance, the conduction of host specificity tests in quarantine should be avoided if possible, as these artificial environmental conditions may overestimate the true host range of the agent, resulting in potentially good agents being rejected on false results. Instead, testing should be done under natural field conditions, possibly in Argentina or Chile.

Climate. The second major factor limiting the identification of potential agents was based on climatic factors. As discussed in the Section 2.9.2, organisms originating from climatic regions dissimilar to southern Australia were given a low priority ranking, based on the assumption that these organisms would be less climatically adapted to Australian environments where SLN currently occurs. However, no surveys on the fauna associated with SLN have previously been conducted in the regions of more comparable climate to the Australian distribution of the weed.

Origins of SLN populations in Australia compared with the native range. SLN is native to the Americas, with geographically separate distributions occurring in southwestern/central America and South America (Argentina/Chile). Despite morphological differences existing in SLN populations between these two ranges, little information is available on the taxonomic relationships and genetic variation within and between these populations. Nor do we know from where, Australian populations of SLN originated from and the degree of genetic variation within Australian SLN populations. Mismatches between biotypes of the host plant in the native range and the target weed in the introduced range can affect the establishment success or effectiveness of biocontrol agents. Hence, an understanding of the origins of Australian SLN populations is critical to future research into the biological control of SLN, as it will assist in prioritising SLN populations from which potential biocontrol agents might be sourced from in the native range.

The *ex-ante* benefit-cost analysis estimated a BCA ratio of 59:1, indicating that a successful biological control program would result in significant savings ($140 million) to Australian agricultural industries. While these figures are highly favourable and suggest that an investment in biological control may be warranted, they need to be treated with some caution. Due to the many technical uncertainties identified through this feasibility study, we are unable to accurately assess the probability of a biological program against SLN being successful. As such, a benefit-cost analysis should be repeated once further studies have identified the likelihood of finding host-specific and damaging agents.

3.5 Recom mendations

To further our knowledge on the potential for biological control of SLN, we recommend that the first phase of a research program be conducted to address key knowledge gaps. The following research is required:

1. Undertake surveys throughout the distribution range in Australia to:
   a) obtain precise information on the weed's distribution and density,
   b) identify the arthropods, fungi and viruses associated with SLN to assess their impact and potential as biocontrol agents, and
   c) collect plant specimens that will be used in studies utilising molecular techniques to compare SLN populations in Australia with populations from the Americas and identify the origin of SLN present in Australia.
2. Conduct overseas surveys in the regions of comparable climates (Buenos Aires and Pampa provinces of Argentina and possibly central Chile) to identify potential biocontrol agents for targeted regions of Australia.
3. Conduct field impact studies and preliminary host testing in the native range to determine the potential of these organisms for further investigation.

Once these key knowledge gaps have been addressed, a re-evaluation of the feasibility of biological control combined with a more refined economic analysis, should be conducted to assist in determining future investment in biological control of SLN.

4 Prairi e Ground Cherry, *Physalis viscosa* L.

4.1 Taxonom y

The scientific name of prairie ground cherry (PGC) is *Physalis viscosa* L. (= *Physalis fuscomaculata* de Rouv. ex Dunal). In Australia the common name for *Physalis viscosa* is prairie ground cherry (PGC) but other names also used are tomato weed, sticky physalis, grape groundcherry, groundcherry and starhair groundcherry. In the flora of Australia sticky cape gooseberry, sticky ground cherry are the vernacular names used (Haegi *et al.* 1982).

The taxonomic position of *Physalis viscosa* L. in the plant kingdom is the following:

Kingdom Plantae –Plants

Subkingdom Tracheobionta – Vascular plants

Superdivision Spermatophyta – Seed plants

Division Magnoliophyta – Flowering plants

Class Magnoliopsida – Dicotyledons

Subclass Asteridae

Order Solanales

Family Solanaceae -- nightshades

Genus *Physalis* L. – ground cherry, groundcherry

Species *Physalis viscosa* L. – (=*Physalis curassavica* L.,
P. fuscomaculata Dunal)

In Australia eight species of *Physalis* are known to occur (Haegi *et al.* 1982): *P. lanceifolia* Nees (from USA and Mexico), *P. ixocarpa* Brot. Ex Hornem., *P. minima* L. (considered native to Australia but from tropical America, Asia and Africa), *P. philadelphica* Lam. (possibly from northern America), *P. peruviana* L. (from Peru), *P. pubescens* L. (from India), *P. virginiana* Miller (from Mexico) and *P. viscosa* L. whose type specimen described by Linné was from Virginia, USA. Some *Physalis* species also occur in temperate and tropical Asia (Haegi *et al.* 1982). According to Symon, *P. viscosa* populations present in Australia are native to North and South America (Symon 1986). Parsons and Cuthbertson (Parsons and Cuthbertson 1992) also give North and South America as the origins of the weed but they also state that, due to the confused taxonomy, it is difficult to know to which species the literature refer to.

The genus *Physalis* L. is mostly an American genus, characterised by pendent flowers and an inflated fruiting calyx enclosing the berry. The genus *Physalis*, is one of the largest in the Solanaceae, containing about 90 species (Sullivan 1985) or about 75 species, primarily in the Neotropics (Sullivan 2004). The North American *Physalis* species were studied by Rydberg (1896), Small (1933) and Waterfall (1958) while Menzel studied the cytotaxonomy and genetics of *Physalis* (Menzel 1951; Menzel 1957). In Central America, the *Physalis* species have been reviewed by Waterfall who lists 32 species present including *P. viscosa* var. cinerascens (Dunal), *P. viscosa* var. spathulaefolia (Torr.) and *P. viscosa* var. *sinuatodentata* Schledhtendal, all species present in Mexico (Waterfall 1967).

The genus *Physalis* contains 18 species and four varieties in the south-eastern USA (Sullivan 2004). Sullivan revised the North American species of the *Physalis viscosa* complex (Sullivan 1984) based on the results of phenetic analysis involving thirty-three different morphological characters and results of foliar flavonoids analysis from 92 populations from south-eastern and south-central USA and Mexico. Sullivan refers to the species *P. viscosa* as a complex of species (Sullivan 1985) and states that *P. viscosa* sensu stricto is a South American taxon (Sullivan 1985). Sullivan clarified the taxonomic position of the species of the *P. viscosa* complex as described by Waterfall, and re-assigned their position. This clearly shows that specimens from the USA previously identified as *P. viscosa* (subspecies, forms and varieties) now belong to, either *P. cinarescens*, *P. walteri* or *P. viscosa*.

The taxonomy of the genus *Physalis* was further clarified in a recent study by Whitson and Manos (2005). The study aimed to verify if the definition of the sections within the genus *Physalis* were congruent with DNA data, and concluded that the genus contained between 75-90 species, most of which occurred in Mexico.

4.2 Global Distribution

Although some websites in the USA see PGC as native to North America, the species originates from South America (Sullivan 1985). According to information provided by USDA Plants Database, in USA *P. viscosa* is present in Texas, Mississipi and Alabama (Figure 7). It is however difficult to know if this information refers to introduced populations or to specimens belonging to other *Physalis* taxa, not yet revised according to the latest taxonomic literature.

In South America *P. viscosa* distribution includes Bolivia (Cochabamba, Santa Cruz and Tarija regions), Argentina (Buenos Aires, Catamarca, Chaco, Cordoba, Corrientes, Entre Rios, Jujuy, La Pampa, Mendoza, Salta, Santa Fe, Santiago del Estero, Tucuman regions) and Paraguay (Alto Parana, Boqueron, Central, Cordillera, Paraguari, Presidente Hayes regions) (Anon. 2005a).

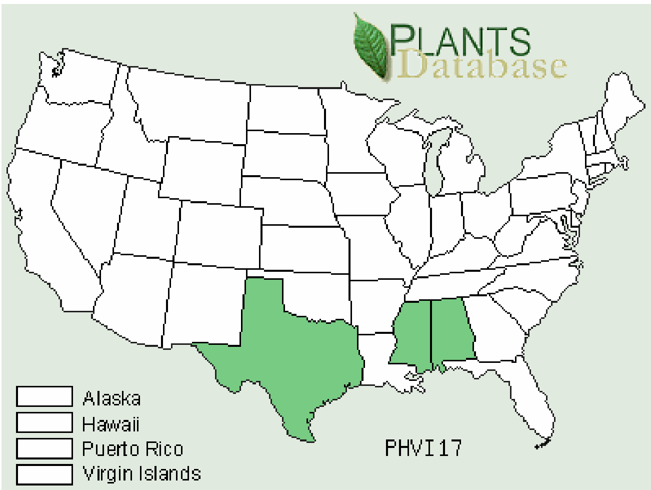


Figure 7. Distribution of the introduced *Physalis viscosa* L. in the USA (Source USDA, http://www.plants.usda.gov/java/profile?symbol=PHVI17)

4.3 Aus tralian Distribution

Prairie ground cherry occurs to a limited extent in all states except the Northern Territory and Tasmania but is particularly troublesome in Victoria and parts of southern New South Wales (Harden 1992, Jessop and Toelken 1986, Parsons and Cuthbertson 1992). In Victoria, significant infestations occur throughout the Goulburn Valley irrigation area, Bacchus Marsh, Geelong and the eastern Mallee. In 1964, PGC was estimated to occur to some level over 24,000 ha in Victoria. A more recent survey conducted in 2003 revealed that of 72 landholders surveyed in Victoria, over 12,300 ha were infested with PGC.

4.4 Biolog y

4.4.1 Description

The following description is from Parsons and Cuthbertson (2001).

An erect perennial herb, 25-60 cm high, reproducing from creeping roots and by seed.

Stems Branched, spreading, longitudinally ribbed, with very short hairs.

Leaves Light green, alternate but with upper leaves often in opposite pairs, almost glabrous but with short hairs on margins and veins, to 6 cm long, margins undulate.

Flowers Yellow, bell-shaped, 2 to 3 cm diameter; calyx 10-angled;petals 5, fused; produced on stalks in axils of upper leaves.

Fruit An orange-coloured globular berry when ripe, 1 to 1.5 cm diameter, sticky, enclosed in a bladder-like case about 2 to 2.5 cm diameter.

Seed Yellow or light brown, numerous, almost round but more or less kidney shaped, flat, about 2 mm long, sticky.

Root Deep and extensive with some horizontal roots close to the surface from which buds produce new aerial growth each year.

4.4.2 Habitat

Prairie ground cherry is adapted to warm-temperate regions, growing mostly on clay or loam soils. In southern Australia it is a summer-growing plant of open grazing land occurring mostly in areas receiving 300 to 500 mm annual rainfall (Parsons and Cuthbertson 2001).

4.4.3 Life Cycle

Seeds germinate in spring and small plants develop an extensive root system over summer. The aerial growth dies back in autumn without flowering, but roots remain alive producing new shoots the following spring. The plant then flowers and fruits during summer and the cycle is repeated annually.

4.4.4 Dispersal

Prairie ground cherry is dispersed by cultivation. Root fragments longer than 1.5 cm are capable of producing new plants, with the regenerative capacity increasing the longer and thicker the root fragments are (Faulkner 2005).

The palatable fruit of PGC, which is readily eaten by stock, foxes and birds, which enables the weed to be spread over long distances. The fruit is enclosed in a bladder enabling it to be dispersed effectively by wind and water. Hence, the weed is often spread along irrigation channels. The distribution of hay cut from infested areas is also an important means of dispersal (Parsons and Cuthbertson 2001).

4.5 Economi c Importance

4.5.1 Detrimental Properties

Prairie ground cherry has a deep (up to 1 metre) and extensive root system enabling it to compete with other vegetation, particularly summer crops, for moisture and nutrients. Once the plants mature and become well established they are hardy and can withstand drought, shading and trampling, but do not persist under constant irrigation (Parsons and Cuthbertson 2001).

In cropping situations, yield reductions of 100% have been recorded where infestations are dense (Anon 2003). Farmers report that PGC is a problem in lucerne crops because it smothers plants and spot spraying is difficult and time consuming. Farmers also complain that they are forced to cut hay early before PGC sets seed, as seeds can contaminate late cut hay.

PGC foliage is suspected of being poisonous however there have been no confirmed accounts of stock toxicity resulting from PGC consumption. Sheep avoid eating the foliage, but readily eat the ripe fruit without ill effect.

Seeds from ingested fruit are highly viable once passed in dung, therefore they must be placed in holding paddocks before being moved to uninfested paddocks. This is costly to farmers in terms of time and effort.

4.5.2 Beneficial properties

The only useful property of PGC is that its fruit are sometimes used for jam making and cooking, hence potential conflicts of interest are unlikely to occur should PGC be targeted for biological control.

4.5.3 Weed Risk Assessment

A WRA was conducted for PGC using the process described in Section 2.5.3 and Appendix 1. The major findings of the assessment are summarised as follows:

- PGC was assessed as being a “Highly invasive” weed, scoring 0.726 out of a maximum score of 1.
- In relation to its impact on agricultural values, PGC was assessed as being of “Medium-High Agricultural Impact”, scoring 0.474 out of 1.

- The predictive potential distribution of PGC in Australia is 409 million ha (Figure 8), with over 90% of this total susceptible area being grazing land.
- The overall final assessment of PGC in comparison to six other significant pasture weeds for invasiveness and impact is demonstrated in Table 1 (see Section 2.5.3).

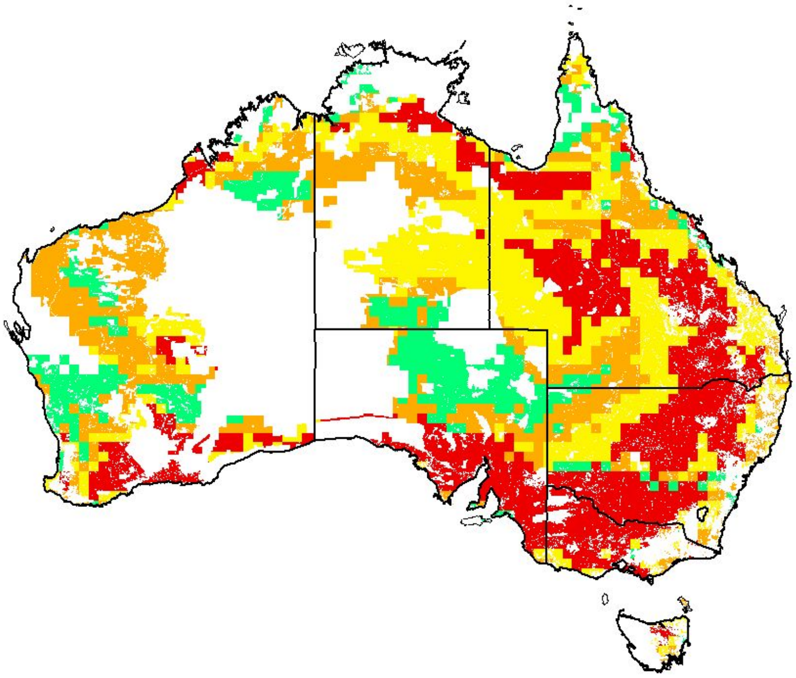


Figure 8. Potential distribution of Prairie ground cherry in Australia.
Areas in red indicate a very high probability that Prairie ground cherry could establish in suitable vegetation and landuse within this region, yellow a high and orange a medium probability of establishment.

4.6 Current Control Methods

4.6.1 Herbicides

Chemical control of PGC is very effective. At least four herbicides, amitrole T, picloram, glyphosate and cloropyralid, give a high level of control with one treatment when applied in the flowering and fruiting stage. Donaldson (1984) noted that although these treatments were an effective means of treating small infestations, however over large areas, their use is not economical.

Pritchard (2004) evaluated boom-spray applications of Roundup Power Max^{TM} (glyphosate), Starane^{TM} (fluroxypyr) and Tordon 75-D^{TM} (picloram plus 2,4-D amine) for the control of PGC in cereal fallow. When applied (4 L per ha rate) during the peak PGC flowering period (December), Roundup Power Max provided a 90.2-95.2% reduction in shoot density when assessed eleven months after application (Figure 9). There was no effect of rate with Roundup Power Max ™, the 4 L per ha rate giving results equivalent to that obtained with 8 L per ha. Addition of the adjuvant Hasten™ (ethylated canola oil plus non-ionic surfactants) did not improve the result with Roundup Power Max ™ at 5 L per ha. Application of Roundup Power Max ™ at 5 L per ha in January reduced shoot density by 97.9%, a slightly better result than the same rate applied in December. Starane™ at 1.5 L and 3 L per ha gave poor control, reductions in shoot density relative to untreated plots being 26.2–48.6%. Control with Starane ™ at 1.5 L per ha was not improved by the addition of Uptake ™ (paraffinic oil plus non-ionic surfactant) spraying oil at 0.5% nor by adding Amicide 500 ™ (2,4-D amine) at 2 L per ha.. Tordon 75-D ™ at label rate of 7.5 L per ha gave excellent control, reducing shoot densities by 99.8%.

Figure 9 Effect of boom-spray application of Roundup Power Max ™ (glyphosate) at 6 L per ha, on prairie ground cheery 3 weeks after application. Photo taken on 13 January 2004 at Quambatook, Victoria by G. Pritchard.

4.6.2 Cultivation and Slashing

Normal cultivation is not very effective at controlling PGC as it is not deep enough to damage the whole root system. In market gardens, repeated cultivation has been an effective means of control in some areas (Parsons and Cuthbertson 2001) However, cultivation is also an effective way of spreading the weed and therefore cultivation needs to be managed correctly if to be effective.

4.6.3 Other Control Measures

The suppression of PGC through competition is effective if vigorous summer-growing species can be established. A thick stand of lucerne has been found to be the most effective competitor in non-irrigated areas, while under irrigation, a much more competitive pasture of either lucerne or white clover can be established which will almost eliminate PGC (Parsons and Cuthbertson 2001).

4.7 Victorian Farmer Experiences with PGC Management

An 'Integrated Management of Prairie Ground Cherry" workshop, facilitated by the Victorian Department of Primary Industries was conducted on 31 July 2003 at Tatura, Victoria. The aims of the workshop were to bring together Victorian farmers affected by the weed and to gather their experiences in dealing with PGC control. This information was distilled into a series of Integrated Weed Management Plans providing real-life examples of the management of PGC on an organic farm (ie no chemical use), and for the management of scattered and widespread infestations (Moerkerk and Snell 2003).

A summary of best practice management options is provided in Appendix 6, as is a summary of research priorities identified by workshop participants.

5 Feasibility of Biological Control of Prairie Ground Cherry

5.1 Arthropod s

As it is common in this kind of study, it is likely that not all information on the fauna associated with PGC was accessible to the authors. Reference books on insect faunas for Central and South American countries may contain valuable information on arthropods associated with PGC but such reference books are only accessible by visiting the libraries where they are held, and by systematically examining such literature.

Surveys for natural enemies of PGC have never previously been undertaken, as this weed has never been the subject for biocontrol elsewhere in the world. There are records of acari (mites) collected on *P. viscosa* during routine surveys in Florida (Dr M. C. Thomas, Head Curator, Florida State Collections, Division of Plant Industry, Gainesville, Florida, pers. comm., Appendix 4.2). These unidentified mites were causing moderate to severe damage to PGC leaves. There is no indication on these mites being further collected at a later date, or of their formal identification at the species level. There is also the question relative to the identification of the *Physalis viscosa* plants on which they were collected, in regard with the recent revision of the *P. viscosa* complex.

The larvae of the moth *Heliothis subflexa* (Guenée) are known to feed on the fruits of *Physalis* species (C. Blanco, USDA-ARS, Stoneville, Mississipi, pers. observ. and pers. comm. and M. Bateman, University of North Carolina, Raleigh, pers. observ. and pers. comm.). *Heliothis* is a cosmopolitan genus containing about 40 species with a cosmopolitan distribution, and its members are generally polyphagous (Mitter *et al.* 1993). Among them, *Heliothis virescens* is a complex of species, including the tobacco budworm. The existence of two sibling species in North America was established in 1941, *H. virescens* and *H. sublexa*, and a recent revision documented the 13 species in the *virescens* species group (Poole *et al.* 1993). *H. subflexa* is an occasional pest of ornamental ground cherries and tomatillo, *Physalis philadelphica* Lam., an edible annual species cultivated in Mexico and California. *H. subflexa* host-plants appears to be restricted to Solanaceae (Mitter *et al.* 1993). Scientists are currently studying *H. sublexa* host-range that could be restricted to *Physalis* species (A. Groot, North Carolina State University, pers. comm. and M. Bateman, University of North Carolina, Raleigh, pers. observ. and pers. comm.).

The fauna associated with PGC in Australia is mostly unknown except for the leaf beetle *Lema trilineata* (three-line potato beetle) being reported to inflict noticeable damage to *P. viscosa* in Victoria in 1994 (I. Faithfull, pers. comm.). The larvae were observed stripping plants bare of leaves but leaving the fruit, and moving in fronts to eventually clear a whole hillside of foliage in a large infestation in the Katamatite area of central Victoria (Faithfull 2000). The beetle was first found in Queensland in the 1970s, and not much is known about the range of *Solanum* species attacked (native and introduced), except that it has also been reported to attack cape gooseberry*, Physalis peruviana* L.. Experience to date indicates that attacks by this insect on PGC in Victoria are sporadic and have had little effect on the extent and severity of infestations. The beetle also damages valued plants of other *Solanum* species (Faithfull 2000).

5.2 Fungi

A relatively large number of non-specific fungi are known from PGC, most of them having an extended host-range (Farr 2006). The white smut *Entyloma australe* (Speg.) (Ustilaginomycetes: Entylomataceae) is recorded to cause leaf and stem damage to *P. viscosa* but also to *Lycopersicon* sp., *Solanum* spp. and *Quincula lobata*. The fungus is widespread (North America; Central America & West Indies; South America; Africa; Asia; Australia; New Zealand) and due to its host-range do not appear as having any potential for the biological control of PGC. No other fungal pathogen was identified in the literature as having a host-range restricted to PGC or to *Physalis* species.

5.3 Benefit-Cost Analysis of a biological control program for PGC

A standard benefit-cost analysis (BCA) was conducted to estimate the impact of a hypothetical biological control program against PGC to Australian agricultural industries (mainly cropping and grazing).

This analysis examined the benefits of biological control of PGC compared with the costs of a reduced dependence on current methods of control. The net economic benefit was calculated by comparing the benefits and costs of the current control technology with the benefits and costs associated with the development and implementation of biological control, estimated to cost a total of $2.6 million over a 12 year period. The benefits estimated were limited to agriculture alone, and was based on the expected control cost savings to grazing and cropping industries following the release of biological control agents in three states (Victoria, New South Wales and South Australia). A full report providing details on the methodology, results and conclusions is provided in Appendix 7.

Positive returns on investment were estimated at all discount rates applied (8, 10, & 12%) with close to $38 million savings in future control costs over a 30-year period and a benefit cost ratio of $26.30 to one dollar investment, at 10% discount rate. During the first seven years from the commencement of a biological control program, no positive benefits would accrue due to the additional costs of the research program to industry, and the absence of any measurable benefits resulting from the project (Figure 10.). However by the eighth year, positive benefits would commence and continue to accrue exponentially as the biological control agents dispersed across the range of the weed.

Sensitivity analysis of results was performed to address uncertainties about the data and assumptions applied in the study. The parameters tested included probability of success of the research program, discount rate and the adoption rate of the technology.

The BCA did not include lost production costs caused by PGC, therfore it underestimates the full costs of PGC to the agricultural industries. Nevertheless, the overall findings indicate that the proposed research investment in the biological control program for PGC is economically viable.

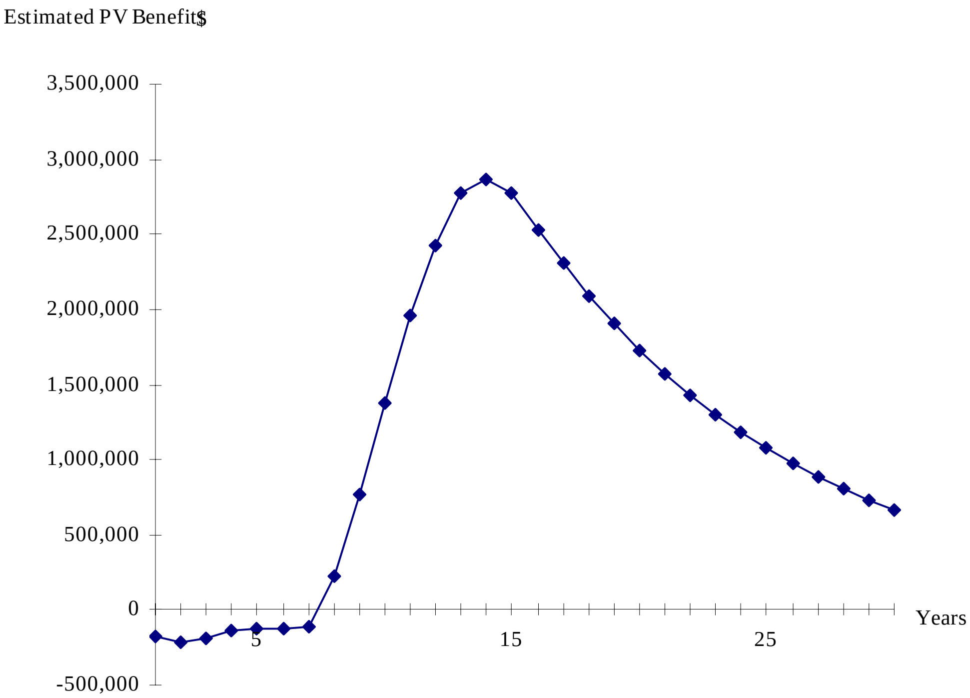


Figure 10. Estimated distribution of present value of benefits of biological control of SLN over a 30-year period, based on a 12-year biological control program costing $2.6 million.

5.4 Discussio n

Since the 1980s, the taxonomy of the *P. viscosa* complex in the USA has been clarified. It has been confirmed that the previously known *P. viscosa* subspecies, varieties and forms, now belong to *P. cinarescens* or *P. walteri* and that the *P. viscosa* populations present in the USA originate from Mexico and South America. The populations of *P. viscosa* present in Australia appear to originate from South America (D. Symon, Adelaide Herbarium, pers. comm.).

No survey has previously been conducted on the natural enemies associated with PGC. A number of generalist fungi have *Physalis* spp among their hosts. The only insect recorded in the literature as being associated with *Physalis* species is the moth *H. subflexa*, whose host-plants and potential needs to be understood. As a general consideration, there is a need to examine the American literature not accessible in Australia, to gather information on potential agents on PGC. If such agents have already been identified they would likely belong to the major orders of insects known to impact on SLN.

Surveys in the Americas are required to determine the guild of organisms associated with PGC. Without this information, we are unable to adequately assess the feasibility of biocontrol of this weed. Initially, these surveys should concentrate in regions of comparable climate to Australian PGC locations. An analysis of climate similarities between PGC locations in Australia and South America (using CLIMATE) indicated that these regions would be the La Pampa province (near Viedma and San Antonio Oeste) of Argentina and in the Araucania region of Chile (around Temuco and Valdivia) (Figure 11). When these climate similarities are overlayed with locations of PGC in South America, it appears that there are no closely matched climates (Figure 11), however it is likely that the full distribution of PGC is under-represented as very little data was available from the sources accessible by us.

The *ex-ante* benefit-cost analysis estimated a BCA ratio of 26.3:1, indicating that a successful biological control program would result in significant savings ($38 million) to Australian agricultural industries. While these figures are highly favourable and suggest that an investment in biological control may be warranted, they need to be treated with some caution. Due to the many technical uncertainties identified through this feasibility study, we are unable to accurately assess the probability of a biological program against PGC being successful. As such, a benefit-cost analysis should be repeated once further studies have identified the likelihood of finding host-specific and damaging agents.

5.5 Recom mendations

Whilst we may be able to argue that the biological control of PCG is desirable, we are unable to assess the feasibility or likelihood of a successful outcome of the biological control of PGC in Australia. This is because:

1. biological control of PCG has not been conducted in other parts of the world, therefore we are unable to extrapolate the success of other programs to determine its potential for Australian situations, and

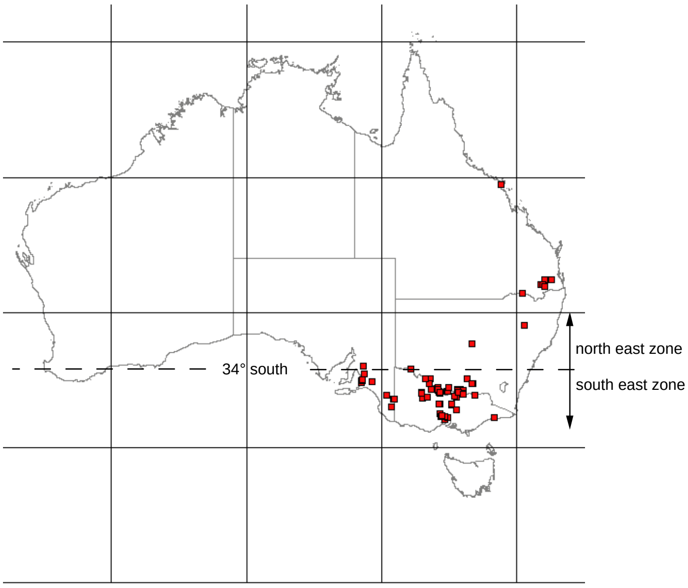
2. no survey has been conducted in the native range of PCG (South America), therefore little is known about the guild of organisms associated with the *P. viscosa* complex, except for the leaf-feeding Chrysomelid beetle, *Lema trilineata* L.. As such, we are unable to assess what organisms may have potential as biocontrol agents for Australia.

To better assess the feasibility of biocontrol, we need to fill key gaps in knowledge related to the taxonomic status of PCG in Australia, centres of origin and natural enemy associations of PCG in its native range. As such, we recommend the following:

1. Undertake surveys throughout the distribution range in Australia to:
   a) obtain precise information on the weed’s distribution and density,
   b) identify the arthropods, fungi and viruses associated with PCG and whether they are native or exotic, and
   c) collect PGC plant specimens for identification using classical taxonomy or molecular techniques.

2. Determine the precise origin(s) of Australian populations of PGC using classical and/or molecular taxonomy by comparing Australian populations with those from the Americas.
3. Review the literature in the Americas for natural enemies in the region(s) of origin of *P. viscosa.*
4. Conduct overseas surveys for organisms associated with PGC, targeting the regions of origin of Australian accessions of the weed, with climatic similarity to the Australian distribution.

The map (right) shows prairie ground cherry locations in Australia used for climate match predictions. Due to the broad distribution of PGC and the variation in climate across this range, it was decided to refine the climate match predictions by separating the Australian locations into two zones (north east and south east).



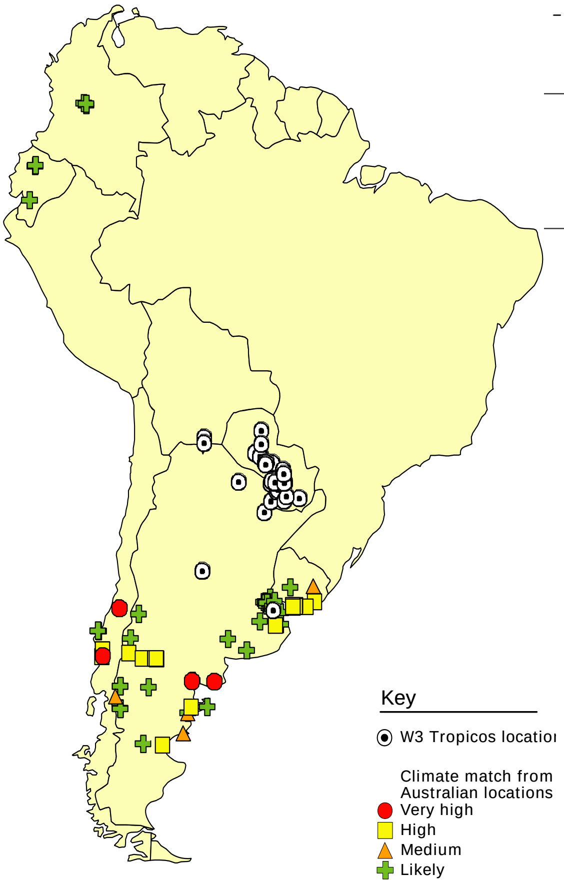


Figure 11. Climate match predicition of PGC infestations in southeastern Australia to South America, overlayed with known PGC locations. CLIMATE software was used to generate climate predictions. The red circles indicate locations with a very high climate match comparable to PGC locations in southeastern Australia (occurring south of 32^{O}). Data source for PGC locations (W3 Tropicos) from http://mobot.mobot.org/W3T/Search/vast.html

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Appendix 1 Australian wide Weed Risk Assessment of prairie ground cherry, *Physalis viscosa* L. and silverleaf nightshade, *Solanum elaeagnifolium* Cav.

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March 2006

Introduction

In order to make informed decisions about setting priorities and to focus on important pest plants it is necessary that the relative importance and potential impact of each weed be determined. Victoria's Pest Plant Assessment project has established a procedure to assess and prioritise any plant on its intrinsic abilities to invade suitable ecosystems and its present and potential impacts on social, environmental or agriculture land use. This procedure utilises a Decision Support System based on the Analytical Hierarchal Process using multi-criteria methodology. This process follows the proposed CRC for Australian Weed Management and the Standards Australia's National Post-Border Weed Risk Management Protocol.

Methodology

A full documented account of the methodology of the pest plant prioritisation process can be found at the Department's Victorian Resources Online Website. (http://www.dpi.vic.gov.au/vro/weeds).

In summary within the biological properties of the plant the three major components required in a decision support system to predict a weeds status are:

1. An indication of the plant's invasiveness, or its rate of spread
2. Its current and potential distribution and
3. The current and potential impacts of the plant on land use and ecosystems

A plant's overall Assessment depends on a combination of its invasiveness and a "ratio" of its present and potential impact. Thus a less invasive plant may rank as a higher priority than a highly invasive plant, if for example;

- Its overall area and / or the number of ecosystems it invades are greater.
- Its present distribution is very insignificant but its potential distribution is very large.
- Its impact is much greater.

Preliminary weed risk assessment

Invasiveness

A set of criteria to assess the biological properties of a plant to indicate its potential to be an invasive weed has been developed and utilised since 1999. The criteria have been published (Weiss *et al*, 2004) and fall into 4 main categories based upon the plants ability to establish, grow and compete, reproduce and disperse.

Table 1. Invasive assessment scores for Prairie ground cherry and Silverleaf nightshade. (H = High, M = Medium, MH= Medium High, ML = Medium Low, L = Low)

Criteria	*Prairie ground cherry*	*Silverleaf nightshade*
Germination requirements?		
1. Germination requirements?	MH	MH
2. Establishment requirement?	MH	ML
3. How much disturbance is required?	MH	MH
Growth/Competitive Ability		
4. Life form?	ML	L
5. Allelopathic properties?	L	ML
6. Tolerates herbivory pressure?	MH	MH
7. Normal growth rate?	MH	MH
8. Stress tolerance?	ML	MH
Reproduction		
9. Reproductive system?	H	H
10. Number of propagules produced?	ML	H
11. Seed longevity	M	MH
12. Reproductive period?	MH	MH
13. Time to reach reproductive maturity?	MH	H
Dispersal		
14. Number of mechanisms?	H	H
15. How far do they disperse?	H	H
TOTAL SCORE (Max =1, Min = 0)	**0.726**	**0.668**

In relation to other assessed weeds, both prairie ground cherry and silverleaf nightshade scored quite highly. Both score greater than 0.65 out of a maximum potential score of 1. Prairie ground cherry scored slightly higher invasiveness than silverleaf nightshade. However their scores indicate that both could be classified as compared to other assessed weeds as a "Highly Invasive weeds".

Comparative invasive scale as compared to over 150 assessed weed species.

Score	Category
<0.5	Moderately Invasive
0.5-0.6	Moderately Highly Invasive
0.6-0.8	Highly Invasive
0.8-0.9	Very Highly Invasive
>0.9	Extremely Invasive

Impact

Criteria to assess potential impact on social, agricultural and environmental values have been developed and utilised since 2002. These focus on social, natural resources, native flora and fauna, vegetation and agricultural values (Weiss *et al*, 2004).

Table 2. Impact assessment scores for Prairie ground cherry and Silverleaf nightshade. (H = High, M = Medium, MH= Medium High, ML = Medium Low, L = Low)

Impact Criteria	Prairie ground cherry	Silverleaf nightshade
Social		
1. Restrict human access?	L	L
2. Reduce tourism?	ML	MH
3. Injurious to people?	L	ML
4. Damage to cultural sites?	ML	ML
Abiotic		
5. Impact flow?	L	L
6. Impact water quality?	L	L
7. Increase soil erosion?	L	ML
8. Reduce biomass?	ML	ML
9. Change fire regime?	L	L
Community Habitat		
10. Impact on composition (a) high value EVC	MH	ML
(b) medium value EVC	L	ML
(c) low value EVC	L	ML
11. Impact on structure?	MH	ML
12. Effect on threatened flora?	M	M
Fauna		
13. Effect on threatened fauna?	M	M

14. Effect on non-threatened fauna?	ML	L
15. Benefits fauna?	H	MH
16. Injurious to fauna?	L	MH
Pest Animal		
17. Food source to pests?	H	ML
18. Provides harbor?	ML	L
Agriculture		
19. Impact yield?	MH	MH
20. Impact quality?	M	MH
21. Affect land value?	M	M
22. Change land use?	M	M
23. Increase harvest costs?	M	L
24. Disease host/vector?	L	M
SubTotal – Standardised Agricultural Impact Alone	***0.474***	***0.538***
Standardised TOTAL SCORE (Max =1, Min = 0)	***0.335***	***0.349***

Both prairie ground cherry and silverleaf nightshade have been assessed to be **Moderately Low** impact when including all the environmental and biodiversity values. However their impact on specifically agricultural values alone, prairie ground cherry (0.47) is assessed to have **Medium High** agricultural impact, while silverleaf nightshade (0.538) has **High** agricultural impact.

Table 3. Comparative impact scale as compared to over 100 assessed weed species.

Score	Category
<0.3	Low Impact
0.3-0.4	Moderately Low Impact
0.4-0.45	Medium Impact
0.45-0.5	Medium High Impact
0.5-0.55	High Impact
>0.6	Very High Impact

Refer to the Appendices for the detailed assessments of SLN invasive (Appendix 1.1) and impact (Appendix 1.2), and PGC invasiveness (1.3) and impact (1.4).

Distribution

Potential distribution is a major factor in comparing the threats posed by weed species (Panetta and Dodd, 1987). The greater the potential distribution of a weed species, the greater the potential impact and management costs. Weed species typically are more invasive in regions that are climatically similar to their native environment. Climate limits distribution according to how temperature and moisture stresses affect the weed's life cycle. Different land uses (e.g. cropping, perennial pasture and forestry) have different disturbance regimes that favour different groups of weeds. Having determined the climatic preferences of a new weed it is necessary to overlay these on a map of the weed's associated land use in Australia. The areas of the nation that are potentially at risk from this weed will then be known.

Potential distribution is a major factor in comparing the threats posed by weed species (Pannetta and Dodd 1987). The greater the potential distribution of a weed species, the greater the potential impact and management costs. Knowledge of potential distribution is also important for devising management programs. Landholders can be alerted of the risk of weed invasion and measures can be enforced to prevent the introduction of weed propagules into such areas. Low priority can be give to areas where the weed might fail to persist, or be of little economic importance (Pannetta and Dodd 1987).

The present Australian distribution of a plant was estimated from a number of GIS and nonspatial databases. These include Australian herbarium records, Scientific Literature, Flora Information Systems and Departmental Pest Management databases. . Potential distribution was estimated for Australia using climate modelling overlayed upon susceptible vegetation and landuse geospatial layers as described by Weiss *et al*. (2002). A ratio of present area and the predicted potential area was used to obtain the intensity level for distribution.

Figure 1. Global locations of *Physalis viscosa* used for CLIMATE prediction.

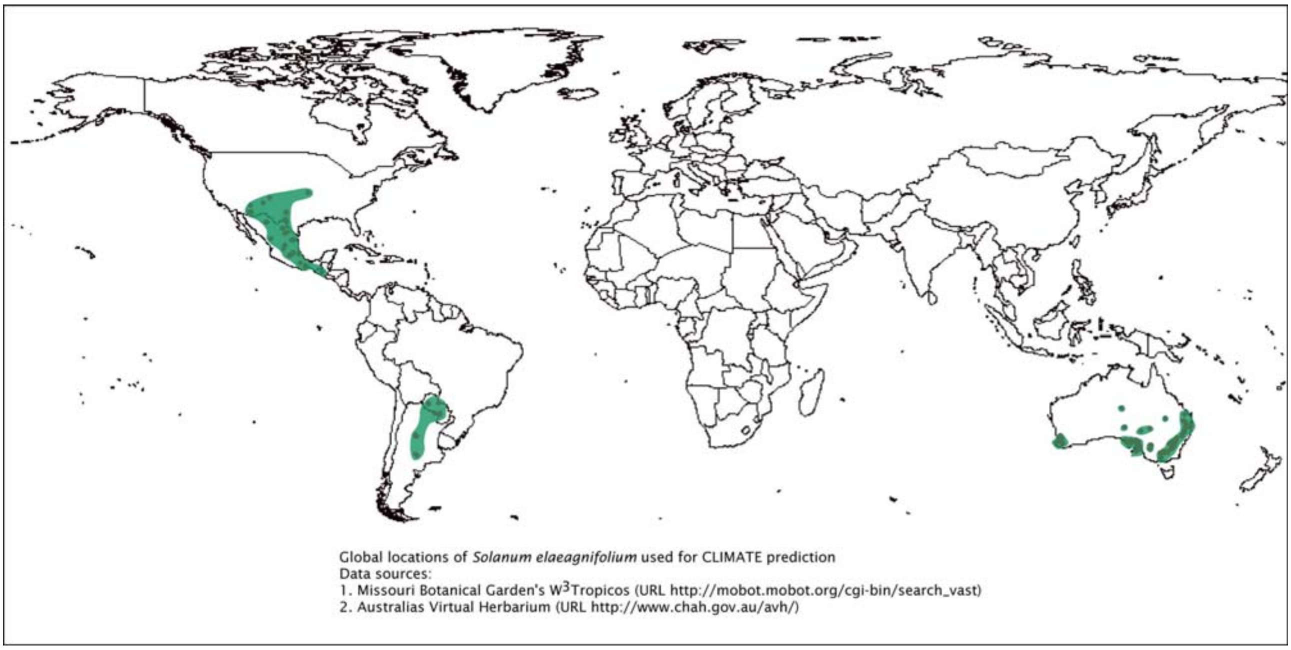

Figure 2. Global locations of *Solanum elaeagnifolium* used for CLIMATE prediction.

Potential Distribution in Australia

The CLIMATE® computer program was used to predict potential distribution in Australia. Using the localities where a species occurs overseas and within Australia, the potential climatic range of any species can be overlaid upon

Australia climatic regions. This was performed on Prairie ground cherry and Silverleaf nightshade and the maps below illustrate the climatic regions most suitable for this species in Australia.

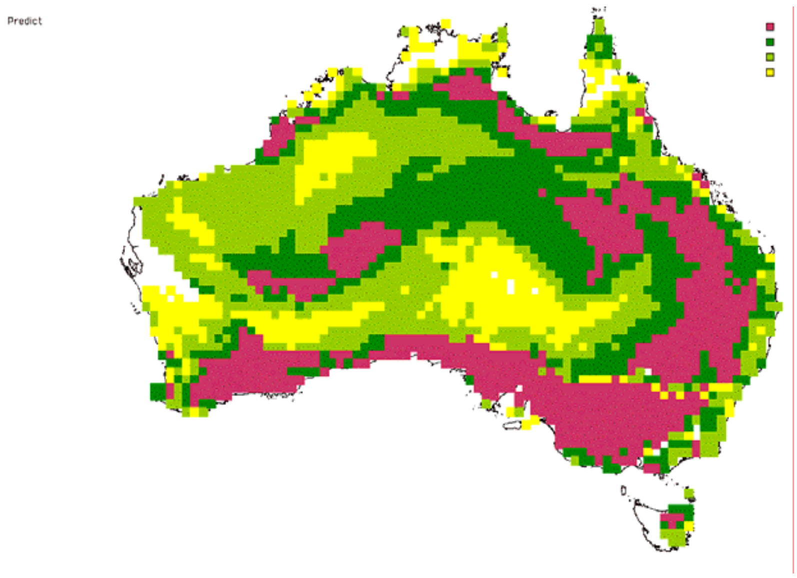

Figure 3. Areas of climatic suitability for Prairie ground cherry in Australia.

Red 90%, dark green 80%, light green 70% and yellow 60% suitable climatic match.

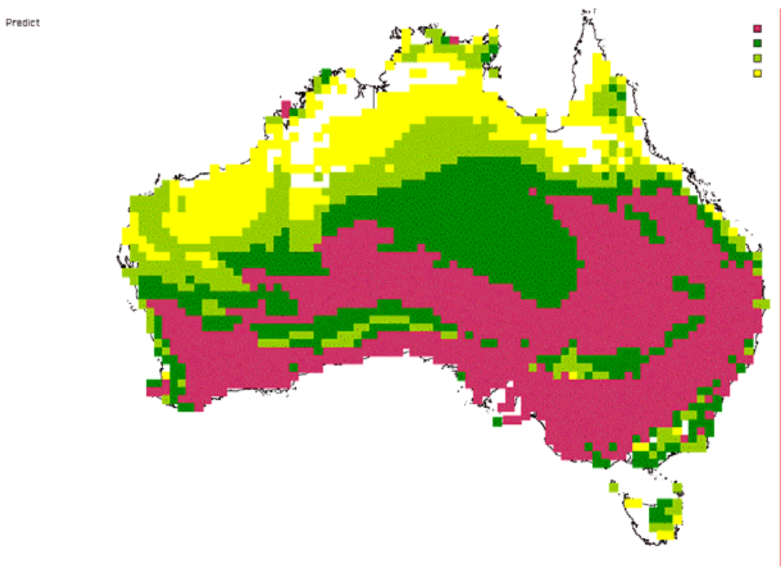

Figure 4. Areas of climatic suitability for Silverleaf nightshade in Australia.

Red 90%+, dark green 80%, light green 70% and yellow 60% suitable climatic match.

This climatic overlay can then be used to determine the potential range of the plant species by linking or intersecting them with susceptible land use or broad vegetation types. The resulting maps illustrate the potential range of prairie ground cherry and silverleaf nightshade in Australia.

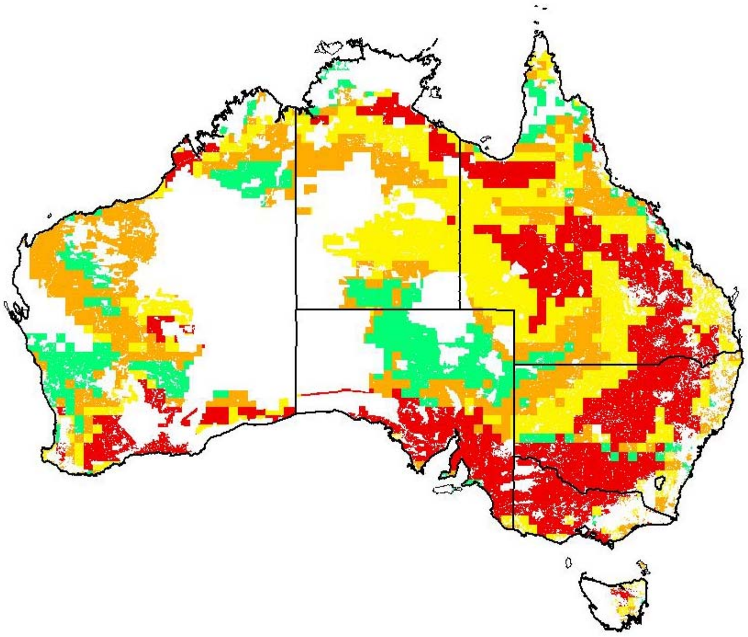

Figure 5. Potential distribution of prairie ground cherry in Australia.

Areas in red indicate a very high probability that prairie ground cherry could establish in suitable vegetation and landuse within this region, yellow a high and orange a medium probability of establishment.

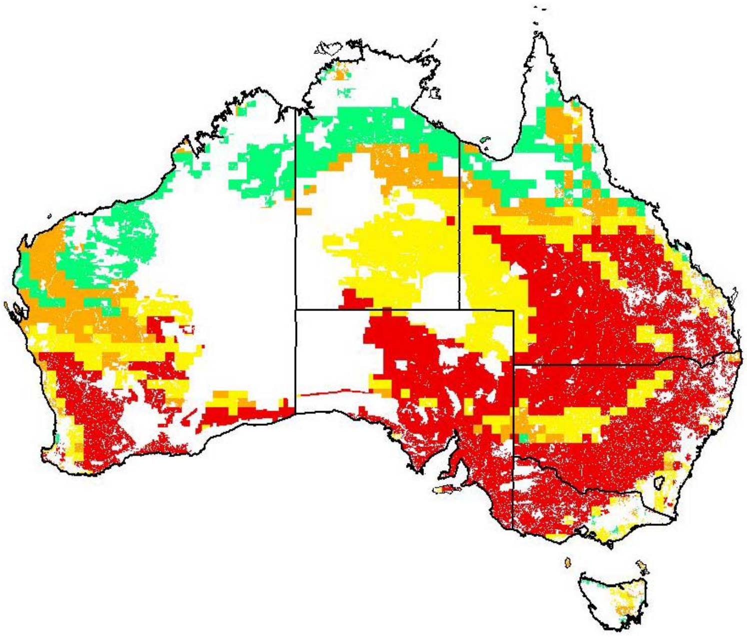

Figure 6. Potential distribution of silverleaf nightshade in Australia.

Areas in red indicate a very high probability that silverleaf nightshade could establish in suitable vegetation and landuse within this region, yellow a high and orange a medium probability of establishment.

Using GIS one can then work out the predictive potential area of each weed by different landuse and by state. The predictive potential distribution of both prairie ground cherry and silverleaf nightshade indicate that both weeds could spread much further than their present recorded distribution. A more detailed analysis by state and landuse is provided in Table 4.

Table 4. Potential area by land use type affected by *Solanum elaeagnifolium* and *Physalis viscosa*

		Potential area (ha) infested by landuse type									
Weed	**State**	**Cropping**	**Grazing Modified Pastures**	**Perennial horticulture**	**Seasonal horticulture**	**Irrigated seasonal horticulture**	**Irrigated perennial horticulture**	**Irrigated cropping**	**Irrigated modified pastures**	**livestock grazing**	**Potential total area**
SLN	**Vic**	2,501,196	3,701,241	5,158	5,432	15,471	27,676	32,426	495,585	6,409,777	13,193,962
	NSW	4,806,689	3,276,610	21,540	749	8,940	19,976	441,102	290,322	51,662,582	60,528,510
	Qld	1,627,729	2,249,068	11,790	339	16,420	8,460	140,512	30,561	112,602,362	116,687,241
	SA	3,131,668	2,053,692	10,627	2,803	6,121	47,496	7,635	38,819	47,012,586	52,311,447
	NT	845	19,206	136	0	0	340	0	0	57,813,811	57,834,338
	ACT	68	10,826	0	0	0	0	0	0	31,660	42,554
	Tas	34,171	682,623	1,153	1,561	15,321	2,445	6,719	24,417	723,143	1,491,553
	WA	6,760,265	4,535,586	1,844	612	3,200	4,611	544	8,872	84,301,050	95,616,584
Total	**AUS**	**18,86 2,631**	**16,528,852**	**52,248**	**11,49 6**	**65,473**	**111,004**	**628,938**	**888,5 76**	**360,556,971**	**397,7 06,189**
PGC	**Vic**	2,501,196	3,700,729	5,158	5,432	15,471	27,676	32,426	495,585	6,408,910	13,192,583
	NSW	4,806,689	3,276,610	21,540	749	8,940	19,976	441,102	290,322	51,535,816	60,401,744
	Qld	1,738,397	2,292,785	12,530	407	16,871	9,405	215,474	31,037	121,662,140	125,979,046
	SA	3,131,668	2,053,692	10,627	2,803	6,121	47,496	7,635	38,819	46,522,828	51,821,689
	NT	913	19,341	136	0	0	340	0	0	60,777,318	60,798,048
	ACT	68	10,826	0	0	0	0	0	0	31,660	42,554
	Tas	32,565	581,704	1,153	919	10,910	2,445	5,507	18,403	647,629	1,301,235
	WA	6,759,233	4,594,488	1,776	612	4,376	4,747	2,516	9,349	84,017,670	95,394,767
Total	**AUS**	**18,97 0,729**	**16,530,175**	**52,920**	**10,922**	**62,689**	**112,0 85**	**704,660**	**883,515**	**371,603,971**	**408,931,666**

Weed Risk Assessment

The final overall assessment of a weed is a combination of the plant's invasiveness and its potential impact. This can be illustrated using the risk matrix below.

		IMPACT		
		High Impact	Moderate Impact	Low Impact
Invasive Potential & Potential Distribution	V Highly Inv & High Potential	**Level 4**	Level 3	**Level 2**
	High Inv and High Potential	Level 3	**Level 2**	**Level 2**
	Mod Inv and Potential	**Level 2**	**Level 2**	**Level 1**
	Mod Inv and Low Pot (or vice versa)	**Level 2**	**Level 1**	**Level 1**
	Low Inv and Potential	**Level 1**	**Level 1**	**Level 1**

Level 4 = Highest Priority/ Response, Level 1 = Lowest Priority/ Response

Prairie ground cherry and silverleaf nightshade were assessed to be **Highly Invasive**, with **High Potential** for further spread. Their impact on specifically agricultural, natural resources and social values are assessed as **Medium Low** however when considering agricultural impact alone their impact is **Medium to High**. Prairie ground cherry is assessed as having less agricultural impact than silverleaf nightshade. In the risk matrix for agricultural impact, provisionally prairie ground cherry may fit into the top end of **Level 2** response while silverleaf nightshade slightly higher in **Level 3** (see below)

		IMPACT		
		High Impact	Moderate Impact	Low Impact
Invasive Potential & Potential Distribution	V Highly Inv & High Potential	Level 4	**Level 3**	**Level 2**
	High Inv and High Potential	Level 3 **Silverleaf nightshade**	**Level 2** **Prairie ground cherry**	**Level 2**
	Mod Inv and Potential	**Level 2**	**Level 2**	**Level 1**
	Mod Inv and Low Pot (or vice versa)	**Level 2**	**Level 1**	**Level 1**
	Low Inv and Potential	**Level 1**	**Level 1**	**Level 1**

Weed risk assessment or prioritisation is a method to assist in the determination of risk of particular issues in comparison to other risks. Thus the above risk matrix is more relevant when other species of weeds are included.

Some of the other species assessed in Victoria that could be used as a comparison and identified in “Weeds of Significance to the Grazing Industries of Australia (Grice, 2002) are; Bathurst burr, cape tulip, serrated tussock, spear thistle and St Johns Wort. The table below indicates the Invasiveness and Impact assessment scores and relative category for these five species

Table 5. Invasiveness and Impact Scores for 5 temperate grazing weeds of perennial pasture zones.

Species I	nvasiveness Score	Invasiveness Category	Impact Score	Impact Category	Distribution Category *
Bathurst Burr	0.5852	Moderately Highly Invasive	0.3563	Moderately Low Impact	Medium potential
Cape Tulip	0.6842	Highly Invasive	0.4174	Medium Impact	High Potential
Serrated Tussock	0.7615	Highly Invasive (nearly Very Highly Invasive)	0.6290	Very High Impact	High Potential
Spear Thistle	0.6935	Highly Invasive	0.3537	Moderately Low Impact	Low potential (widespread)
St Johns Wort	0.6606	Highly Invasive	0.3343	Moderately Low Impact	Medium potential.

* Estimated based on preliminary climate analysis without detailed area by climate and landuse calculation. Based upon widespread (Low potential), Common (either locally or widespread but not dense infestations – Moderate potential) or only locally common but with great potential to expand (High Potential). The detailed invasiveness and impact score and justification for the above species can be found at the Victorian Resources Online Weeds web site at http://www.dpi.vic.gov.au/vro/weeds

		IMPACT		
		High Impact	Moderate Impact	Low Impact
	V Highly Inv & High Potential	***Level 4***	***Level 3***	Level 2
Invasive Potential & Potential Distribution	High Inv and High Potential	Level 3 **Silverleaf nightshade**	Level 2 **Prairie ground cherry** Cape tulip	Level 2 Spear thistle St John's wort
	Mod Inv and Potential	Level 2	Level 2	Level 1 Bathurst burr
	Mod Inv and Low Pot (or vice versa)	Level 2	Level 1	Level 1
	Low Inv and Potential	Level 1	Level 1	Level 1

The above table illustrates (without the detailed Australia wide analysis of the potential distribution), the ranking or priority of silverleaf nightshade and prairie ground cherry to a number of similar temperate grazing weeds. In rank order (from highest to lowest priority) the seven species would be;

Serrated Tussock

Silverleaf nightshade

Prairie ground cherry & Cape Tulip

Spear Thistle

St Johns Wort

Bathurst Burr

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Appendix 1.1 Silverleaf nightshade Weed Risk Assessment - Invasiveness

QUESTION CO	MMENTS	REFERENCE	RANK
Establishment			
1. Germination requirements?	"Seeds germinate in autumn".	P & C (1992 p. 610)	**MH**
2. Establishment requirements?	Establishes in open areas (i.e. pastures and crops). "Seeds require fluctuating temperatures to germinate." For optimal germination a pH of 6 or 7 is required. Parsons & Cuthbertson (2001) record that, "…seedlings are rarely found except in occasional years and it appears there might be quite specific requirements for germination."	P & C (2001) WSNWCB (1999)	**ML**
3. How much disturbance is required?	Invades pastures and crops → "Perennial pastures do not check its growth".	P & C (1992 p. 611)	**MH**
Growth/Competitiv e			
4. Life form?	Perennial herb. Other.	P & C (1992 p. 609)	**L**
5. Allelopathic properties?	"It has been suggested that germination may be inhibited by the mucilaginous material surrounding the seed either because it forms a physical barrier to water imbibition or it contains a germination – inhibiting chemical". "Allelopathic effects have been demonstrated in cotton". (P & C 1992 p. 611).	P & C (1992 p. 611)	**ML**
6. Tolerates herb pressure?	Consumed by cattle, sheep and goats. However, probably not preferred due to its highly toxic properties.	P & C (1992 p. 611)	**MH**

QUESTION CO	MMENTS	REFERENCE	RANK
7. Normal growth rate?	"Competes directly with summer-growing crops and pastures and reduces production of winter crops such as cereals".	P & C (1992 p. 611)	**MH**
8. Stress tolerance to frost, drought, w/logg, sal. etc?	Tolerant of drought. (See distribution in P &C 1992 p. 609). "Not confined to any particular soil type". "The shoot growth is killed off by the first frost in autumn and the rootstock is dormant until the following spring." The deep root system would ensure the plant could survive frost.	P & C (1992 p. 609) P & C (1992 p. 609) Lemerle & Leys (1991)	**MH**

Appendix 1.1 Silverleaf nightshade Weed Risk Assessment - Invasiveness (cont'd)

QUESTION CO	MMENTS	REFERENCE	RANK
Reproduction			
9. Reproductive system	"Reproducing by seed and from roots".	P & C (1992 p. 609)	**H**
10. Number of propagules produced?	About 75 seeds in each fruit x 30 fruits per plant. (See picture on page 609), = 2,250 seeds per plant.	P & C (1992 p. 609/610)	**H**
11. Propagule longevity?	"Seeds are … long lived". It is reported that seeds can remain viable for up to 15 years.	P & C (1992 p. 611)	**MH**
12. Reproductive period?	Perennial herbs: aerial growth dies at end of summer, but new shoots are produced each spring.	P & C (1992 p. 610)	**MH** Assumption
13. Time to reproductive maturity?	"Seeds germinate in autumn…flowering commences in November".	P & C (1992 p. 610)	**H**
Dispersal			
14. Number of mechanisms?	Numerous → See 'dispersal' (P & C 1992 p. 611). Including birds.	P & C (1992 p. 611)	**H**
15. How far do they disperse?	Birds could disperse seeds > 1 km.		**H**
7 Social			
1. Restrict human access?	"An erect summer-growing perennial herb, commonly 30 to 45 cm high." The low growth habit would not restrict human access.	P & C (2001)	**L**

QUESTION CO	MMENTS	REFERENCE	RANK
2. Reduce tourism?	"The stems are usually armed with numerous slender prickles 2 to 4 mm long. Aerial growth dies at the end of summer but the dead stems usually remain standing for several months." The prickly property of the plant may affect some recreational activities.	P & C (2001)	**MH**
3. Injurious to people?	See comment in 2 above. Prickles present for much of the year. Potential for minor injury.	P & C (2001)	**ML**
4. Damage to cultural sites?	Dense patches may create a negative visual impact.		**ML**

Appendix 1.2 Silverleaf nightshade Weed Risk Assessment - Impact

QUESTION CO	MMENTS	REFERENCE	RANK
Abiotic			
5. Impact flow?	Terrestrial species.	P & C (2001)	**L**
6. Impact water quality?	Terrestrial species.	P & C (2001)	**L**
7. Increase soil erosion?	Root system comprises deep, much branched, vertical and horizontal roots to 2 metres deep and wide. However, aerial growth dies at the end of summer leaving bare areas of soil. Potential for moderate probability of large scale soil movement.	P & C (2001)	**ML**
8. Reduce biomass?	"An erect summer-growing perennial herb, commonly 30 to 45 cm high. Silverleaf nightshade competes directly with summer-growing crops and pastures." Replaces biomass.	P & C (2001)	**ML**
9. Change fire regime?	"In Victoria…it usually occurs in discrete patches." Although aerial growth dies at the end of summer and dead plants remain standing, the amount fuel would be limited. Fire regime not affected.	P & C (2001)	**L**
Community Habitat			
10. Impact on composition (a) high value EVC	EVC=Plains grassland (E); CMA=North Cental; Bioreg=Victorian Riverina; VH CLIMATE potential. A weed of open pasture/cropping situations. Not known in natural ecosystems in Victoria. Minor displacement of grasses/forbs.	P & C (2001)	**ML**
(b) medium value EVC	EVC=Grassy dry forest (D); CMA=North Cental; Bioreg=Goldfields; VH CLIMATE potential. Impact as in 10(a) above.	P & C (2001)	**ML**

QUESTION CO	MMENTS	REFERENCE	RANK
(c) low value EVC	EVC=Grassy dry forest (LC); CMA=Goulburn Broken; Bioreg=Highlands – Northern Fall; VH CLIMATE potential. Impact as in 10(a) above.	P & C (2001)	**ML**
11. Impact on structure?	Primarily a weed of cropping, it also occurs in summer-growing pasture and, " perennial pasture does not check its growth." The extensive root system enables the plant to draw moisture and nutrients from a large volume of soil and thus compete effectively against other species. Although it infests broad areas, the infestations tend to be populated as discrete patches (some though to several hundred hectares). Infestation aided by cultivation. Minor effect on 20–60% of the floral strata.	P & C (2001)	**ML**
12. Effect on threatened flora?	No documented impact on threatened flora in Victoria.		**M**

Appendix 1.2 Silverleaf nightshade Weed Risk Assessment - Impact (cont'd)

QUESTION CO	MMENTS	REFERENCE	RANK
Fauna			
13. Effect on threatened fauna?	No documented impact on threatened fauna in Victoria.		**M**
14. Effect on non-threatened fauna?	Primarily a weed of agriculture. Limited threat due to fauna not co-existing within infested area.	P & C (2001)	**L**
15. Benefits fauna?	"Birds and animals eat the fruit." Minor food source.	P & C (2001)	**MH**
16. Injurious to fauna?	"Feeding trials have confirmed that all parts of the plant, but particularly the fruit either green or ripe, are toxic to animals." Fruit supply is seasonal; threat not present all year.	P & C (2001)	**MH**
Pest Animal			
17. Food source to pests?	"Birds and animals eat the fruit." Possible limited food source for minor pest birds.	P & C (2001)	**ML**
18. Provides harbor?	A summer-growing perennial. Not known to provide harbor.	P & C (2001)	**L**
Agriculture			
19. Impact yield?	"Silverleaf nightshade competes directly with summer-growing crops and pastures, and reduces production of winter crops such as cereals because of the depletion of nutrients and moisture from the soil in the previous summer. In Texas…it considerably reduces cotton and grain sorghum yields." Major impact on yield in the United States. The potential exists for a similar response in Victoria. Lemerle and Leys (1991) document that in one instance winter pasture production doubled when silverleaf nightshade was chemically controlled the previous summer.	P & C (2001) Lemerle & Leys (1991) NSWA (2003)	**MH**

QUESTION CO	MMENTS	REFERENCE	RANK
	The significant reduction in pasture without control would limit stocking rates, leading to a reduction in yield. In 2003, a preliminary study into the impact of SLN in the Murrumbidgee Irrigation Area found that most growers are unaffected by the presence of this plant, but most thought it would become a moderate to significant problem in the future. "[T]he cost of control was of more concern than yield loss or disruption to their land management system.		
20. Impact quality?	"…the plant's spiny leaves and coarse stems may lower the quality of hay taken from infested areas." See also comments in 19 above. In cropping situations (the most likely to be affected), the perception is that this plant is unlikely to lead to serious impacts.	WSNWCB NSWA (2003)	**MH**

Appendix 1.2 Silverleaf nightshade Weed Risk Assessment - Impact (cont'd)

QUESTION CO	MMENTS	REFERENCE	RANK
21. Affect land value?	"Silverleaf nightshade is one of the most difficult weeds to kill." The value of land infested with this plant would be reduced due the weed's persistence and its potential impact on agricultural production.	P & C (2001)	**M**
22. Change land use?	In cropping situations, land use may not need to change depending upon the impact on production. In pasture situations, however, as "sheep are more resistant to the toxins and goats are unaffected," choice of grazing animal may change.	WSNWCB (1999)	**M**
23. Increase harvest costs?	Not known to affect harvest costs.		**L**
24. Disease host/vector?	None documented, however, it is noted that solanaceous weeds (the nightshades) are possible hosts to a variety of potato virus', bacteria and thrips. Potential to be a host to common potato diseases and pests.	DPIVic	**M**

Appendix 1.3 Prairie ground cherry Weed Risk Assessment - Invasiveness

QUESTION CO	MMENTS	REFERENCE	RANK
Establishment			
Germination requirements?	Seeds germinate in spring.	P & C (2001)	**MH**
Establishment requirements?	A summer growing plant of open grazing land. Withstands shading.	P & C (2001)	**MH**
How much disturbance is required?	A summer growing plant of open grazing land.	P & C (2001)	**MH**
Growth/ Competitive			
Life form?	The aerial growth dies in autumn without flowering but roots remain alive producing new shoots in the following spring therefore Geophyte.	P & C (2001)	**ML**
Allelopathic properties?	No Allelopathic properties described.		**L**
Tolerates herb pressure?	Rarely eaten by stock.	P & C (2001)	**MH**
Normal growth rate?	Competition is effective (for control) if vigorous summer growing species can be established.	P & C (2001)	**MH**
Stress tolerance to frost, drought, w/logg, sal. etc?	Withstands drought, but does not persist under constant irrigation. It is frost tender	P & C (2001) PFAF (nd)	**ML**

Appendix 1.3 Prairie ground cherry Weed Risk Assessment – Invasiveness (Cont'd)

QUESTION CO	MMENTS	REFERENCE	RANK
Reproduction			
Reproductive system	Reproducing from creeping roots and by seed.	P & C (2001)	**H**
Number of propagules produced?	Estimate: 15 berries per plant x 20 seeds per berry = 300 seeds per plant.	P & C (2001) KTRI (1998)	**ML**
Propagule longevity?	?		**M**
Reproductive period?	Perennial herb. → Flowers and fruit are produced in summer and the cycle is repeated annually.	P & C (2001)	**MH**
Time to reproductive maturity?	Seeds germinate in spring → aerial growth dies in autumn without flowering → flowers and fruit are then produced in summer and the cycle is repeated annually.	P & C (2001)	**MH**
Dispersal			
Number of mechanisms?	Cultivation, wind and water: animals – birds, foxes and stock eat the fruit, and it seems that germination is enhanced after seeds pass through animals.	P & C (2001)	**H**
How far do they disperse?	The frequent occurrence of prairie ground cherry along railway lines is probably due to birds and animal droppings falling from railway trucks.	P & C (2001)	**H**
Social			
1. Restrict human access?	An erect perennial herb 25 cm to 60 cm high. It would not restrict human access.	P & C (2001)	**L**

Appendix 1.3 Prairie ground cherry Weed Risk Assessment – Invasiveness (Cont'd)

QUESTION CO	MMENTS	REFERENCE	RANK
2. Reduce tourism?	A summer growing plant of open grazing land, its presence would not affect tourism. Dense patches may create a negative visual effect.	P & C (2001)	**ML**
3. Injurious to people?	No. "Mature berries of grape groundcherry [*P. viscosa*] are edible, and are sometimes used in cooking or made into jam in some regions [United States]."	P & C (2001) CDFA (nd)	**L**
4. Damage to cultural sites?	Dense patches may create a moderate negative visual impact.		**ML**
Abiotic			
5. Impact flow?	Terrestrial species.	P & C (2001)	**L**
6. Impact water quality?	Terrestrial species.	P & C (2001)	**L**
7. Increase soil erosion?	Occurs in open grazing land. Perennial roots are deep and extensive. "The root system is often more than one metre deep with horizontal roots forming close to the surface." Not likely to contribute to soil erosion.	P & C (2001) GMLN (1999)	**L**
8. Reduce biomass?	Invader replaces biomass. In the United States, *P. viscosa* occurs in disturbed areas, persists in agricultural fields, and is a naturalised component of prairie grasslands where it competes with other species for water and nutrient.	CDFA (nd)	**ML**
9. Change fire regime?	Aerial growth dies in autumn. Little material left to establish or support fire.		**L**

Appendix 1.3 Prairie ground cherry Weed Risk Assessment – Invasiveness (Cont'd)

QUESTION CO	MMENTS	REFERENCE	RANK
Community Habitat			
10. Impact on composition (a) high value EVC	EVC=Plains grassland (E); CMA=Goulburn Broken; Bioreg=Victorian Riverina; VH CLIMATE potential. Occurs on open grazing land where it can form dense patches. Major impact on grasses/forbs.	GMLN (1999)	**MH**
(b) medium value EVC	Most commonly found in open grassland or disturbed situations. Does not appear likely to occur in medium value EVCs in Victoria.	GMLN (1999)	**L**
(c) low value EVC	Most commonly found in open grassland or disturbed situations. Does not appear likely to occur in low value EVCs in Victoria.	GMLN (1999)	**L**
11. Impact on structure?	"It is a perennial herb that is very invasive, forming dense coverages in pastures, crops and roadsides." Once established, it is likely to have a major impact on ground flora in native grasslands.	GMLN (1999)	**MH**
12. Effect on threatened flora?	No documented impact on threatened flora in Victoria.		**M**
Fauna			
13. Effect on threatened fauna?	No documented impact on threatened fauna in Victoria.		**M**
14. Effect on non-threatened fauna?	"…forming dense coverages in pastures, crops and roadsides." In natural ecosystems, its presence would reduce available fodder for native species.	GMLN (1999)	**ML**
15. Benefits fauna?	No known benefits		**H**

Appendix 1.3 Prairie ground cherry Weed Risk Assessment – Invasiveness (Cont'd)

QUESTION CO	MMENTS	REFERENCE	RANK
16. Injurious to fauna?	"Prairie ground cherry is suspected of being poisonous but the foliage is rarely eaten by stock, however, sheep readily eat the ripe fruit, apparently without ill effect." Not considered injurious.	P & C (2001)	**L**
Pest Animal			
17. Food source to pests?	"The fruit is eaten by birds and foxes."	P & C (2001)	**H**
18. Provides harbor?	"Aerial growth dies in autumn." During summer it may provide limited harbor to minor pest species such as rodents.	P & C (2001)	**ML**
Agriculture			
19. Impact yield?	"…forms dense coverages in pastures and crops…reduces stock summer carrying capacities." Likely to have a major impact on yield (>5%).	GMLN (1999)	**MH**
20. Impact quality?	"The distribution of hay cut from infested areas is an important means of dispersal." Contaminated product may be unsuitable for sale, but there is no evidence of such rejection. Original infestation in the Goulburn Valley of Victoria was through contaminated lucerne seed.	P & C (2001)	**M**
21. Affect land value?	Because of the deep root system control by cultivation is not effective. Chemical controls, while effective, are expensive over large areas. Due to persistence of the weed and its impact on both pastures and cropping, its presence may reduce land value. Repeated cultivation can weaken plants and reduce infestations.	P & C (2001)	**M**
22. Change land use?	Land use could continue, though with reduced agricultural return.		**M**

Appendix 1.4 Prairie ground cherry Weed Risk Assessment – Impact (Cont'd)

QUESTION	COMMENTS	REFERENCE	RANK
23. Increase harvest costs?	"It interferes with crop harvesting."	GMLN (1999)	**M**
24. Disease host/vector?	"Closely related species are known hosts of virus diseases affecting tomatoes in the United States but similar problems are not known in Australia."	P & C (2001)	**L**

Abbreviations for References

CDFA California Department of Food and Agriculture (CDFA). (no date). 'Physalis genus', online http://www.cdfa.ca.gov/phpps/ipc/weedinfo/physalis.htm Accessed 23/08/05

DPI Vic DPI VicDepartment of Primary Industries Victoria, (DPIVic), Silverleaf nightshade Landcare Note. online http://www.dpi.vic.gov.au (Agriculture & Food/Horticulture/Horticulture-Information Notes).

GMLN Goulburn Murray Landcare Network (1999). Prairie Ground Cherry, Available: http://www.gmln.org.au/regional_projects/weeds/Prairiegc.htm Date accessed: 15/04/03

KTRI Keith Turnbull Research Institute (KTRI) (1998). Landcare Notes: Prairie ground cherry, PP0025, Department of Natural Resources and Environment, Melbourne, Victoria.

P&C Parsons, W.T. and Cuthbertson, E.G. (2001). Noxious Weeds of Australia, 2nd ed, Inkata Press Melbourne & Sydney.

PFAF Plants for a Future (PFAF) (no date). 'Physalis viscosa', online: http://www.ibiblio.org/pfaf/cgi-bin/arr_html Accessed 23/08/05

NSW Agriculture, (NSWA), 2003, 'Silverleaf nightshade in the MIA', Vegie Bites, No 22, online: http://www.agric.nsw.gov.au/reader/vegiebites Accessed 24/08/05

WSNWCB Washington State Noxious Weed Control Board, (WSNWCB). (1999). *Silverleaf nightshade.* Available: http://www.nwcb.wa.gov/weed_info/sleafnightshade.html Accessed 29/04/03.

Appendix 2 National Silverleaf Nightshade Workshop

University of Adelaide

19 June 2002

Gap Analysis

A gap analysis was used to set priorities in research and other future directions for managing silverleaf nightshade. Possible actions were listed within the four broad areas of biological control, herbicide control, containment or eradication, and integrated weed management. The workshop participants voted on the relative feasibility and impact of each action. Results were as follows:

Biological Control		
	Feasibility	Impact
Determine whether the beetle *Leptinotarsa texana* attacks eggplant in South Africa by comparing the cultivars grown in South Africa and Australia.	11	9
Host specificity testing of native *Solanum* spp. and Australian biotypes of silverleaf nightshade in South Africa.	6	7
Possibility of an underground or above ground pathogen as biological control agent	0	4
Geographical range of *Leptinotarsa texana* and climate matching	1	0
Biological control using redistribution of a native control agent	0	1
Scoping consequences of introduction of an agent with approving organisations	0	0
New associated organisms in Asia or Africa as potential agents	0	0
Genetic engineering of biological control agents	0	0
Host specificity data for the moth *Frumenta* from the literature	0	0
Finding any unpublished work on biological control that has been done overseas	0	0

Herbicide control		
	Feasibility	Impact
Enhancing herbicide translocation in the root system, including studies on mapping this translocation	11	12
Trials of Graslan® with a view to obtaining registration	4	3

or an off-label use permit as a spot treatment.		
Timing of application to prevent seed set	1	2
Consistency of results with glyphosate and spot spray rates	2	1
Application by rotary wipers	1	0
Deep application of herbicides to reach roots	0	0
Literature review of alternative herbicides	0	0
Response of different silverleaf nightshade biotypes to herbicides	0	0

Containment or eradication?		
	Feasibility	Impact
Risk assessment of not doing anything to control the weed	8	6
Education and publicity program: publicity to poorer farmers, mass media, Landcare groups, government, agropoliticians, tri-state press release	6	6
DNA analysis to determine mechanism of spread (seed or root fragments), comparing genotypes vs. geography	4	3
Communication strategy	3	2
Hygiene practices and containment strategy for livestock eg. by vendor declarations	1	4

Integrated weed management		
	Feasibility	Impact
Documenting the true costs , and potential costs, of the weed	8	7
Produce a best-practice control guide.	5	6
Use of spray-grazing and goats for control	4	3
Cost/benefits of management practices	3	1
Allelopathy	1	1
Seed longevity and germination stimulants	1	1
Use of a deep rooted perennial pasture or summer cropping for control by competition	0	0
Stabilising spot-sprayed areas	0	0
Solarisation	0	0

Appendix 3 Victorian Farmer Experiences with SLN Management

Worshop Outcomes

A workshop facilitated by the DPI-Victoria was conducted on 6 August 2003 in Bendigo, Victoria. The 'Integrated Management of Silverleaf Nightshade' workshop, which involved farmers from central and northern Victoria, developed what they considered the best management practices for:

- eradication of small silverleaf nightshade infestations and
- containment of widespread silverleaf nightshade infestations.

Best Practice Management

The workshop identified the following issues and requirements to achieve best management practice of SLN:

1. Awareness and education
    - Eduction of farmers that SLN is a deep rooted and persistent perennial that becomes very difficult to control when young plants are left to mature. We need to promote a "Get in as early as possible on new infestations" message.
    - The impact of cultivation on weed spread.
    - An awareness in the community that SLN it is a declared noxious weed and therefore by law must be controlled.
    - Better understanding of weed identification, ie confusion of SLN with other Solanums.
    - Better awareness of the mechanisms of weed spread such as stock movement and quarantine times, machinery cleaning, birds and vermin as vectors of seed.
    - Consistent monitoring of sprayed infestations and of property for new infestations.
2. Best Control Strategies:
    - Attempt to manage uniform populations (cultivate, slash, disc, blade). Integrate cultivation or slashing prior to spray application to increase success rates.
    - Optimum spraying

      → time of year/plant growth stage. When chemicals will be best translocated throughout extensive root system.

      → time of day (morning, early evening) to reduce spray drift and ensure plants are adequately soaked.
    - Need to choose between a seed reduction and a mature plant (root reduction) focus.

      → Spray before flowering for seed reduction.

      → Spray after flowering and seed set for mature plant focus.
    - Roundup/Ally or Roundup/Starane mixes appear most effective chemicals.

- Spot spraying is the most effective application technique.
- Monitoring is essential.

  → follow-up spray treatments.

  → for new infestations.
- Record/map infestations.
- Record details of control techniques: eg conditions, paddock use (crop, stock and rates), types, rates and application of chemicals, and levels of control achieved. This will help determine the best program for the land and define progress/success.

A series of best practice management senarios were developed (Table 1).

Research required for optimum management

The following topics were raised as important areas of research required to improve the management of SLN:

i) Growth cycle weaknesses

These are relatively unknown. Energy stores and growth of roots and shoots can affect optimum spray timing. Possibly best to attack plant when flower and fruit formation is complete and energy is being transferred back to roots: chemicals more readily distributed throughout roots.

ii) Competitive species

Competitive species are basically unknown. Trees slightly reduce infestation, but silverleaf nightshade will still persist at reasonably high densities and will be much harder to kill due to difficulty of spray applications.

iii) Seed biology/ecology

Factors controlling seed germination and seed viability are relatively unknown and poorly researched.

Longevity: How long do seeds persist?

Viability: Do chemicals or other elements (eg fire, flood) affect seed viability?

Disposal: What reduces or depletes seed viability for safe disposal (eg burning)?

Germination: What factors affect seed germination (eg temperature, moisture)?

iv) Biological control

- Green grub has been found to eat SLN seed pods in Australia. What other organisms (native or exotic) are attacking SLN?
- Biological control of SLN was initially investigated for Australia back in the 1980s. The nematode was imported to quarantine but testing showed that it was not host-specific enough for Australia. What other agents have promise for release into Australia?

v) Technology and knowledge

Night or evening spraying: does this produce better uptake of herbicides?

Rosette spraying: are they more/less susceptible to chemicals? Evidence suggests that they do not appear more susceptible than bolting plants.

<u>Solarisation:</u> was tested and silverleaf nightshade eventually grew out from sides of plastic. Could perhaps work with chemicals as a buffer around the edge of the blanket.

vi) Education/social:

<u>Identification issues:</u>

- Provide educational days with live plants to ID.
- Provide ID guides and information on easy spotting (eg check bare fallows and channel banks).

vii) Information on dispersal of seed through stock:

- Requires holding paddocks to allow passing of seed.
  - → Recommended minimums: 4 days for sheep and 14 days for cattle.
  - → Are these minimums enough?
  - → How does ingestion affect seed viability? It is known that ingestion and excretion by sheep enhance germination.

Table 1 Silverleaf Nightshade Management Table (developed from Integrated Management of Silverleaf Nightshade workshop August 2003).

	PRE-SPRAY TREATMENT	CHEMICALS AND RATES	APPLICATION METHODS	SPRAY TIMING	FOLLOW-UP TREATMENT	RESULTS
1	Chemical fallow (late Aug) Cultivation on crop rotation (Sept/Oct)	Roundup+Starane (1L each /100L) Roundup+Ally: (1L+10g+ 50ml wetter /100L) Starane (1L/100L)	Spot spray; Dye to mark sprayed areas; Ally: spray ~2m circle around plant.	2-4 weeks after Sept/Oct cultivation to allow for plant regrowth.	Revisit sites 4-6 times, or as necessary to spray regrowth and missed plants. Where paddock wet less follow-up treatments are required.	Excellent control: reduced a heavy infestation to scattered over 10 years
2	Blade plough, Chemical fallow	Ester (1L/ha + 50L water) Roundup+Ester (1.2L + 200ml/ha)	Spot spray	Late Nov/Dec	Spray usually lasts two months. Dry conditions usually require no follow-up. Wet conditions require further treatment, as necessary.	Containing infestation. 95% success rate when able to spray late (Dec). Trials on Starane showing some potential.
3	None	Ester (2L/100L)	Boom spray. Mark infestations using iron post	Late December – early February in the morning.	Only if required	Containment
4	Mark infestations with iron posts, remove once sprayed.	Tordon (recommended rates)	Spot spray: only used on young plants and seedlings.	Sweep late January then spray	Revisit (usually March) and spray emerging plants. Continue to respray emergent plants as long as possible.	Excellent results as roots are not yet developed
5	Cultivation in dry conditions	$Roundup_{CT}$ + Starane + Oil: (2L + 50ml + 1L/ha)	Spot spray.	--	---	Success in dry when cultivated. Oil allows longer spraying and easier application.
6	Cultivation	Roundup (2L/100L) RoundupMAX (1.6L/100L)	Spot spray	--	---	Higher success when cultivated first.
7	None	Tordon (recommended rates)	Spot spray	--	---	Good results, although causes bare patches on ground.
8	None	Roundup + Starane	Spot spray	--	---	Worked for 2 years, but infestation back after 3rd year.
9	Grazing	Starane (1.5L/100L) Roundup (1-3L/200Lwater/ha)	Boom spray	--	5-6 follow-up applications	Reasonable results, Starane showing some potential.

Appendix 4 Review on the fauna associated with sliverleaf nightshade

1 History of surveys for natural enemies of silverleaf nightshade

1.1 Surveys in South-West USA 1966- 1968

A detailed account of the first surveys conducted between 1966 and 1968 in the USA is given by Goeden (1971). These results include surveys done in Colorado and southern California in 1966 and 1967 (30 populations surveyed) and surveys in Arizona, Texas and New Mexico in 1968 (40 populations surveyed). Goeden reports that in southern California the roots, stems, branches and reproductive organs of SLN were largely free of insect injury and that most of the plants examined at the 30 sites showed no or few symptoms of insect damage. Most of the insects reported were foliage feeders or sap-feeding species, with the exception of the fruit fly *Zonosemata vittigera* and the eggplant leaf miner *Keiferia glochinella* (Zell.). None of these two species were widely associated with the weed. After examining published and unpublished records Goeden concluded that the endophagous weevils *Anthonomus aeneolus* Dietz and *A. brevirostris* Linell and the chrysomelid defoliators *Leptinotarsa decemlineata* (Say) and *L. defecta* Ståhl known to feed and breed on the weed did not occur in California. Most of the insects associated with SLN in southern California were polyphagous or used the plant as an alternative food plant.

1.2. Surveys in Argentina 1971-1972

Between November 1971 and April 1972, a South African scientist, Dr Zimmerman conducted surveys on natural enemies of SLN in Argentina. A total of 55 populations were surveyed between 34 and 23 degrees latitude South. The most promising insect candidates identified for the biological control of SLN were *Gratiana lutescens* (Boh.) (Coleoptera: Chrysomelidae) and the flower bud feeders *Carpophilus* sp. (Coleoptera: Nitidulidae) and *Symmetrischema ardeola* (Lepidoptera: Gelechiidae).

Zimmerman found that adults of the Nitidulid *Carpophilus* sp. fed on pollen, flower buds and flowers in early summer and females oviposited in flower buds approximately 2 mm in size and larvae completed development before bud maturation. Fully developed larvae left the bud before opening and entered the soil to pupate. Extensive searches to find *Carpophilus* sp. larvae inside buds of *S. meloncillo* growing in the vicinity of SLN were negative and in cage experiments, *Carpophilus* adults avoided *S. meloncillo* buds. Zimmerman observed that the damage to *Solanum elaeagnifolium* flower buds in the Tapia (Tucuman) region ranged from 82% in December 1971 to 20% in February 1972. Zimmermann comments that because the damage was restricted to the stamens it was unlikely that *Carpophilus* sp. damage would have much effect on fruit formation because SLN is cross-pollinated.

The larvae of *Symmetrischema ardeola* develop inside closed buds of SLN and also partly in mature flowers where they spin stamens together and feed on stamens and pistils. Zimmerman notes that attacked flower buds are difficult to identify until the late instars spin the petals together, which give the flowers a lantern like appearance. In the Tapia region the observed occurrence of *S. ardeola* on SLN flower buds ranged from 0% in December 1971 to 20% in February 1972.

Zimmerman compared *Carpophilus* sp. and *S. ardeola* damage and observed that damage to stamens and pistils varied from 15% in January to 9% in February for

Carpophilus while damage for *S. ardeola* varied from 50% to 54% at the same dates. He concluded that *Carpophilus* potential to limit fruit formation was much lower than *S. ardeola.* Oviposition tests with *S. ardeola* exposed to flower buds of tomatoes, peppers and potatoes were negative, but Zimmerman mentions that the insect was also collected on *S. meloncillo* without mention of the stage(s) or numbers collected.

Another insect found to be common at all the collecting sites within the area surveyed was the beetle *Gratiana lutescens* (Boh.) (Coleoptera: Chrysomelidae). Although some adults were found on *S. meloncillo* when it was growing near *S. elaeagnifolium*, no *G. lutescens* eggs were found on this plant species. Eggs are laid in packets of two to six, onto leaves of *S. elaeagnifolium* and larvae and adults feed on leaves, petioles and flower buds. In summer a generation is completed in about 20 days and Zimmerman estimated that four to five generations occurred every year. No parasitism was observed but heavy predation by reduviid bugs was noted. In preliminary host specificity tests with adults combining feeding, survival and oviposition on potato, tomato, pepper and SLN, no oviposition was observed outside of *S. elaeagnifolium*. Limited feeding occurred on potato and pepper but adults survived and laid eggs on SLN only. However, during further tests repeated with the same plant species plus eggplant, *S. melongena*, larvae of *G. lutescens* survived and reached the adult stage on eggplant (25% survival compared with 50% survival on *S. elaeagnifolium*). As with the previous tests, no larvae survived on potato, tomato or pepper, although moderate feeding was observed on potato plants. Surveys in Argentina, including neglected eggplant cultivations, found no evidence of *G. lutescens* feeding damage on either eggplant or other economic plants. However Zimmerman reports that Bosq (1942) mentioned that *G. lutescens* was common on *S. elaeagnifolium* around Buenos Aires and that it was occasionally found on eggplant and *S. tomatillo*, a wild solanaceous weed. Additionally Zimmerman mentions that *G. pallidula*, a possible synonym of *G. lutescens,* was an occasional pest on eggplants in Texas. He concluded that unless these two species are proven not being synonyms, and unless *G. lutescens* is demonstrated not being damaging to eggplant, the potential use of *G. lutescens* to control SLN remained unlikely. However in a letter (dated 24 September 1974) to Dr Zimmerman by Richard E. White, Systematic Entomology Laboratory, U. S. National Museum, Washington, Dr White reports that W. W. Siebert conducted breeding experiments. The results of these experiments indicate that *pallidula* and *lutescens* were one species but their populations were not contiguous and therefore they should be regarded as two different subspecies, *Gratiana lutescens lutescens* (Boh.) for the southern population and *Gratiana lutescens pallidula* Boh. for the northern population. Close examination of external morphology and male genitalia did not reveal significant differences.

In addition to the organisms summarised above, Zimmerman mentions that "*other promising enemies were… an eriophyid mite and tingids*" however little information was provided on their host range and impact on SLN.

1.3. Surveys in Mexico-USA in 1973

Further in his report, Zimmerman comments on phytophagous insects associated with satansbos (SLN) in Central and North America and mentions a brief survey conducted in Mexico, Texas, New Mexico and Arizona in July 1973. This survey confirmed Goeden's findings and further suggested that the highest concentration of insects may be found in the district of Monterrey, Mexico. Zimmermann lists the insects as future candidates for biological control of SLN from North America:

- *G. pallidula lutescens* (Boh.) (Coleoptera: Chrysomelidae)
  This synonym of *G. lutescens* from Argentina is reported to be a pest of eggplant in Texas.
- *Asapharca nephelomicta* Meyrick (Lepidoptera: Gelechiidae)
  A high percentage of SLN berries is reported destroyed by larvae of this insect at San Luis Potosi, Mexico through their feeding on seed and pulp. A high larval parasitism is also reported.
- Cecidomyidae
  Zimmerman reports the occurrence of large galls near the crowns of satansbos, characteristic of Cecidomyidae presence, symptoms of stunted plants and which prevented them from flowering.
- *Trichobaris texana* (Coleoptera: Curculionidae). The larvae of this curculionid are reported to feed on pith but attacked plants did not show much damage.
- *Leptinotarsa defecta* Stahl. (Coleoptera: Chrysomelidae).The damage of this defoliating insect was commonly found.
- *Anthonomus* spp. (Coleoptera: Curculionidae).
  Zimmerman mentions a complex of small weevils inhabiting flower buds and eriophyid galls common around Monterrey, however literature records show that *Anthonomus* presence is associated with the SLN nematode and not with cecidomyid galls as mentioned by Zimmerman.

Zimmerman concludes that a region where the greatest biodiversity of specialised organisms exploiting the vegetative and reproductive organs of SLN could be considered as this plant's centre of origin, as these organisms have co-evolved with their host-plant. From his own observations Zimmermann agrees with Goeden's conclusions (1971) in that the centre of origin of satansbos in North America is located in south-western Texas and north-eastern Mexico. The complex of insects associated with SLN in Argentina suggests that the weed may also be native to South America although the diversity and specificity of the insects suggests that the more promising candidates for biological control will be found in Mexico and Texas. Zimmerman proposes a list of candidate agents listed in order of preference (Table 1).

Table 1. List of potential biological control agents for SLN in South Africa in order of preference (Zimmerman 1974)

Species	Order and Family	Region of origin
Asapharca nephelomicta	Lepidoptera: Gelechiidae	Mexico
Unidentified Cecidomyidae	Diptera: Cecidomyidae	Mexico (Monterrey)
Symmetrischema ardeola	Lepidoptera: Gelechiidae	Argentina (Tucuman)
Eriophyid mites	Acarina: Eriophyidae	Mexico, Argentina and USA
Carpophilus sp.	Coleoptera: Nitidulidae	Argentina
Anthonomus spp.	Coleoptera: Curculionidae	Mexico and USA
Trichobaris texana	Coleoptera: Curculionidae	Mexico and USA
Leptinotarsa defecta	Coleoptera:	Mexico and USA

	Chrysomelidae	
Unidentified Agromyzidae	Diptera: Agromyzidae	Argentina
Gratiana pallidula	Coleoptera: Chrysomelidae	Mexico (Monterrey), Texas
Gratiana lutescens	Coleoptera: Chrysomelidae	Argentina (Tucuman)

1.4. Surveys in Mexico 1986

In the 1980s, a CSIRO scientist, Dr Tony Wapshere examined the results of the surveys previously conducted to find suitable biological control agents in North America (Goeden 1971), Argentina and Central America (Zimmermann 1974). Wapshere (1988) reports that based on Zimmerman's results, two insects were introduced in to South Africa. The first one, the chrysomelid beetle *Gratiana lutescens* (Boh.) which was later described as a subspecies of *Gratiana pallidula* (Boh.) from Texas, was not released because it attacked eggplant, *Solanum melongena* L. (Siebert 1975; Wapshere 1988). The second insect introduced in to South Africa, the pentatomid *Arvelius albopunctatus* (De Geer), was later rejected because it attacked various cultivated Solanaceae (Siebert 1977; Wapshere 1988). Wapshere reports that the only insect released in South Africa was the fruit-feeding gelechiid moth *Frumenta nephelomicta* (Meyr.) (Wapshere 1988). Wapshere also reports that scientists in Texas had investigated the use of the endemic nematode *Orrina phyllobia* (Thorne) Brzeski (=*Nothanguina phyllobia*), which causes foliar galls on SLN, to control the weed in cotton regions of Texas (Northam and Orr 1982; Parker 1986; Robinson *et al.* 1978; Robinson *et al.* 1979; Wapshere 1988). Based on the results of Goeden and Zimmerman's explorations and their conclusions that a richer guild of organisms on SLN should exist in Mexico, Wapshere undertook a survey in this country in 1986 expecting to find specialised organisms attacking SLN rootstocks. His survey comprised the areas of Chihuahua, Torreon, Saltillo, Monterrey in the North down to San Luis Potosi and Queretaro North of Mexico City (Figure 1). Wapshere found that the most common organisms on SLN were the leaf-galling nematode *O. phyllobia*, the defoliating cassidinid beetle *G. pallidula*, and the defoliating chrysomelid beetles *L. texana* Schaeffer and *L. defecta* (Stahl) (found only in the Monterrey region). A range of other insects including the leaf tingid bugs *Gargaphia* spp., the stem-boring weevil *Trichobaris texana* LeConte, a stem-galling cecidomyid species, the fruit-feeding gelechiid moth *F. nephelomicta* and the fruit-feeding tephretid *Zonosemata vittigera* Coq. were also common. All these damaging herbivores were found on the aerial parts of the plants and no organisms were found attacking rootstocks, a result similar to Goeden and Zimmerman's results.

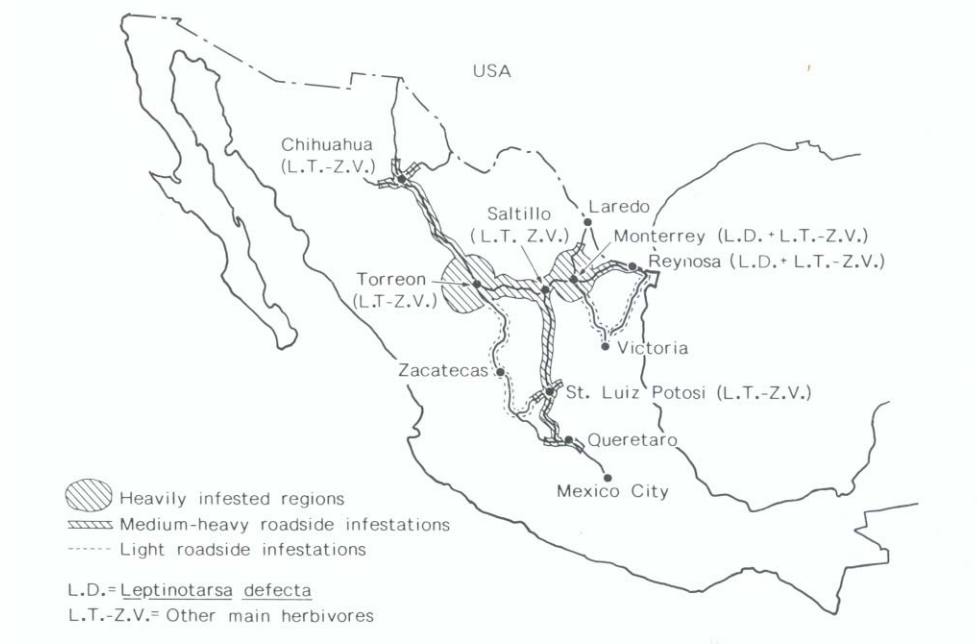

Fig. 2. Survey of *Solanum elaeagnifolium* in Mexico.

Figure 1. Map of Wapshere surveys in Mexico (reproduced from Wapshere 1988).

Wapshere found that the most common and most damaging organism to SLN was the nematode *Orrina phyllobia*. The nematode galls appear on the leaves on regenerating stems in spring. Gall formation continues throughout summer depending on adequate rainfall and favourable humidity levels, critical for the nematode survival.

Gratiana pallidula was the most frequently encountered leaf-feeding insect on *S. elaeagnifolium* in Mexico. However this species was found to attack weedy and cultivated *Solanum* species under laboratory conditions (Siebert 1975) and was recorded as an occasional pest of eggplant (Zimmermann 1974).

Wapshere reports that both the adults and larvae of *Leptinotarsa* species heavily defoliate plants in some occasions during summer. *L. texana* is the most widespread species, being recorded through most of the range of SLN in Mexico and Texas but it seems that its distribution has recently extended (Neck 1983). Wapshere also reports that according to Jacques (Jacques 1972) *L. texana* is specific to *S. elaeagnifolium* under field conditions. Burke (Burke 1963) and Goeden (Goeden 1971) recorded *L. defecta* as occurring widely in Texas, but Burke's examination and description of Goeden's material (Burke 1963) has revealed that the records are of *L. texana* (Bernon 1986). *L. defecta* has a limited distribution in north-west Mexico and adjacent regions of Texas (Jacques 1972) and has only been recorded on two wild *Solanum* species, *S. elaeagnifolium* and the closely related *S. dimidiatum* Raf. (Wapshere 1988). Wapshere provides details of tests conducted with *Leptinotarsa*: "*Laboratories studies have confirmed the restriction of* L. texana *and* L. defecta *to* S. elaeagnifolium*, since the weed has the optimum host in tests* (Hsaio 1974)*.* Solanum dulcamara *L. was attacked in the laboratory by both chrysomelids, but this nightshade of European origin is not a host under field conditions*. Solanum rostratum *Dunal, buffalo-burr, could be a secondary host of* L. texana *in the field. Very minor feeding by* L. texana *occurred* *on potato,* Solanum tuberosum *L. and by* L. defecta *on eggplant,* S. melongena *(Hsaio 1974), but neither is recorded as a pest of these cultivated* Solanum *spp*."

The tingid bugs *Gargaphia* species heavily colonise the leaves of SLN and feed on their cell contents and Wapshere found that young plants were killed. *G. opacula* Uhler has a broad host range, which includes species outside the Solanaceae. Goeden (1971) reports *G. arizonica* Drake and Carvallo from *S. elaeagnifolium*. This is the first record of a host-plant for this insect and this suggests that its host range might be restricted to SLN and would not include cultivated Solanaceae.

The larvae of the weevil *Trichobaris texana* bore the central part of main and side stems of SLN but do not descend beyond the collar into the root. In Texas the weevil had one generation per year and adults overwinter in the plant and emerge in spring (Cuda 1983). The insect has a weakening effect on the weed (Goeden 1971) and causes stunting of vegetative growth (Cuda 1983; Cuda and Burke 1985) and has been recorded on a small group of non-cultivated *Solanum* species including *S. elaeagnifolium*, however there is a record from eggplant (Cuda 1983).

Wapshere reports that the attack of an unidentified cecidomyid fly causes the formation of a swollen gall on stems of SLN, however heavy infestations were not observed in the field.

Wapshere also mentions that one of the most common and abundant insects found was the gelechiid moth, *Frumenta nephelomicta* whose larvae feed on seeds and cause fruit enlargement (Zimmermann 1974). According to Wapshere, the larvae found in fruits by Goeden (Goeden 1971) and believed to be those of a carponsinid, would instead be the larvae of this gelechiid. This species has not been recorded on fruits of cultivated Solanaceae in the USA and this suggests that it is restricted to *S. elaeagnifolium*.

The adults of *Zonosemata vittigera* were found to visit fruits of SLN where occasionally several eggs were deposited. The larvae of this tephritid fly destroy fruits and pupate in the soil. *S. elaeagnifolium* is the only known host of this insect and in laboratory tests the fly did not oviposit on any other cultivated or wild Solanaceae (Goeden and Ricker 1971).

Wapshere discusses the distribution of agents and notes that Goeden (Goeden 1971) did not record the presence of the nematode *O. phyllobia* but recorded the first eastern occurrence of the weevil *Anthonomus aeneolus* Dietz whose larvae feed within the nematode leaf-galls. Wapshere believes that based on its associated herbivores, SLN evolved in the Monterrey region of Mexico. He states that the specific *L. texana* is restricted to that region and has recently spread from there (Neck 1983) and that other herbivores have a distribution range with Monterrey as the centre. Wapshere considers that the plant and its herbivores are adapted to the Monterrey climate (Wapshere 1988), which has a maximum rainfall in summer and/or a marked excess rainfall over evaporation from spring to autumn and a winter drought (Wapshere 1993). This climatic characteristic seems to be the most important feature explaining why herbivores gradually disappear as the distance from Monterrey increases in the absence of summer rainfall even if SLN plants are still present (Figure 2). Rainfall and humidity are important characteristics for the survival of the nematode *O. phyllobia* in the soil and its movement between the different parts of the plant (Robinson *et al.* 1978). Wapshere points out that in Australia the main SLN infestations are in the Adelaide (South Australia), Swan Hill (northern Victoria) and Leeton (southwest New South Wales) regions and the main climatic characteristic of these regions is a marked summer drought. This characteristic would make these locations unlikely to support any of the agents originating from the Monterrey region, except potential marginal populations of the tephritid *Z. vittigera* and the tortoise beetle *G. pallidula* at levels at which they are recorded in California (Goeden 1971; Goeden and Ricker 1971). On the contrary, northerly infestations of SLN in the higher summer rainfall areas surrounding Mudgee and Inverell could possibly support agent populations. However, in regions of wheat cultivation or wheat/fallow rotation where SLN control is desired, cultivation would be detrimental to agents over wintering in the soil and would negatively affect their populations. Wapshere also notes the absence of organisms attacking SLN rootstock in the region of origin. In terms of biological control, the absence of specialist rootstock agents is disappointing, as SLN plants regenerate from root fragments.

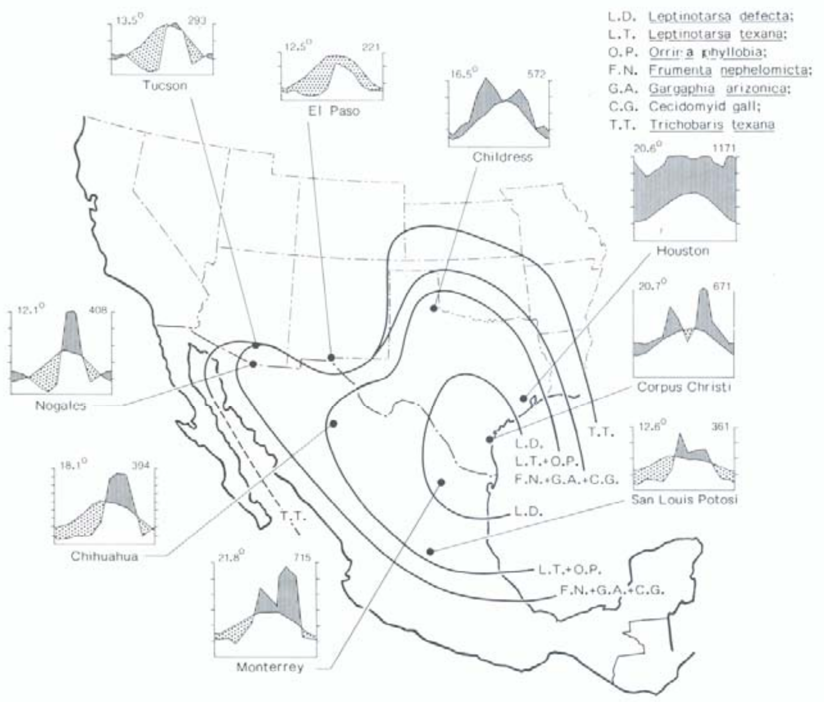

Fig. 3. Distribution of herbivores of *Solanum elaeagnifolium* in Mexico and U.S.A. and climates of the regions (Climadiagrams from Walter and Lieth 1964).

Figure 2. Climatic charts of the regions surveyed by Wapshere (reproduced from Wapshere 1988)

2. Biological control of SLN in South Africa

2.1. Surveys in South Africa

SLN was first recorded in South Africa in 1952 (Siebert 1975) where it has become an invasive weed of arable and pastoral lands. Mechanical and herbicidal attempts to control it have been unsuccessful (Olckers and Zimmermann 1991). Other invasive Solanaceae in South Africa are *Solanum mauritianum* Scop. (bugweed or bugtree), a species indigenous to Argentina, Brazil and Uruguay, which has been introduced to Africa, Australia, India and islands of the Atlantic, Indian and Pacific oceans (Olckers and Zimmermann 1991) and *Solanum* *sisymbriifolium* Lam, indigenous to warm temperate South America. Both weeds have been targeted for biological control in South Africa for some time. Pre-introduction surveys on the herbivores of exotic, native and cultivated *Solanum* spp. were undertaken in South Africa (Olckers and Hulley 1995). The objectives of these surveys were to determine the diversity of herbivores on native *Solanum* species, their pre-adaptation and relationships to exotic species, the impact of native herbivores on weedy and cultivated species and the possible presence of potential biological control agents. The taxonomic and ecological similarities between native herbivores and exotic agents were also investigated to determine to which extent native parasitoids may later transfer to imported hosts (Olckers and Hulley 1995). The results of these surveys were published by Olckers and Hulley (Hill *et al.* 1993; Olckers and Hulley 1989; Olckers and Hulley 1991a; Olckers and Hulley 1994) (Olckers and Hulley 1995) and are summarised in Table 2.

Table 2. Diversity of insect herbivores on exotic, cultivated and native species of *Solanum* in South Africa (reproduced from Olckers and Hulley (1995).

	7.1.1.1.1 Number of herbivores species			
***Solanum* species**	**Specialists**	**Generalists**	**Total**	**Rank[a]**
Exotic				
S. elaeagnifolium	12	9	21	6
S. mauritianum	5	17	22	8
S. sisymbriifolium	2	10	12	9
Cultivated				
S. melongena	17	11	28	3
Native				
S. panduriforme	27	28	55	1
S. incanum	22	15	37	2
S. linnaeanum	16	17	38	4
S. coccineum	15	5	20	5
S. rigescens	8	7	15	7

[a] According to diversity of specialist herbivore species

The three exotic *Solanum* spp. had few generalist herbivores and were relatively undamaged in comparison to native *Solanum* spp. and no evidence was found of accidentally introduced herbivores (Olckers and Hulley 1995). The authors observed that the exotic *Solanum* were under-exploited and that the herbivores of native *Solanum* were not pre-adapted to exploit the exotic *Solanum*. The only appreciable damage to SLN in South Africa was caused by polyphagous hemipteran insects inflicting up to 46-67% seed mortality (Olckers and Hulley 1991b). This damage was caused by the polyphagous cosmopolitan *Nezara viridula* L., the indigenous *Dryadocoris apicalis* (H. Sch.) (Hemiptera: Pentatomidae) and the native *Spilostethus furculus* (H. S.) (Hemiptera: Lygaeidae). The observed damage also resulted in a severe reduction in the germination potential of seeds from damaged fruits (Olckers and Hulley 1991b). The surveys showed that the fauna supported by native *Solanum* included similar herbivores (similar families of insect specialised on the same plant parts) which increased the chance for parasitoids to shift to newly imported agents. Thus, it was predicted that many candidate agents would be parasitised in South Africa. This was confirmed when results showed that parasitism strongly affected the populations of the imported gelechiid *Frumenta* sp. accounting for 51% of insect mortality (Olckers 1991), thus compromising its success. However the defoliating *Leptinotarsa* spp. were considered less likely to attract parasitoids because their larvae pupate in the soil and because the native parasitoids which attack the related native defoliator *Conchyloctenia* spp. (Coleoptera: Chrysomelidae: Cassidinae) parasitise eggs only. *Leptinotarsa* spp. eggs are more similar to the eggs of the native *Epilachna* spp. from which no parasitoids were identified. It was concluded that the most promising candidates were *Leptinotarsa* spp., *Trichobaris texana* LeConte and *Anthonomus* sp. (Olckers and Hulley 1995). The surveys also identified a greater number of insects injurious to eggplant than reported in the literature (Olckers and Hulley 1994). During host specificity tests *Leptinotarsa* spp. and *Gratiana* spp. were found to attack eggplant while other solanaceous crops were not accepted. These insects were not known to attack eggplant on the American continent but were considered for a while as presenting a risk. However, due to the wide use of pesticides to protect eggplant cultivations from generalist insects it was considered that the crops were sufficiently protected against any potential damage by the biological control agents considered. This was later confirmed after trials demonstrated that the most commonly used chemicals were lethal to *Leptinotarsa* spp., thus preventing any long-term damage to the crops (Olckers and Hulley 1994).

2.2. Implementation of biological control

2.2.1. The leaf beetles *Gratiana lutescens* (Boh.) and *G. pallidula* (Coleoptera: Chrysomelidae: Cassidinae)

The first biological control agent considered was the tortoise beetle *Gratiana lutescens* (Boh.) which was seen by Zimmermann (1974) as one of the most promising agents as it was present at all the sites he surveyed in central Argentina. A small consignment of insects was imported in Stellenbosch in February 1973 from Argentina and a smaller number of individuals of the related species *G. pallidula* (Boh.) was imported from Texas in September 1973. The results of the work conducted on their biology and host-specificity has been published by Siebert (1975).

Zimmermann had previously conducted host specificity tests in Argentina under cage conditions. He found that adults *G. lutescens “hardly fed at all on potato and pepper and failed to feed on tomato plants*” and that *“no oviposition was observed on potato, tomato or pepper plants but eggs were found on SLN*”. Adults survived only on SLN plants. In tests conducted with first instar larvae, no feeding was observed on tomato or pepper plants and larvae died after four days, slight feeding was seen on potato plants but all larvae died within two weeks. Normal feeding occurred on eggplant in comparison with SLN. Siebert also reports that Zimmermann visited neglected eggplant cultivations near Tucuman in Argentina and did not find any damage caused by *G. lutescens* nor any report of such damage. However in one reference examined by Zimmermann “*it was stated that G. lutescens is occasionally found on eggplant and a wild solanaceous weed around Buenos Aires.*” In his study Siebert observed that *G. lutescens* fed voraciously on eggplant, a variety of sodom apple (*S. sodomeum* L. var. *hermannii* Dun.) and SLN plants. It is important to note that Siebert conducted his tests using excised leaves (Hill 1999) a detail that he did not reveal in his paper. In comparison a limited amount of feeding occurred on potato, green pepper and *Datura inoxia* (Mill.) but no oviposition occurred on these plants. Adult *G. lutescens* did not feed on the leaves of *S. nigrum* L., *S. mauritianum* Scop., *Antizoma capensis* Diels, tobacco, sunflower, spinach and beetroot under confined conditions (Table 3). During his study *G. lutescens* completed three generations and successfully over wintered in tests on eggplants and the insect was successfully and easily reared on *S. sodomeum* for several successive generations, probably due to the on-going supply of fresh leaves. Importantly, adults from colonies maintained for a few generations on eggplant, SLN or apple of sodom, did not show any feeding preference when given the choice between these three species.

Table 3. Partial results of host-specificity tests conducted in South Africa with *Gratiana lutescens*

Plant species tested	Number and stage tested and survival duration (days)	Zimmermann (1974) results	Siebert (1975) results*
S. tuberosum (potato)	20 Adults (13)	Minimal feeding, no oviposition, no survival	Slight feeding, no oviposition
	20 1st instar larvae (14)	Slight feeding	Slight feeding
Lycopersicon esculentum (tomato)	20 Adults (4)	No feeding, no oviposition, no survival,	
	20 1st instar larvae (4)	No feeding	Slight feeding
Capsicum sp. (green pepper)	20 Adults (9)	Minimal feeding, no oviposition, no survival	Slight feeding, no oviposition
	20 1st instar larvae (4)	No feeding	
SLN	20 Adults	Eggs deposited	
SLN	Adults		Heavy feeding
SLN	1st instar larvae		Heavy feeding
S. melongena (eggplant)	Adults		Heavy feeding
	1st instar larvae		Heavy feeding
S. sodomeum var. *hermanii* (apple of sodom)	Adults		Heavy feeding
	1st instar larvae		Heavy feeding
S. nigrum	Adults		No feeding
	1st instar larvae		Slight feeding
Datura inoxia	Adults		Slight feeding, no oviposition
	1st instar larvae		No feeding

* no indication given on the number of individuals (adults or larvae) utilised in the tests

When imported in September 1973 from Texas, *G. pallidula* adults did not overwinter on arrival as expected coming from the Northern hemisphere, and laid eggs under spring conditions as experienced in South Africa. Cross breeding between *G. lutescens* and *G. pallidula* using virgin females of both species occurred readily and virgin female *G. lutescens* confined with *G. pallidula* males laid fertile eggs at an average of 69 eggs/female producing about 40 mature offspring. In reciprocal crosses, fertile eggs were produced, averaging 94 eggs/female of which about 50 adults were obtained and offspring produced both ways were fertile. Following these results and despite their geographical isolation, Dr R. E. White, from the United States National Museum considered that the two taxa should be viewed as two geographically isolated subspecies rather than true species. He proposed the name *G. lutescens lutescens* (Boh.) for the South American populations and *G. lutescens pallidula* (Boh.) for the North American populations (White 1975).

In his conclusion Siebert recommended that, in the case where no other effective biological control agent would be discovered on SLN, it would be necessary to conduct more studies to determine precisely the threat posed by *Gratiana* species to cultivated solanaceous plants, especially eggplant. In the meantime he did not recommend the release of the *Gratiana* species under consideration (Siebert 1975). Zimmermann also reports that *G. pallidula* is a recorded pest in Texas where it feeds and breeds on eggplants (Zimmermann 1974). In a different study, Hill and Hulley (Hill and Hulley 1995) examined the suitability of *Gratiana spadicea* (Klug) (Coleoptera: Chrysomelidae: Cassidinae) for the biological control of *Solanum sisymbriifolium* Lamarck. In their discussion on *Gratiana* species, Hill and Hulley report that *G. lutescens* and *G. pallidula* were previously rejected because these insects completed several generations on eggplant and the native *S. linnaeanum* Hepper and Jaeger. They also report that Spaeth (Spaeth 1914) considers *Cassida pallidula*, *Nuzonia pallidula* and *Gratiana pallidula* as the same species. As *Nuzonia pallidula* (Boh.) is a recorded pest of eggplant in the USA (Rolston *et al.* 1965), Hill and Hulley suggest that this could explain the host range observed by Siebert during his tests. However in a letter dated 24 September, 1974 to H. G. Zimmermann, Dr. R. E. White expressed serious doubts about the assignation of *G. pallidulla* to *Nuzonia*, as he found significant differences between the two.

Siebert's tests results were revisited by Hill (1999) because he had used excised leaves in no-choice tests. During these tests larvae were able to develop on *S. melongena* and the indigenous *S. linnaeanum* (Hepper & Jaeger). It had also been demonstrated that leaf excision initiated chemical changes in leaves that affected leaf-feeding chrysomelids (Jones and Coleman 1988) and these authors recommended that results obtained using excised leaves should be interpreted with caution (Hill 1999). Olckers and Hulley (Olckers and Zimmermann 1994) also questioned Siebert's use of excised leaves as they recorded high mortalities of *G. lutescens* larvae reared on cut leaves of SLN, that were not significantly different from mortalities on non-target *Solanum* species (Hill 1999). Olckers and Hulley demonstrated that Siebert's results were flawed due to the use of excised leaves. Excised leaves induced a change in the acceptability of hosts by the insect and led to the rejection of *G. lutescens* (Olckers and Zimmermann 1994). Hill decided to re-evaluate *G. lutescens*, and collections were made from SLN in the Gualeguachu, Campana and Uspallata regions of Argentina in 1995 (Hill 1999). Hill re-tested *G. lutescens* through no-choice tests using larvae on potted plants and a larger number of *Solanum* species than tested by Olckers and Hulley (Olckers and Zimmermann 1994), adult paired-choice tests and adult multi-choice tests. The results of this study were that *G. lutescens* was capable of attacking eggplant and a number of indigenous *Solanum* species, and the conclusion was that the insect should not be released for the biological control of SLN in South

Africa. It was later reported that *G. lutescens* was a minor pest of eggplant and potato in the USA (Olckers *et al.* 1999).

2.2.2. The leaf beetles *Leptinotarsa texana* (Schaeffer) *and Leptinotarsa defecta* Stål (Coleoptera: Chrysomelidae)

These beetles were identified during surveys in the southern USA (Goeden 1971) and Mexico (Wapshere 1988) as causing important damage to SLN through larval and adult feeding on leaves, flowers, young fruits and stems. The biology of both species is similar (Hoffmann 1985). Females lay batches of 20-40 eggs on the lower sides of leaves and larvae feed on SLN plants before pupating in the soil. Adults go through a winter diapause. SLN is the primary host for both species but *L. defecta* has also been occasionally collected on *S. rosratum* Dun. and *S. tridynamum* Dun. Neither species has been recorded feeding on any solanaceous crop including *S. melongena*. *L. texana* and *L. defecta* were imported from Texas in 1985 and 1989. In South Africa *S. melongena* supported full development of both *Leptinotarsa* species under caged conditions (Olckers and Zimmermann 1991). However, larval mortality was much higher and fecundity of adults reared on these hosts lower than on SLN (Olckers and Zimmermann 1991). It was suggested that eggplants were unlikely to maintain viable field populations after release (Zimmermann 1987). In cages, adult *L. texana* and *L. defecta* showed clear oviposition preference for SLN, and the level of feeding damage on two of the species tested, *S. melongena* and *S. coccineum*, were similar to the levels of feeding on SLN (Zimmermann 1987). The release of adult *L. texana* and *L. defecta* was not approved, pending inquiry on their host specificity and their potential to establish on cultivated eggplants. As *L. texana* and *L. defecta* were still regarded as promising agents for the control of SLN the risk to eggplant cultivations was re-assessed by evaluating cultivation practices, damage inflicted by native solanaceous insects to the crops and the nature of crop protection procedures (Olckers *et al.* 1999). Several South African solanaceous insects feed on cultivated eggplant but their damage was seen as negligible in comparison with generalist pests. Imported agents were not seen as a significant additional risk as the existing intensive pesticide regimes would provide a deterrent should these agents inflict some damage to eggplant (Olckers *et al.* 1999). It was considered that the native *Solanum* species would be unlikely to suffer more than incidental damage. None of the native *Solanum* were seen as endangered or having any special aesthetic value as, in fact several species were seen as minor weeds. The fact that native *Solanum* are pioneer plants of disturbed areas and thus, more threatened by exotic *Solanum* species rather than by imported agents, was regarded as a fair “trade off” for the possibility of controlling the weeds (Olckers 1996b).

At this point of the program the South African scientists had to decide about the safety of some agents should they be released. This decision was made through a risk-analysis process weighing all available information:

Risks to eggplant

1. Due to the vegetative growth of SLN, defoliating agents were seen as having the most potential for inflicting indirect but continual stress to the root-stocks to cause gradual dieback (Olckers and Zimmermann 1995).

2. The defoliators *Leptinotarsa texana* (Schaeffer) and *Leptinotarsa defecta* Stål (Coleoptera: Chrysomelidae) were the most promising candidates. Both adults

and larvae are voracious feeders and cause considerable damage, *L. texana* being the most destructive and having the highest fecundity (Olckers and Zimmermann 1995).

3. SLN is the primary host of both species and neither species has been recorded on any solanaceous crop on the American continent (Olckers and Zimmermann 1995). Eggplant is extensively cultivated in North America in regions where SLN and the beetles occur but *Leptinotarsa* was never recorded as a pest of eggplant in the USA (Olckers and Zimmermann 1995).

4. *Leptinotarsa* species, like other agents, have displayed expanded host ranges under host specificity tests conducted in cages.

5. Most of eggplant cultivations in South Africa were distant to SLN infestations and therefore a geographical barrier existed between the crops and the weed infestations.

6. Ovipositing *Leptinotarsa* females showed an ovipositing preference for SLN over eggplant and higher insect mortality, extended development periods and reduced fecundity were observed on eggplant (Olckers and Zimmermann 1995).

7. Eggplant is an annual winter crop grown in rotation with non-solanaceous crops and few insects would survive the rotational programs and soil fumigation (Olckers and Hulley 1994; Olckers and Zimmermann 1995).

8. Chemical defences against insects seem to be lower in eggplant and chemicals used to protect the crops were lethal to *Leptinotarsa* species (Olckers and Zimmermann 1995).

Risks to native *Solanum* species

1. Cage tests conducted in the USA showed that the beetles could attack some native species, although this did not occur in the field (Olckers and Zimmermann 1995).

2. Native South African *Solanum* species probably had more inherent chemical defences and thus should be less prone to attack (Olckers and Zimmermann 1995).

3. Reduced fitness of *Leptinotarsa* species was apparent on five native *Solanum* and native *Solanum* were rarely selected by ovipositing females. Damage causing mortality and population extinction of native *Solanum* was considered unlikely.

4. Due to their patchy distribution, native *Solanum* species were seen as less vulnerable to attack by oligophagous insects, which concentrate on most abundant hosts.

5. The five Solanum species attacked during the cage tests were listed as indigenous weeds with low conservation and aesthetic values and therefore minor damage could be accepted (Olckers and Zimmermann 1995).

Olckers & Hulley (Olckers and Hulley 1994) conducted extensive studies on the importance of eggplant cultivation, the rotational and chemicals used as well as insects and mites recorded as pests of the crop (Olckers and Hulley 1994). The final conclusion of these studies was that it was unlikely that *L. texana* and *L. defecta* would cause significant damage to eggplant and that their release to control SLN was justified.

2.3. Evaluation of the Biological control of SLN in South Africa

Following the surveys for natural enemies of SLN in the Americas conducted by Goeden (Goeden 1971) and Zimmermann (Zimmermann 1974) an account on the research results was published by Neser *et al.* (Neser *et al.* 1989). Neser *et al.* report that the insects collected in the USA on SLN could be easily identified and their records verified while in contrast there were problems in the identification, host records and literature concerning the material collected in South America. Below is a summary of the different biological control agents introduced in South Africa for host-specificity testing and their subsequent status (Table 4).

Table 4. Status of potential biological control agents introduced in South Africa from Neser *et al.* (1989).

Organism Date	**introduce d**	7.1.2 Ori gin	**Status**
Gratiana lutescens (Boh.) (Coleoptera: Chrysomelidae)	1973	Argentina	Breeds successfully on *Solanum melongena*. Not released
Gratiana pallidula (Boh.) (Coleoptera: Chrysomelidae)	1973	Argentina	Not host-specific. Not released
Conotrachelus bisignatus Boh. (Coleoptera: Curculionidae)	1974	Texas	Not host-specific. Not released
Frumenta nephelomicta (Meyr.) (Lepidoptera: Gelechiidae)	1976	Mexico	Host-specific, released between 1978 and 1983. Not established.
Orrinia phyllobia (Thorne) (Nematoda: Neotylenchidae)	1982-84	Texas	Produced slight galling on *S. melongena* and some native *Solanum* species. Not released.
Leptinotarsa texana (Schaeffer) (Coleoptera: Chrysomelidae)	1985, 1987	Texas	Completes life cycle on *S. melongena* and on six native *Solanum* species under cage conditions.
Leptinotarsa defecta Stål (Coleoptera: Chrysomelidae)	1985, 1987	Texas	Develops on *S. melongena* and on a few native *Solanum* species.

Of the six insect herbivores and one nematode tested for their host-specificity to SLN, the moth *Frumenta nephelomicta* (Meyr.) (Lepidoptera: Gelechiidae) was the only insect that did not develop on any indigenous or economic Solanaceae tested. The insect was released on three occasions but failed to establish. *G. lutescens* (Boh.) and *G. pallidula* (Boh.) were tested in 1973 and were rejected because they developed equally well on *S. melongena* and SLN (Neser *et al.* 1989; Siebert 1975). The nematode *O. phyllobia* (Thorne), and the chrysomelid beetles *L. texana* (Schaeffer) and *L. defecta* Stål showed the same ability during starvation and multiple-choice host-specificity tests. No difference in their biological characteristics (fecundity, survival, rate of development and longevity) was observed between their natural host SLN and *S. melongena* and all three species completed three generations without loss of fitness (Neser *et al.* 1989). In this respect it is important to note that none of these species was recorded to attack *S. melongena* either in the USA or South America. In their discussion Neser *et al.* raise the question of the reliability of starvation and multiple-choice tests under caged conditions considering the non-pest status of the candidates tested in their countries of origin. The authors suggest the "host plant masking" effect generated by the *S. melongena* cultivars tested which may have lost some of their toxins and chemical deterrents through domestication and therefore may have appeared as "neutral" hosts acceptable under artificial conditions during the tests (Neser *et al.* 1989). In South Africa *S. melongena* is not known to be attacked by any phytophagous insects feeding on indigenous *Solanum* species. Field tests are underway in South Africa to verify the behaviour and host preferences of *L. texana* behaviour under natural conditions (Zimmermann and Hoffman 2005) after its establishment. The indigenous tortoise beetle *Henesepilachna hirtas* Thunberg which has various indigenous *Solanum* spp. as hosts has not been recorded as attacking eggplant, however when placed on eggplant in caged conditions it readily developed on this plant (Neser *et al.* 1989). This illustrates that host-specificity test results in cages may show a range of unexpected results that may lead to the early rejection of some agents.

A more recent account on the research on SLN agents was published by Olckers (1996a). In this article Olckers highlights the difficulty of interpreting host-specificity test results, especially after results led to the rejection of most of the agents considered, including the most promising *Leptinotarsa* species (Table 5).

Table 5. Status of candidate agents evaluated for the biological control of SLN in South Africa (Olckers 1996a).

Agent 7.	**1.2.1.1**	**Origin Dam**	**age**	**Status**
Gratiana lutescens (Boh.) (Col. Chrysomelidae)	1973	Argentin a, Texas	Defoliator	Rejected
Arvelius albopunctatus (DeGeer) (Hemip. Pentatomidae)	1974	Argentin a	Seed feeder	Rejected
Conotrachelus bisignatus (Boh.) (Col. Curculionidae)	1974	Argentin a	Seed feeder	Rejected
Frumenta nephelomicta Meyrick (Lep. Gelechiidae)	1976	Mexico	Fruit galler	Released; not established
Ditylenchus phyllobius (Thorne) Filip'ev (Nematoda)	1984	Texas	Leaf galler	Rejected
Leptinotarsa texana Schaeffer (Col. Chrysomelidae)	1985-1989	Texas	Defoliator	Released; established
7.1.2.2 Leptinotarsa defecta *Stål* (Col. Chrysomelidae)	1985-1987	Texas	Defoliator	Released; established
Frumenta sp. nov. (Lep. Gelechiidae)	1989	Texas	Fruit and stem galler	Released locally; not established

2.3.1. The leaf beetles *Leptinotarsa texana* (Schaeffer) *and Leptinotarsa defecta* Stål (Coleoptera: Chrysomelidae)

L. texana and *L. defecta* were released in South Africa in 1992 (Olckers 1996b) and both species have since established but, while *L. texana* has proliferated at several release sites, *L. defecta* has remained localised and relatively scarce (Hoffman *et al.* 1998). Although *L. texana* adults can fly, the insects are apparently not inclined to do so and their populations have been observed to increase on SLN plants in one area until they exhaust their food supply, stripping all edible parts of the plants. The insects then move to adjacent plants (Hoffman *et al.* 1998) in bands, phenomenon which has been described as "solitary population wave" (Kovalev 1988). Hoffmann *et al.* conducted a field study in 1994-97 to evaluate the extent of damage caused by measuring the above-ground biomass of SLN plants subjected to the wave and in plots with and without *L. texana*. Their results showed that behind the advancing wave of beetles the plants were stripped of leaves, meristems and flowers, with only fruits remaining. They also demonstrated that there was a dramatic reduction in the stem length, above-ground biomass and number of fruits due to *L. texana* feeding. The authors concluded that even at low density, the insects substantially impacted on the weed and although the insects did not feed on the fruits, fruit production was almost prevented. However additional studies were needed to know if the above-ground damage was sufficient to stop or slow the regeneration of plants (Hoffman *et al.* 1998).

Since 1998, the South African scientists have not been able to continue the monitoring and evaluation of *Leptinotarsa* spp. impact on SLN due to the redirection of research funding and priorities toward invasive exotic *Acacia* species. However the landowners and farmers feedback on *Leptinotarsa* spp. is very positive as several of them believe that SLN is no longer a problem. Many landowners have collected beetles for redistribution and are excited by the level of damage observed (John Hoffmann, pers. comm. 2006). Despite the absence of quantitative data, scientists believe that SLN is less prolific than in the past and the beetles appear to impact on the regenerative ability of SLN suggesting that root reserves are indirectly affected by beetles feeding on the aerial parts of plants (John Hoffmann, pers. comm. 2006). Scientists however, have not been able to establish *Leptinotarsa* species in the winter rainfall areas of South Africa.

2.3.2. The fruit feeder *Frumenta nephelomicta* Meyrick (Lepidoptera: Gelechiidae)

The larvae of *Frumenta nephelomicta* destroy a high proportion of SLN fruits in Mexico (Olckers and Zimmermann 1991; Zimmermann 1974). The females apparently scatter the minute eggs on the soil around the plants and while some eggs hatch immediately others diapause for long periods (Olckers and Zimmermann 1991). Neonate larvae enter the flower buds and ovaries and feed inside developing fruits preventing seed formation (Neser and Siebert 1977). Infested fruits have a spongy texture and are larger than healthy fruits (Olckers and Zimmermann 1991). In the absence of flowers the larvae become stem gallers (Olckers and Zimmermann 1991). *F. nephelomicta* was imported in South Africa from Mexico in 1976 (Olckers and Zimmermann 1991). The insect did not develop on indigenous *Solanum* species or solanaceous crops (Neser and Siebert 1977; Neser *et al.* 1989). Between 1979 and 1985 three releases were made but the insect failed to establish (Olckers and Zimmermann 1991). After the last release, a survey was conducted and revealed that 60% of the 50,000 eggs released had hatched but only six infested fruits were found, and some of the remaining eggs were still viable (Olckers and Zimmermann 1991). It was also found that climatic conditions at the time of the release caused a diminished fruit set and may have contributed to the poor survival of neonate larvae (Olckers and Zimmermann 1991; Zimmermann 1986). *F. nephelomicta* was reintroduced from Texas in 1989 and more suitable methods of release were investigated (Olckers and Zimmermann 1991). In a later article, Olckers (Olckers 1995) reveals that two North American species of *Frumenta* were imported in South Africa. Olckers confirms that the first species was *F. nephelomicta* released between 1979 and 1985 failed to establish. The second *Frumenta* (Sp. A) is an undescribed species imported in 1989. The biology of immature stages of both species is similar (Olckers 1995), neonate larvae enter the flower buds and ovaries singly and initiate the development of galled seedless fruits (Olckers 1995). *F. nephelomicta* is abundant in Mexico (Wapshere 1988; Zimmermann 1974) and *Frumenta* (Sp. A) occur in the adjacent American states (Olckers 1995). Goeden (Goeden 1971) collected caterpillars of an "unidentified carposinid or near" in swollen immature fruit of SLN in Texas and Arizona, which were assumed to be *F. nephelomicta* (Wapshere 1988), but were probably *Frumenta* (Sp. A) (Olckers 1995). During the 1989 import, both stem galls and fruit galls, normally associated with *F. nephelomicta* had been collected in Texas and the stem galls were assumed to be caused by a different moth species (Olckers 1995). The moths emerging from the fruits and stems were kept separately and used to rear two separate colonies in quarantine at the Uitenhage Weed Laboratory but the comparison of female genitalia showed that a single species was involved. This was confirmed when neonate larvae from fruit-reared moths initiated stem galls on the shoots of budless plants (Olckers 1995). However, in the same article Olckers states that in 1991 Hodges (personal communication) confirmed that *Frumenta* (Sp. A) from Texas was an undescribed species that had been only collected on SLN. After the failure of the releases of *F. nephelomicta* in 1985, releases of 570 neonate larvae of *Frumenta* (Sp. A) on flower buds and shoots of SLN plants was attempted between November 1989 and January 1990 (Olckers 1995). In 1990, only 21% of larvae initiated galls on SLN plants (118 galls from 570 larvae released), this result being much higher that the result obtained with the release of *F. nephelomicta* in 1985. Unfortunately adult moths emerged from only 14% of the galls giving a final result of 3% of successful emergence (17 adults out of 570). In contrast hymenopteran parasitoids emerged from 44% of the galls, irrespective of the gall location (fruits or stems). The native parasitoids involved were not identified but the parasitism levels were found to be similar to those of the native gelechiid species developing on native *Solanum* plants in South Africa (Olckers 1995). The numbers of galls recovered in the field was 9 in 1991, 12 in 1992 and none in 1993. It was concluded that the moth was unlikely to establish in South Africa and consequently it was not planned to reintroduce *F. nephelomicta* or *Frumenta* (Sp. A) for the biological control of SLN.

2.4. Biological control agents previously assessed for SLN but not released

2.4.1. The leaf-galling nematode *Ditylenchus phyllobius* (Thorne) Filip'ev (Nematoda Tylenchina: Anguinidae)

Previously known as *Nothanguina phyllobia* (Thorne) (=*Orrina phyllobia* (Thorne) =*Ditylenchus phyllobius* (Thorne) Filip'ev) the taxonomic status of the nematode was reassessed and on the basis of its general appearance and biology. It was renamed *Ditylenchus phyllobius* (Thorne) (Fortuner and Maggenti 1987) while the genus name *Orrina* is considered a junior synonym.

The nematode was first reported from central Arizona (Thorne 1961) and its distribution extends to the Rio Grande valley in Texas and coincide with SLN distribution in south-west USA (Robinson *et al.* 1978). The nematode was identified to infect SLN in Texas in 1974 (Orr *et al.* 1975) and was considered to have some potential for the biological control of this weed. Larvae of the nematode infect leaves that become galled and abscissed. Larvae remain in the soil but can be dispersed by irrigation, rainwater, dust, wind and soil movement (Esser and Orr 1979) but the nematode larvae were never found in SLN root tissue (Robinson *et al.* 1978). A limited number of economic plants and wild species were inoculated with a nematode isolate and failed to produce galls, while at the same time SLN inoculated control plants developed galls as observed under natural conditions (Orr *et al.* 1975). From these results these authors concluded that the nematode was specific to SLN and could be used as an economically important agent to control the weed. Further studies on the pathogenicity of the nematode showed that up to 50% of SLN plants were killed while sixteen other plant species which included crops and various solanacaeous crops and weeds remained uninfected (Orr 1976). Surveys conducted throughout areas with high nematode infestations to identify the nematode presence on other plant species returned negative results (Robinson *et al.* 1978). These authors concluded that the nematode distribution and its pronounced host specificity to SLN suggested strong coevolution between the parasite and its host, thus minimising the possibility of the nematode switching host if its populations were augmented through a biological control program (Robinson *et al.* 1978). In 1983 and 1984 field trials were conducted in Texas to control SLN growing in cotton crops. Up to 68% of SLN plants were found to be infected by the nematode when a 28 kg/acre nematode inoculum was applied in May 1984 to cotton seeds in furrows at plantation time, with a 270 mm rainfall. No infection was observed on SLN plants that had been sprayed with the same inoculum in August.

A pilot project was established in Texas to determine the feasibility of the use of the nematode to control SLN infestations (Parker 1986).

The nematode was considered for the biological control of SLN in Australia. After the nomination of SLN as a target for biological control in 1985, the nematode was imported into a quarantine facility in Frankston, Victoria in 1987 for thorough host specificity studies. A total of 118 plant species were screened and only species in the genus *Solanum* and from the section *Oliganthes* and *Melongena* were found to be suitable for the nematode survival. The nematode produced galls on 13 native Australian *Solanum* species and on 13 out of 15 *S. melongena* (eggplant) cultivars tested (Field unpublished results).

Although *D. phyllobius* has never been reported as a pest of eggplant in the USA, these results demonstrated that the potential host range of the nematode was larger than initially thought. Due to the risk posed to native Australian *Solanum* species, the nematode was considered unsuitable for release.

In South Africa, Scott (1985) tested the host specificity of *D. phyllobius* on 14 plant species in a greenhouse and under confined field conditions between 1984 and 1986. Although a high percentage of *S. melongena* plants were colonised, damage to fruits was minimal and fruit development was unaffected. Three indigenous *Solanum* weeds, *S. panduriforme* E. Mey, *S. coccineum* Jacq. and *S. burchellii* Dun., were also slightly galled but only SLN was affected to some degree (Scott 1985). Permission for release was withheld pending further investigations. The nematode was later rejected as a suitable agent (Table 7) (Olckers 1996a).

2.4.2. The fruit and seed feeder *Arvelius albopunctatus* (De Geer) (Hemiptera: Pentatomidae)

Goeden (1971) listed *A. albopunctatus* as one of the phytophagous insects on SLN collected at one location in the Rio Grande City area, USA (South West Texas). However Zimmermann (1974) discounted most hemiptera as promising candidates for biological control. This included *A. albopunctatus* which had been recorded feeding on various cultivated solanaceae and soybeans in South America (Costa-Lima 1968; Hayward 1958 cited in Zimmermann 1974). Despite this clear statement, Siebert (1977) proceeded and investigated *A. albopunctatus* life cycle and damage to seeds when he imported the insect from Argentina in 1974. The damage to SLN fruits and seeds appeared to be relatively small but the insect damage to other species tested was more considerable. Nymphs and adults were found to feed on fruits, stems and leaves of sodom apple (*S. sodomeum*), green pepper (*Capsicum* sp.) eggplant (*S. melongena*) and on fruits of varieties of tomato (*Lycopersicon* sp.) and pepper (*Capsicum* sp.). During host-specificity tests, adults and nymphs *A. albopunctatus* showed no preference for SLN and fed on fruits of *S. sodomeum*, *S. mauritianum*, peppers, eggplant and several types of tomato (Siebert 1977) and completed several generations on these hosts. As expected the release of *A. albopunctatus* for the control of SLN was not recommended (Siebert 1977).

Surveys conducted in South Africa showed that the only appreciable damage to SLN in South Africa was caused by polyphagous hemipteran insects inflicting 46-67% seed mortality (Olckers and Hulley 1991b). This damage was caused by the polyphagous cosmopolitan *Nezara viridula* L., the indigenous *Dryadocoris apicalis* (H. Sch.) (Hemiptera: Pentatomidae) and the native *Spilostethus furculus* (H. S.) (Hemiptera: Lygaeidae), which resulted in a reduction of germination potential of seeds from damaged fruits (Olckers and Hulley 1991b). Hill *et al.* (1993) state that imported seed-feeding agents may complement the high seed mortality inflicted by these insects. This statement is surprising as Siebert did not follow Zimmermann's recommendations and undertook tests with *A. albopunctatus,* which confirmed the lack of specificity of this insect. Also, the different surveys conducted did not reveal any fruit or seed feeder with any potential for SLN. However, it is clear that no hemiptera was found in the region of origin, feeding specifically on SLN on fruits and seeds and likely to contribute to limit SLN expansion through the reduction in the number of seeds produced or germinating.

2.4.3. The stem borer weevil *Trichobaris texana* LeConte (Coleoptera: Curculionidae)

The biology of *Trichobaris texana* has been thoroughly studied and described and the following information is from Cuda (Cuda and Burke 1985), as part of a Ph.D dissertation. Cuda studied *T. texana* biology through field observations, sampling and laboratory experiments conducted at College Station, Texas between 1978 and 1979. The insect's distribution range radiates from Texas and extends to Colorado and Kansas, Arkansas in the east and Mexico in the south. In addition to SLN, other host plants of *T. texana* are *S. rostratum* Dunal (Barber 1935; Burke 1963), *S. dimidiatum* Raf. (= *S. torreyi* Gray) and *S. citrullifolium* A. Br. (= *S. heterodoxum* Dunal).

T. texana is univoltine and eggs were present in the field from mid-April to late June and were found to be the most abundant in late May. Eggs are inserted by the females in the petiole or midrib on the underside of leaves near the base of the lamina. Eggs developed during a 4 to 18 days period, for an average duration of 6.2 days. The percentage of eggs hatching successfully was 88% at about 24° C. In the field a maximum of seven eggs, each deposited on a different leaf, was found on a single plant. Cuda observed that an *Anaphes* sp. (Hymenoptera: Mymaridae) parasitised more than 10% of the field collected eggs.

Newly hatched *T. texana* larvae tunnel toward the base of petioles and enter the stem pith as 2nd of 3rd instar larvae. The larval feeding inside the leaf petioles cause the premature abscission of leaves. The subsequent feeding and maturation of larvae occur within the stem pith of SLN and intra-specific competition and cannibalism generally leads to the survival of only one larva. In the laboratory, *T. texana* was found to have six or seven instars and the duration of the larval period observed was 23-86 days for six instars and 30-107 days for seven instars. About 90% of the larvae did not survive until the pupal stage and only about 10% percent of the eggs laid produced adults. Larvae were found to be parasitised by *Neocatolaccus tylodermae* (Ashmead) (Hymenoptera: Pteromalidae) and *Eurytoma* sp. (Hymenoptera: Eurytomidae), possibly *E. tylodermatis* Ashmead known to attack *T. texana* and *T. trinotata.* The parasitism of *N. tylodermae* accounted for 3.2% in 1978 but no parasitism was detected in 1979. The total larval mortality due to parasitism was 4.5% and larvae parasites were present from late July to early November.

Mature larvae pupate in the stems of SLN and construct a pupal chamber of xylem fibres. The pupal stage lasts 10 to 12 days and in the laboratory only nine percent of an egg cohort reached the adult stage.

Adults feed on the epidermal layer of leaves petioles or terminal portions of stems. Oviposition begins 1 to 23 days after mating and active females were observed to live for about 35 days. The average number of eggs laid was 5 eggs/female/day with an average of 33 ± 20 eggs per female over a 5.5 weeks period. Generally adults over winter inside the stems or possibly in ground litter.

Cuda observed a significant difference in height between uninfested and infested SLN plants by *T. texana*. The maximum height of uninfested SLN plants ranged from 84.6 to 91.1 cm while values for infested plants ranged from 72.8 to 79.3 cm. Cuda concludes that the data confirmed that the larval tunnelling activity ultimately stunts growth of SLN. The weevil damage may also reduce regrowth from underground parts of the plants and reduce the spread of SLN, thus making *T. texana* a biological control agent worth consideration for South Africa and Australia.

2.4.4. The leaf beetle *Metriona elatior* (Klug) (Coleoptera: Chrysomelidae: Cassidinae)

The beetle *Metriona elatior* (Klug) was considered as having some potential for the biological control of SLN (Ponce de Leon *et al.* 1993). However the insect was recorded on sweet potato (*Ipomea batatas* (L.) Lam. (Convolvulaceae) and *Solanum aculeatissimum* Jacq. (Costa-Lima 1968) in addition to *S. sisymbriifolium* in Brazil. The different life stages have been described by Morelli *et al.* (1993) and field observations on its biology were conducted in Uruguay, at the National Parks San Miguel and Santa Teresa, Rocha district, by Ponce de Leon *et al.* (1993). Insects are active between October and April. Eggs are laid on the underside of leaves, usually near the mid-rib, and generally 8 to 19 eggs are laid in egg-masses. Larvae are green in colour and feed on leaves with the maximum of leaf amount consumed during the last instars. The most developed larvae remain grouped near the mid-rib and pupation occurs on young and smaller leaves. The larval stages are found on plants from November until April and pupae from January until May. There are between four and five generations per year with the first adults appearing on plants in October and being present until April. The adults are active during the day and are able to fly on short distances. Like the larvae, the adults are leaf-feeders and skeletonise young and middle age leaves. Feeding occasionally result in the death of middle size plants (30 cm high plants in average). No predators or parasites were identified.

Metriona elatior was one of the considered potential biological control agents for the weed *Solanum sisymbriifolium* Lam. (Hill and Hulley 1996), a shrubby weed of South American origin (Symon 1981). The insect was collected on *S. sisymbriifolium* in Argentina in the Misiones area and imported into quarantine in South Africa in 1992 (Hill and Hulley 1996) to study its biology and assess its host-specificity. Larvae of *M. elatior* were observed to develop on ten out of eleven native *Solanum* species tested, on five exotic *Solanum* and on eggplant and tomato (*Lycopersion esculentum* Mill.). These results showed that under quarantine conditions *M. elatior* was an oligophagous herbivore (Hill and Hulley 1996), and that several of the *Solanum* species tested appeared to be equally suitable hosts. Additionally females oviposited on several plant species. SLN was found to be a poor host for this insect with only 2% of *M. elatior* larvae completing pupation on this plant, in comparison with 75% pupation completed on *S. sisymbriifolium* and 45 on eggplant (Hill and Hulley 1996). Furthermore, SLN was found to be the least accepted host of 18 *Solanum* species tested (1.18% host suitability rating) while the best suited hosts were *S. aculeatissimum* (100% host suitability rating) and *S. sisymbriifolium* (98.6% host suitability rating). Eggplant was rated at 62.7% and tomato was rated at 6.0% host suitability rating. On the basis of the number of eggs deposited and the high survival rate of insects on eggplant, Hill & Hulley recommended the insect not to be released. This insect cannot be seen as a suitable agent to control SLN, which has been shown not to be its primary or preferred host (Hill and Hulley 1996).

2.4.5. The gall weevil Anthonomus aeneolus Dietz (Coleoptera: Curculionidae)

The weevil *Anthonomus aeneolus* occurs in New Mexico, north-central Mexico, Oklahoma and Texas (Gates and Burke 1972). Gates and Burke report that this species was mentioned to develop in the flower buds of SLN, *S. Torreyi* Gray and *S. rostratum* Dun. by Pierce (1907) and that the association of *A. aeneolus* with galls caused by the nematode *Nothanguina phyllobia* on the leaves and stems of SLN was first reported by Burke (1961). *A. aeneolus* normally develops in the flower buds of SLN (Gates and Burke 1972). The females begin laying eggs in flower buds and in galls caused by *N. phyllobia* in June and it seems that the weevils prefer galls as oviposition sites. Under laboratory conditions adults fed on both buds and galls but most eggs were laid in gall tissue. Up to 24 larvae have been found in a single gall while usually only one larva develops per bud. Larvae present inside a flower bud feed on the anthers and the feeding damage prevents the bud opening. The larvae complete their development in 10 to 20 days and the pupal stage lasts up to seven days (Gates and Burke 1972). In a recent revision of the species of *Anthonomus* associated with Solanaceae, Clark (1996) has confirmed that *A. aeneolus* is the only species associated with SLN, however the species has also been collected on *S. rostratum* Dunal and *S. triquetrum* Cav. in Texas. *Anthonomus aeneolus* do not have any potential for the biological control of SLN being associated with galls of *N. phyllobia.*

2.5 Biological control agents not yet assessed for SLN

2.5.1. The stem and fruit galling lepidoptera *Frumenta solanophaga* Adamski and Brown (Lepidoptera: Gelechiidae: Gnorimoschemini)

During surveys conducted in Mexico for potential biological control agents for *S. elaeagnifolium,* specimens of an undescribed species were found and reared in

San Luis Potosi by personnel associated with the Plant Protection Research Institute, Pretoria, South Africa. H. G. Zimmermann collected insect material, possibly at San Luis de la Paz, on *S. elaeagnifolium* and larvae were found to feed on seeds and fruit flesh. The adults obtained were sent to the Systematic Entomology Laboratory, USDA at the National Museum of Natural History, Washington for identification. Superficially the adults looked similar to *Frumenta nundinella*, a lepidoptera herbivore on horse-nettle *Solanum carolinense* Linnaeus and considered as a potential biological control agent against this weed in the United States and Canada (Adamski and Brown 2002). However the genitalia morphology was more similar to *F. nephelomicta* and it was subsequently described as the new species, *Frumenta solanophaga* Adamski and Brown. But, in spite of its potential for the biological control of SLN the biology of *F. solanophaga* has not been investigated and remains mostly unknown (Adamski and Brown 2002).

The larval use of Solanaceae is common in the gelichiid tribe Gnorimoschemini where many species are known pests of solanaceous crops (Adamski and Brown 2002). Adamski states that the discovery of *F. solanophaga* further support the hypothesis that the genus *Frumenta* is closely associated with the genus *Solanum* (Adamski and Brown 2002). *Frumenta nundinella,* which occurs in the southern and mid-western USA is an important herbivore of *Solanum carolinense*. Another apparently undescribed species of *Frumenta* from Texas and New Mexico also has been reared from *S. elaeagnifolium* (specimen data from USNM) (Adamski and Brown 2002). *F. nephelomicta* is known from Arizona and New Mexico and Mexico (Wapshere 1988). According to Julien and Griffiths (1998), *F. nephelomicta* has been introduced into South Africa for the biological control of silverleaf nightshade in 1978 from populations from Mexico, but it failed to establish due to drought conditions and small releases (Neser *et al.* 1989). Renewed attempts in 1984 and 1985 to release it were also unsuccessful (Julien and Griffiths 1998), but according to Adamski further releases are intended (Adamski and Brown 2002). Adamski also reports that "*the source of the specimens of* F. nephelomicta *released was not indicated but if it was Mexico rather than south-western United States, then* F. nephelomicta *was most likely a misidenfication of* F. solanophaga*, and because of possible differences in feeding habits among species of* Frumenta*, the accurate identification of this biocontrol organism is critical."* This statement should be taken with caution as it seems to cast a doubt on the identity of the insect released into South Africa (*F. nephelomicta*) and this will need to be clarified through communication with the South African scientists involved on the project.

2.5.2. The fruit fly *Zonosemata vittigera* (Coquillett) (Diptera: Tephritidae)

The fruit fly *Zonosemata vittigera* has been collected on a number of plants (Cazier 1962; Foote 1960) but its only recognised host is SLN (Foote 1960). Adults have been observed to mate on SLN plants in June and July by Cazier in Arizona but oviposition may actually occur in May or June. Eggs are laid underneath the skin of green or maturing fruits and darkening spots on the fruits denotes the presence of larvae. Up to nine oviposition marks were recorded but a maximum of three maturing larvae inside a single fruit has been observed. Larvae feed on the pulpy endocarp and the placental tissue material inside fruits and do not feed on seed material which remain undamaged. Fully developed larvae exit the fruits and drop to the ground where pupation occurs. The insect over-winters as a pupa between October and May-July. Under laboratory conditions the pupal period ranged from 185 to 311 days with an average of 263 days (Cazier 1962).

Z. vittigera larvae are parasitised by *Opius sanguineus* (Ashmead) (Hymenoptera: Braconidae) and parasites emerge from their host during the host's pupal stage. Following the discovery of a population of *Z. vittigera* in south-eastern California in 1965, Goeden and Ricker (1971) studied its biology and evaluated its potential to control SLN in California where the weed is non-indigenous and has been accidentally introduced. *Z. vittigera* has one main generation and a partial 2nd generation annually. Contrary to Cazier, Goeden and Ricker observed only up to 4 oviposition marks per fruit and from these observations conclude that multiple oviposition punctures on a single fruit is the exception and not the rule as stated by Cazier. Goeden and Ricker also confirmed that larval feeding is limited to the endocarp and placenta and that only in a few occurrence when the endocarp and placenta did not provide enough food supply it was observed seed feeding accounting for 37.7 ± 9.5% seed destruction (range 5.0-94.4%, n = 20). The observed duration of larval development (hatching to pupa formation) was 17-19 days under laboratory conditions. The sex ratio of adults was males-females 1.3:1 under insectary conditions while it was 2:1 in field collections. Adult longevity was 38 ± 3 day for the males and 34 ± 4 days for the females and the pre-oviposition period averaged 9 ± 1 days. Females laid an average of 52 ± 9 eggs during a period of 15 ± 2 days and the average number of eggs laid was 5.5 ± 0.5 eggs/day.

Although *Z. vittigera* has been collected in Texas, New Mexico and Arizona, it failed to establish permanently on SLN infestations in California. *Z. vittigera* has not been reported to damage cultivated Solanaceae in the USA. Goeden and Ricker conducted oviposition tests with cultivated and wild Solanaceae and the only species accepted by the insect for oviposition was *S. xanthocarpum* Schrader & Wendland, only when spiny calyxes surrounding the fruits where removed. Although Goeden and Ricker recognise that *Z. vittigera* is closely adapted to SLN, they believe that even at high densities the insect would have a minimal effect on the reproductive capacity of SLN and therefore its introduction in California to control the weed would serve no practical purpose. From all information available, especially considering this final recommendation, *Z. vittigera* cannot be regarded as a potential or useful biological control agent for SLN in Australia.

2.5.3. The leaf mite *Aceria bicornis* Trotter (Acarina: Eriophyidae)

This species was originally described by Trotter (1900) under the name *Eriophyes bicornis* from specimens discovered by Spegazzini on SLN at La Plata, Argentina. Trotter reports large populations on SLN, especially on the leaves where the mites induce the development of erineum, generally on the upper side of leaves, as well as on petioles, stems and fruits. However the damage to SLN fruit seems restricted to surface irregularities. At this stage no other information concerning this mite is available nor on its potential as biological control agent for SLN. Another mite from Argentina (Mendoza and San Juan regions) is reported in the literature on SLN under the name *Eriophyes* sp.? (Amrine and Stasny 1994; Kieffer and Jörgensen 1910) but no information is available concerning the damage to the weed. It could be possible that these two mite species may be only one entity. *Eriophyes* sp. were collected in Argentina (Santa Fe, Feb 1979 and Cordoba Jan 1980) by C. Orr (Dr M. C. Thomas, Head Curator, Florida State

Collections, Division of Plant Industry, Gainesville, Florida, pers. comm.) but no information on the damage to SLN was provided.

2.5.4. The flower midge Asphondylia spp. (Diptera: Cecidomyiidae)

A reference was found through an Internet search of *Asphondylia* spp. attacking SLN flowers (Anon. 2005b). Dr R. Patrock who collected the insect material while working on *Anthonomus aenolus* was contacted. Dr Patrock confirmed that *Asphondylia* sp. was relatively rare on SLN and to his knowledge identification has not yet be confirmed by American expert, Dr R. Gagné.

A summary of the arthropod fauna associated with SLN is provided in Appendix 4.1.

2.5.5. Fungi

All the surveys for natural enemies of SLN have targeted arthropods. None of the surveys undertaken has identified fungal pathogens present on SLN, let alone fungal pathogens of substantial importance to the plant. The fungal floras of North and South America are well known and the vast majority of the records are accessible through a USDA database (Farr 2006). A number of non-specific fungi are known from SLN, most of them having an extended host-range. The only fungus with a relatively limited host-range identified during this study is *Pseudocercospora atromarginalis* (Atk.) Deighton (Dothideomycetidae: Mycosphaerellaceae) causing leaf-spot symptoms. The host-plants of this fungus include *Solanum elaeagnifolium*, *S. biflorum*, *S. carolinense*, *S. gracile*, *S. nigrum*, *Solanum* spp., *Capsicum* sp. (Appendix 4.3). Due to its host-range outside of SLN this agent cannot be seen as having any potential for the biological control of silverleaf nightshade.

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Appendix 4.1. List of organisms associated with SLN.

Order Family Species	Host-plants	Plant association	Host range	Distribution	References
Nematoda Tylenchida: Anguinidae					
Orrina phyllobia (Thorne)	*Solanum elaeagnifolium*	leaf galling nematode	*S. elaeagnifolium*	Mexico	Surveys (Wapshere 1988)
Orrina phyllobia (Thorne) as *Nothanguina phyllobia* Thorne	*Solanum elaeagnifolium*	leaf galling nematode	*S. elaeagnifolium*	Texas, Arizona	Infection and host plants (Orr *et al.* 1975, Orr 1976), symptoms (Esser and Orr 1979), Distribution and potential (Robinson et al. 1978), Pilot project (Parker 1986), Biological control and field experiments (Keeling and Abernathy 1985)
Orrina phyllobia (Thorne) as *Nothanguina phyllobia* Thorne	*Solanum elaeagnifolium*	leaf galling nematode	*S. elaeagnifolium*	Texas	Host-specificity (R. Field unpubl.)
Ditylenchus phyllobius (Thorne) Filipjev (=*Nothanguina phyllobia* Thorne)	*Solanum elaeagnifolium*	leaf galling nematode	*S. viarum*, *S. tampicense*	USA	Host-specificity (Cuda *et al.* 1998)
Acarina Eriophyidae					
Getrapodili sp.	*Solanum elaeagnifolium*?	leaf galls	unknown	Argentina	Surveys (Zimmermann 1974)
Eriophyes bicornis Trotter	*Solanum elaeagnifolium*	leaf erineum	possibly restricted to SLN	Argentina	Description (Trotter 1900)
Eriophyes ? sp.	*Solanum elaeagnifolium*	deformed leaves	possibly restricted to SLN	Argentina	Record (Kieffer and Jörgensen 1910 in Amrine 1994)
Hemiptera Cicadellidae					
Tapajosa rubromarginata (Signoret)	*Solanum elaeagnifolium*?	leaves	Generalist pest	Argentina	Surveys (Zimmermann 1974)
Hemiptera Tingidae					
Gargaphia arizonica Drake and Carvalho	*Solanum elaeagnifolium*	leaves, cell sucking	*S. elaeagnifolium* only host known	Mexico	Surveys (Wapshere 1988)
Hemiptera Pentatomidae					
Arvelius albopunctatus (De Geer)	*Solanum elaeagnifolium*	Fruits and seeds	Polyphagous within *Solanum*	Texas	Surveys (Goeden 1971)
Arvelius albopunctatus (De Geer)	*Solanum elaeagnifolium*	Fruits and seeds	Polyphagous within *Solanum*	Mexico	Surveys (Zimmermann 1974), host-specificity (Siebert 1977)

Arvelius albopunctatus (De Geer)	*Solanum elaeagnifolium*	Fruits and seeds	Polyphagous within *Solanum*	Argentina	Host specificity (Siebert 1977)
Lepidoptera Gelechiidae					
Frumenta nephelomicta Meyrick as *Asapharca nephelomicta* Meyrick	*Solanum elaeagnifolium*	fruits and seeds larval feeding	*S. elaeagnifolium* only host known	Mexico	Surveys (Wapshere 1988)
Frumenta nephelomicta Meyrick	*Solanum elaeagnifolium*	fruits and seeds	*S. elaeagnifolium*	Central and North America, Mexico	Surveys (Zimmermann 1974)
Frumenta nephelomicta Meyrick	*Solanum elaeagnifolium*	fruits and seeds	*S. elaeagnifolium*	introduced in South Africa ex Mexico but not established	Parasitism evaluation (Olckers 1995), releases (Julien and Griffiths 1998)
Frumenta (Sp.A)	*Solanum elaeagnifolium*	fruits and seeds	*S. elaeagnifolium*	Introduced in South Africa ex Texas, establishment not confirmed	Parasitism evaluation (Olckers 1995), releases (Julien and Griffiths 1998)
Frumenta solanophaga Adamski and Brown	*Solanum elaeagnifolium*	fruits and seeds	*S. elaeagnifolium* only host known	Mexico	Description and potential use for biocontrol (Adamski and Brown 2002)
Symmetrischema ardeola (Meyr)	*Solanum elaeagnifolium*	flowers and flower buds, stamens and pistils	S. elaeagnifolium	Argentina (Tucuman)	Surveys (Zimmermann 1974)
Keiferia glochinella (Zell.)	*Solanum elaeagnifolium*	leaf miner	Egg-plant leaf-miner	California	Surveys (Goeden 1971)
Keiferia sp.	*Solanum elaeagnifolium*	leaf miner	unknown	Argentina	Surveys (Zimmermann 1974)
Gnorimoschema sp.	*Solanum elaeagnifolium*?	stem galls	unknown	Argentina	Surveys (Zimmermann 1974)
Lepidoptera Carposinidae					
unidentified species	*Solanum eleagnifolium*	fruits and seeds	unknown	USA	Surveys (Goeden 1971)
Coleoptera Nitidulidae					
Carpophilus sp.	*Solanum elaeagnifolium*	flowers and flower buds	*S. elaeagnifolium*	Argentina	Surveys (Zimmermann 1974)

Appendix 4.1. List of organisms associated with SLN (continued).

Order Family Species	**Host-plants**	**Plant association**	**Host range**	**Distribution**	**References**
Coleoptera Chrysomelidae					
Gratiana pallidula (Boh.)	*Solanum elaeagnifolium*	leaves, defoliator	*Solanum* spp.	Mexico	Surveys (Wapshere 1988)
Gratiana pallidula (Boh.)	*Solanum elaeagnifolium*		*S. elaeagnifolium*	USA	Surveys (Goeden 1971)
Gratiana lutescens (Boh.)	*Solanum elaeagnifolium*	leaves, petioles and flower buds	*S. elaeagnifolium* and possibly *S. melongena*	Argentina	Surveys, feeding (Zimmermann 1974), Biology and host specificity tests (Siebert 1975) review of host specificity methodology (Olckers and Hulley 1994), new host specificity tests (Hill 1995)
Leptinotarsa defecta Stahl	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium* and *S. dimidatium*	Mexico, USA	Reported (Zimmermann 1974), surveys (Wapshere 1988)
Leptinotarsa defecta Stahl	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium* and *S. dimidatium*	Introduced in South Africa in 1992 ex Texas and released in two locations	Resolution of host-specificity tests results and risk assessment (Olckers and Hulley 1994), rationale for release (Olckers and Zimmermann 1995), releases and establishment (Olckers *et al.* 1999)
Leptinotarsa defecta Stahl	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium* and *S. dimidatium*	Florida	Exotic host plants in Florida evaluation (Cuda *et al.* 2002)
Leptinotarsa texana (Schaeffer)	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium*, possibly *S. rostratum*	Mexico	Surveys (Wapshere 1988)
Leptinotarsa texana (Schaeffer)	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium*, possibly *S. rostratum*	Introduced in South Africa ex Texas in 1992	Resolution of host-specificity tests results and risk assessment (Olckers and Hulley 1994), rationale for release (Olckers and Zimmermann 1995), releases and establishment (Olckers *et al.* 1999)
Leptinotarsa texana (Schaeffer)	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium*, possibly *S. rostratum*		Exotic host plants in Florida evaluation (Cuda *et al.* 2002)
Leptinotarsa decimlineata (Say)	*Solanum elaeagnifolium*	leaves, defoliator	*S. elaeagnifolium*, possibly *S. rostratum*	USA	Surveys (Goeden 1971)
Metriona elatior (Klug)	*Solanum elaeagnifolium, S. sisymbriifolium, S. aculeatissimum*	Leaves, defoliator	also *Ipomea batatas* (Convolvulaceae)	Uruguay	Host plants (Costa-Lima 1068), biology (Ponce de Leon *et al.* 1993), stages description (Morelli *et al.* 1993)

Appendix 4.1. List of organisms associated with SLN (continued).

Order Family Species	Host-plants	Plant association	Host range	Distribution	References
Coleoptera Curculionidae					
Anthonomus aeneolus Dietz (= *Anthonomus brevirostris* Linell)	*Solanum elaeagnifolium*	flower buds or as inquiline in galls of Nothanguina phyllobia	*S. elaeagnifolium*	USA	Surveys (Goeden 1971), review of gall weevils (Gates and Burke 1972), bionomics (Burke 1976), plant association (Clark 1996)
Anthonomus spp.	*Solanum elaeagnifolium*			Mexico, Usa	Reported (Zimmermann 1974), Bionomics of Anthonominae (Burke 1976)
Trichobaris texana LeConte	*Solanum elaeagnifolium*	stems, borer	*S. elaeagnifolium* and three closely related *Solanum* spp.	Mexico	Surveys (Wapshere 1988)
Trichobaris texana LeConte	*Solanum elaeagnifolium*	stems, borer	*S. elaeagnifolium*	Mexico, USA	Zimmermann (1974)
Trichobaris texana LeConte	*Solanum elaeagnifolium*	stems, borer	*S. elaeagnifolium*	USA	Surveys (Goeden 1971)
Trichobaris texana LeConte	*Solanum elaeagnifolium*	stems, borer	*S. elaeagnifolium*	Texas	Biology and impact (Cuda 1985)
Trichobaris texana LeConte	*Solanum elaeagnifolium*	stems, borer	*S. elaeagnifolium*	Mexico	Surveys (Wapshere 1988)
Conotrachelus bisignatus Boh.	*Solanum elaeagnifolium*	fruits, seeds	*S. elaeagnifolium*, *S. hyeronimii*	Argentina	Surveys (Zimmermann 1974)
Diptera Cecidomyiidae					
Asphondylia sp.	*Solanum eleagnifolium*	flowers, galls?	unknown	USA (Texas)	Provisional Checklist of the Cecidomyiidae (Diptera) (Gall Midges) of Brackenridge Field Laboratory, Compiled by R.W. Patrock (24 Aug. 1989), http://www.utexas.edu/research/bfl/species/cecido.html
unknown species	*Solanum eleagnifolium*	stem galls	unknown	Mexico (Monterrey)	Surveys (Zimmermann 1974)
unnamed species	*Solanum elaeagnifolium*	Stems, distortion by galling	S. elaeagnifolium	Mexico	Surveys (Wapshere 1988)
Diptera Agromyzidae					
Haplomyza sp.	*Solanum elaeagnifolium*	leaves		Argentina	Surveys (Zimmermann 1974)

Appendix 4.2. List of organisms associated with prairie ground cherry.

Order Family Species	Host-plants	Plant association	Host range	Distribution	References
Diptera Tephritidae					
Zonosemata vittigera(Coquillett)	*Solanum elaeagnifolium*	fruits and seeds	S. elaeagnifolium	Mexico	Surveys (Wapshere 1988)
Zonosemata vittigera(Coquillett)	*Solanum elaeagnifolium*	fruits and seeds	S. elaeagnifolium	USA (California)	Surveys (Goeden 1971), biology and potential (Goeden and Ricker 1971)
Zonosemata vittigera(Coquillett)	*Solanum elaeagnifolium*	fruits and seeds	S. elaeagnifolium	Arizona	Bionomics (Cazier 1962)
Zonosemata vittigera(Coquillett)	*Solanum elaeagnifolium*	fruits and seeds	S. elaeagnifolium	Mexico, USA	Description, distribution (www.sel.barc.usda.gov/diptera/tephriti/Zonosem/vittiger.htm)
Lepidoptera Noctuidae					
Heliothis subflexa (Guenée)	*Physalis* spp.	Fruits	Solanaceae	New World (USA, Mexico)	Mitter *et al.* (1993)

Appendix 4.3. List of fungi associated with silverleaf nightshade and prairie ground cherry.

Order Family	Species	Host-plants	Damage	Distribution	References
Ascomycetes, Dothideomycetidae, Mycosphaerellales, Mycosphaerellaceae	*Pseudocercospora atromarginalis* (Atk.) Deighton 1976 (=*Cercospora atromarginalis* Atk. 1892, *Cercospora nigri* Tharp 1917, *Cercospora rigospora* Atk. 1892)	*Solanum elaeagnifolium, S. biflorum, S. carolinense, S. gracile, S. nigrum, Solanum spp., Capsicum sp.*	Leafspot disease	Florida, Brazil, Venezuela, Asia, New Zealand (Subtropical and tropical regions)	Farr, D.F., Rossman, A.Y., Palm, M.E., & McCray, E.B. (n.d.) Fungal Databases, Systematic Botany & Mycology Laboratory, ARS, USDA. Retrieved January 30, 2006, from http://nt.ars-grin.gov/fungaldatabases/
Ustilaginomycetes, Exobasidiomycetidae, Entylomatales, Entylomataceae	*Entyloma australe* (Speg.)	*Physalis spp., Lycopersicon sp., Solanum spp., Quincula lobata*	On Solanaceae; white smut of Physalis. Infection mainly on leaves, but is also found on stems and other parts	North America; Central America & West Indies; South America; Africa; Asia; Australia; New Zealand.	Farr, D.F., Rossman, A.Y., Palm, M.E., & McCray, E.B. (n.d.) Fungal Databases, Systematic Botany & Mycology Laboratory, ARS, USDA. Retrieved January 30, 2006, from http://nt.ars-grin.gov/fungaldatabases/

Appendix 5 Benefit-Cost Analyses of SLN

Benefit Cost Analysis of Biological Control Program for Silverleaf Nightshade

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March 2006

Executive Summary

The Victorian Department of Primary Industries (DPI) has conducted a feasibility study on the biological control of silver leaf nightshade (*Solanum elaeagnifolium*) for Meat and Livestock Australia (MLA). As part of the study, an *ex ante* economic analysis was undertaken to quantify, in monetary terms, the expected benefits of the biological control research program to the grazing and cropping industries of Victoria, New South Wales and South Australia.

The standard benefit cost analysis (BCA) technique of economic analysis was used in estimating the impact of a biological control program targeted against silver leaf nightshade. The BCA spreadsheet of the Victorian Department of Primary Industries (DPI) dubbed ‘appraisal’ is the economic model applied in this study. This model has been designed and applied for the economic evaluation of agricultural research and development projects in Victoria.

This analysis examined the benefits and costs that may accrue to graziers and growers, due to the reduced need for current control technology for silver leaf nightshade, with biological control. The net economic benefit was calculated by comparing the benefits and costs of the current control technology with the benefits and costs with biological control. The benefits estimated were limited to agriculture alone, that is, in terms of expected control cost savings to grazing and cropping industries following the release of biological control agents in the three states.

Positive returns on investment were estimated at all discount rates applied (8, 10, & 12%) with close to $140 million savings in future control costs and a benefit cost ratio of $58.60 to one dollar investment, at 10% discount rate. A higher return on investment could be expected if other benefits were quantified e.g., control cost savings to horticulture, governments. Due to data limitations, however, the benefits to these sectors have not been quantified and as such the quantified benefits may be considered conservative estimates.

Sensitivity analysis of results was performed to address uncertainties about the data and assumptions applied in the study. The parameters tested include probability of success of the research program, discount rate, and the adoption rate of the technology.

Return on investment was found to be more sensitive to a change in the adoption rate of the biological control technology compared to a change in the success rate of the research program. In particular, a 10% change in adoption rate was found to lead to 23% change in the return on investment whilst a 10% change in the rate of research success resulted in a

lower (17%) percentage change in the return on the same investment. This suggests that the rate of adoption is more critical than the research program's likelihood of success.

The impacts of lower gross margin value savings and slower rate of weed spread were also separately tested and analysed. When the expected gross margin value savings for grazing and cropping enterprises were simultaneously reduced by 20%, the return on investment remained positive at $46.80 for every dollar of research investment. Meanwhile, a $50.15 return for every dollar investment resulted from a slower rate of weed spread (80% of the maximum predicted infestation).

The overall findings indicate that the proposed research investment in the biological control program for silver leaf nightshade is economically viable. Based on proportion of future costs to graziers and growers, at least 80% of the expected benefits is likely to be captured by grazing industries in Victoria, New South Wales and South Australia.

1. Introduction

A recent economic impact assessment of biological control programs for 26 weed species in Australia reported an average benefit cost ratio of 17.40 for agriculture alone (control cost savings and increased production) (1). This means a generated return of $17.40 for every dollar of investment. A higher average benefit cost ratio of 23.10 was reported when other benefits were likewise quantified (health, control cost savings to government). Economic analysis of biological control programs for weeds can provide an important contribution towards making informed decisions as potential benefits and costs of such investments are quantified and evaluated.

The Victorian Department of Primary Industries (DPI) has conducted a feasibility study on the biological control of silver leaf nightshade (*Solanum elaeagnifolium*) for Meat and Livestock Australia (MLA). As part of the study, an *ex ante* economic analysis was undertaken to quantify, in monetary terms, the expected benefits of the biological control of this weed to the grazing and cropping industries in Victoria, New South Wales and South Australia.

2. Methodology

To determine the total area of grazing and cropping lands potentially at risk from silver leaf nightshade infestation in Victoria, New South Wales and South Australia over the evaluation period (between 2006 and 2038), a logistic-type weed spread model was applied.

The standard benefit cost analysis (BCA) technique of economic analysis was used to estimate the impact of the proposed biological control program targeted against silver leaf nightshade. The model applied in this study is the BCA spreadsheet of the Victorian Department of Primary Industries (DPI) dubbed 'appraisal'. This model has been designed and applied for the economic evaluation of agricultural research and development projects in Victoria (2).

The following steps were taken in performing the BCA of the biological control option for silver leaf nightshade (3).

Define scope of analysis

Identify benefits and costs

Value benefits and costs

Tabulate annual benefits and costs

Calculate the net benefit

Perform sensitivity analysis

This analysis examined the expected benefits and costs that may accrue to the grazing and cropping industries in Victoria, New South Wales and South Australia, due to the reduced need for current technology for the control of silver leaf nightshade, with biological control between 2006 and 2038. The net economic benefit was calculated only in terms of expected savings in future control costs to grazing and cropping industries, with biological control. Because of the lack of reliable data, other beneficial impacts of biological control of this weed such as quantity and quality improvement of agricultural production were not accounted in this benefit cost analysis. Therefore, the estimated total benefits in this analysis may be under estimated.

The net present value (NPV), benefit cost ratio (BCR) and internal rate of return (IRR) are three decision criteria estimated. These decision criteria allow the determination of whether or not the investment is economically viable as well as the level of expected benefits from the investment program.

Net present value (NPV) is the difference between the present value of future benefits and costs associated with the program. A positive NPV means the program is economically viable. Benefit cost ratio (BCR), meanwhile, is the ratio of the present value of program benefits to the present value of program costs. A BCR greater than one means the program is economically viable. For example, a BCR of 1.50 means that one-dollar investment in the program, generates $1.50 worth of benefits. Internal rate of return (IRR) is the break-even discount rate. This is the rate at which the present value of program benefits equals the present value of program costs. The higher the IRR, the more economically attractive the program.

Due to the limited knowledge currently available, particularly about the potential control agents, sensitivity analysis of results was performed to address such uncertainties about the data and assumptions applied. The parameters tested include probability of success of the research program, discount rate, and the adoption rate of the technology by graziers and growers. Additionally, the impacts of lower gross margin value savings and slower rate of weed spread were also tested separately and analysed. Gross margin (GM) is the difference between farm revenue less variable costs of production, calculated per unit of land ($/ha).

3. Data and assumptions

The rate of weed spread is difficult to accurately predict because of a number of environmental factors that influence it. Expert opinion is that silver leaf nightshade will take between 75 and 200 years to reach its potential maximum geographical distribution. This rate of spread would depend on factors including present distribution, potential distribution as predicted using climatic factors and land use, number of current infestations, and invasiveness rating as key variables (4). The major data sets used as inputs to the logistic-type weed spread model are shown in Table 1. Present distribution data were based on a survey conducted by McLaren *et al.* 2004 (5). Potential distribution data were estimated using CLIMATE software (6).

Table 1. Weed spread model inputs

Present distribution estimates, ha	
Victoria	30 814
New South Wales	25 117
South Australia	48 062
Potential distribution, ha million (%) [A]	

Victoria	13.2 (77%)
New South Wales	60.5 (91%)
South Australia	52.3 (94%)

[A] Figures in parentheses are percentages referring to proportion of predicted infestations likely to occur on pastures

Around 60.5 million ha in New South Wales are assessed to be suitable for silver leaf nightshade infestation, with 91% of such infestation likely to occur on pasture areas. The next state most susceptible to silver leaf nightshade infestation is South Australia (52.3 million ha) followed by Victoria (13.2 million ha). The potential distributions of silver leaf nightshade, over 50 years, in cropping and grazing areas of Victoria, New South Wales and South Australia are shown in Appendix 5.1.

In order to complete this *ex ante* analysis, few necessary assumptions were made as inputs to the BCA model. These include:

Year biological control is first adopted – 8

Maximum rate of adoption – 60%

Year maximum adoption is obtained – 20

Probability of research success – 60%

Discount rate – 10%

Extra cost of control on cropping areas, no biological control ($/ha) - $3.90

Extra cost of control on pasture areas, no biological control ($/ha) - $5.95

DPI Frankston-based weed research scientists, using the knowledge available at the time, provided the estimates for the first four dot points. A preferred discount rate of 10% was chosen to reflect the fairly high degree of uncertainty about the future impact of the biological control agents. The estimates of control costs were based on a survey conducted in 2004 involving respondents from Victoria, New South Wales and South Australia (5). Again, sensitivity analysis was performed to examine how parameter values lower or higher than the assumed 'most likely' value would impact on the results.

4. Project costs

The projected estimates of annual investment cost to complete a biological control program for silver leaf nightshade is shown in Table 2. Details of the cost estimate for each research activity to be undertaken over the first seven years, and the subsequent release, distribution and monitoring of the agents' to ensure adoption of the technology from the 8th to the 15th year are presented in Appendix 5.2.

Table 2. Projected annual investment cost, undiscounted

Year	Investment ($ '000)	Year	Investment ($ '000)
1	290	9	390
2	260	10	390
3	260	11	390
4	260	12	390
5	260	13	390
6	260	14	390
7	260	15	390
8	390		

5. Results and analysis

Environmental factors can influence the rate of weed spread as well as its reduction due to the effect of biological control agents. For example, Figure 1 illustrates a scenario where the rate of spread of silver leaf nightshade on pasture areas in Victoria, New South Wales and South Australia, is reduced to 60%, with the successful biological control program.

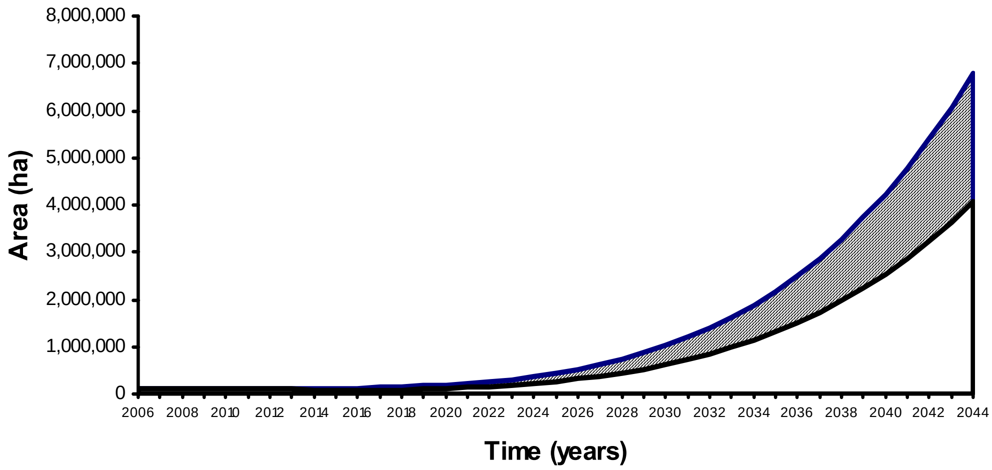

Figure 1. Illustrates a 60% reduction in rate of silver leaf nightshade spread (hatch area) on pasture land in Victoria, New South Wales and South Australia with biological control, between 2006 and 2044 or 30 years after the target initial release and distribution of agents.

To deal with these uncertainties associated with the limited currently available knowledge about the agents, sensitivity analysis was performed particularly on the rate of research success, adoption rate for the biological control technology and the applied discount rate. The results are summarised in Table 3.

Table 3. Sensitivity analysis [A]

	Investment decision criteria		
	NPV ($ million)	BCR	IRR (%)
(a) Discount rate			
8%	200.5	73.50	68.9
10%	139.8	58.60	68.9
12%	100.2	47.60	68.9
(b) Research success			
50%	116.1	48.80	65.5
60%	139.8	58.60	68.9
70%	163.5	68.40	71.9
(c) Adoption rate			
50%	107.3	45.20	65.5
60%	139.8	58.60	68.9
70%	172.3	72.10	71.9

[A] Base model (most likely) values are highlighted

Positive returns on investment were estimated at all discount rates applied (8, 10 & 12%). Graziers and growers in Victoria, New South Wales and South Australia may receive a return of $58.60 for every dollar investment, at 10% discount rate, if a successful biological control program for silver leaf nightshade were implemented.

The sensitivity analysis results indicate that return on investment is more sensitive to adoption rate than the rate of research success. A 10% change in adoption rate was found to lead to 23% change in the return on investment whilst a similar 10% change in the rate of research success resulted in a lower (17%) percentage change in the return on the same investment. This suggests that the rate of adoption of biological control as a new technology is more critical than the research program's likelihood of success.

In addition, when the expected gross margin savings of $3.90 and $5.95 per ha, respectively, for cropping and grazing enterprises, were reduced by 20, 40 and 60%, returns on investment remained positive. The expected returns on investment are $46.80 (20% reduction), $36.40 (40%) and $24.50 (60% reduction). Meanwhile, a slower rate of weed spread (80% of the maximum predicted infestation) resulted in a $50.15 return for every dollar investment.

The benefits estimated in this analysis were limited to agriculture alone, that is, in terms of control cost savings to grazing and cropping industries following the targeted release of biological control agents. A higher return on investment could be expected if other benefits were quantified e.g., control cost savings to other minor agricultural land uses such as horticulture. However, as mentioned earlier, due to non-availability of required data on possible beneficial impacts of biological control of this weed on quantity and quality improvement of agriculture production, the net economic benefit was calculated only in terms of expected savings in future control costs, with biological control. Therefore, the estimated benefits in this analysis may be under estimated.

The findings of this analysis indicate that the proposed research investment in the biological control program for silver leaf nightshade is economically viable with approximately 80% of total expected benefits likely to accrue to grazing industries of Victoria, New South Wales and South Australia.

It is recommended that a detailed economic study should be conducted as a part of this research program when more accurate cost and weed spread information become available, possibly as output of focus group workshop around the third year of the implementation of this project.

References

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Appendix 5.1

Predicted Potential Distribution of Silver Leaf Nightshade (SLN) in Victoria (Vic), New South Wales (NSW), and South Australia (SA), by Major Land Use (2006-2056)

Vic	Yr	Cropping	Pasture	**NSW**	Yr	Cropping	Pasture	**SA**	Yr	Cropping	Pasture
	0	17564	10477		0	13563	8791		0	26434	16822
	1	17565	10478		1	13564	8792		1	26435	16823
	2	17575	10488		2	13573	8806		2	26445	16832
	3	17607	10524		3	13603	8861		3	26479	16861
	4	17678	10605		4	13669	9005		4	26556	16925
	5	17807	10757		5	13786	9298		5	26697	17039
	6	18017	11008		6	13974	9817		6	26929	17221
	7	18331	11388		7	14253	10655		7	27278	17489
	8	18774	11931		8	14644	11916		8	27775	17865
	9	19373	12674		9	15169	13721		9	28450	18368
	10	20156	13655		10	15851	16202		10	29337	19021
	11	21152	14914		11	16714	19508		11	30473	19846
	12	22393	16495		12	17784	23799		12	31893	20867
	13	23911	18442		13	19087	29249		13	33637	22107
	14	25738	20803		14	20648	36044		14	35744	23593
	15	27909	23625		15	22496	44384		15	38256	25349
	16	30458	26960		16	24659	54482		16	41217	27402
	17	33423	30859		17	27165	66564		17	44670	29778
	18	36839	35376		18	30045	80866		18	48662	32505
	19	40747	40566		19	33327	97641		19	53238	35612
	20	45183	46487		20	37044	117150		20	58448	39125
	21	50188	53198		21	41226	139668		21	64341	43076
	22	55803	60757		22	45905	165484		22	70967	47492
	23	62068	69226		23	51114	194896		23	78378	52405
	24	69027	78669		24	56886	228217		24	86627	57844
	25	76722	89150		25	63254	265770		25	95766	63841
	26	85197	100734		26	70252	307890		26	105852	70427
	27	94497	113488		27	77915	354925		27	116940	77633
	28	104666	127480		28	86278	407234		28	129087	85493
	29	115750	142780		29	95375	465189		29	142351	94038
	30	127,797	159,459		30	105,244	529,171		30	156,790	103,302
	31	140852	177588		31	115921	599577		31	172465	113319
	32	154965	197241		32	127441	676811		32	189436	124121
	33	170183	218493		33	139844	761291		33	207765	135744
	34	186556	241419		34	153165	853447		34	227513	148222
	35	204133	266095		35	167443	953719		35	248746	161590
	36	222966	292600		36	182718	1062559		36	271526	175883
	37	243104	321013		37	199027	1180430		37	295919	191136
	38	264599	351414		38	216409	1307807		38	321992	207387
	39	287504	383884		39	234905	1445177		39	349810	224670
	40	311872	418505		40	254555	1593035		40	379441	243024
	41	337755	455361		41	275399	1751892		41	410954	262484
	42	365207	494536		42	297477	1922266		42	444418	283088
	43	394283	536116		43	320831	2104688		43	479903	304874
	44	425038	580188		44	345502	2299701		44	517480	327880
	45	457527	626838		45	371532	2507857		45	557220	352143
	46	491806	676155		46	398964	2729720		46	599196	377703
	47	527932	728229		47	427839	2965865		47	643480	404598
	48	565961	783151		48	458201	3216878		48	690147	432867
	49	605952	841012		49	490092	3483357		49	739271	462550
	50	647,961	901,904		50	523,557	3,765,909		50	790,927	493,686

Appendix 5.2 Pojected Cost of Research and Development for Biological Control of Silver Leaf Nightshade (SLN)

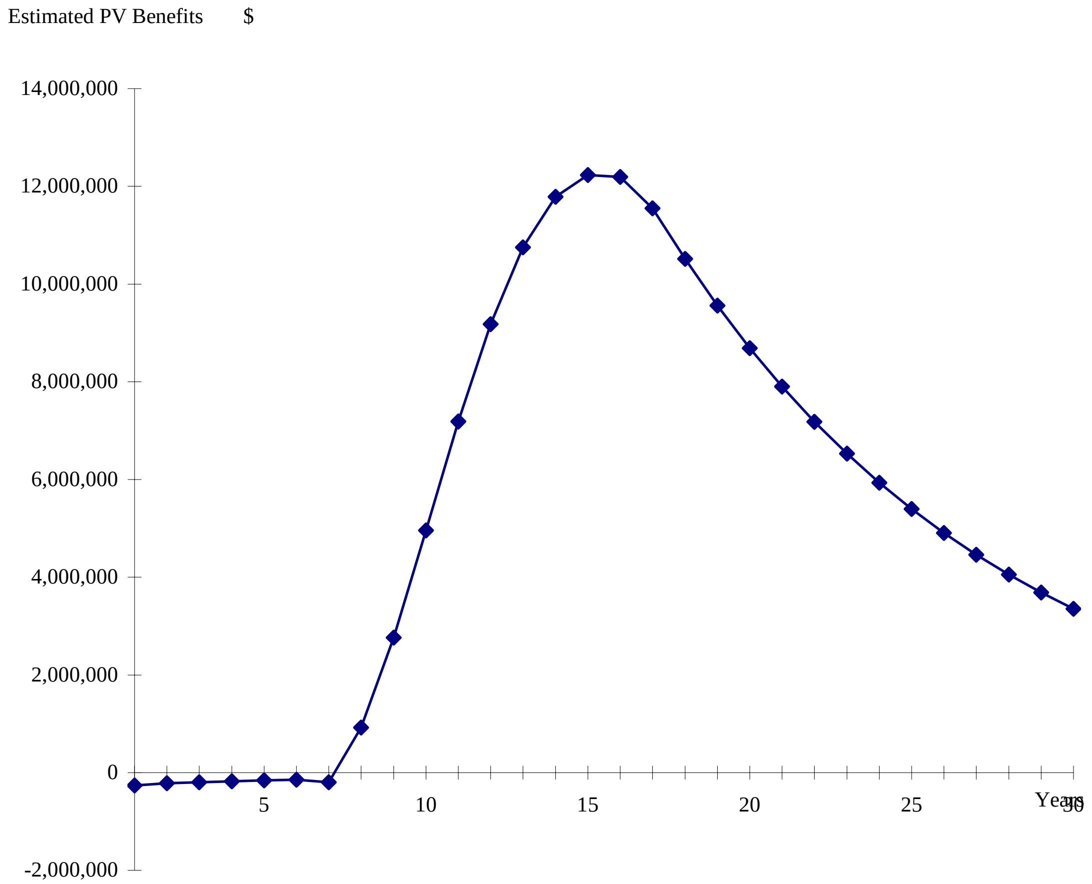
Research Activity	Year	Costs	Total Research Costs[A]
Molecular characterisation of SLN populations in Australia compared to North, Central and South America Survey organisms associated with SLN populations in Australia to determine what fauna (native and exotic) are already attacking the weed and to determine if any of these have potential as biocontrol agents. PhD project on SLN population ecology commences.	1	1 FTE (Grade 4 @ $100,000) 0.5 FTE (Grade 3 @ $50,000) $110,000 operating ($80 molecular studies, $50,000 fauna surveys) 1 PhD student ($30,000 stipend)	$290,000
Overseas surveys in Argentina. PhD project (SLN population ecology continued).	2	1 FTE (Grade 4) 0.5 FTE (Grade 3) $80,000 1 PhD student ($30,000 stipend)	$260,000
Selection of potential agents and submission of applications for host test list and importation. PhD project (SLN population ecology completion).	3	1 FTE (Grade 4) $30,000 1 PhD student ($30,000 stipend)	$260,000
Development of agent cultures, preliminary impact studies and host testing conducted in Argentina.	4	1 FTE (Grade 4) 0.5 FTE (Grade 3) $60,000	$260,000
Development of agent cultures, preliminary impact studies and host testing conducted in Argentina. Importation of cultures into quarantine in Australia.	5	1 FTE (Grade 4) 0.5 FTE (Grade 3) $60,000	$260,000
Completion of host testing of Australian native Solanaceae in Australia quarantine. Application for release.	6	1 FTE (Grade 4) 0.5 FTE (Grade 3) $30,000	$260,000
Release from quarantine and development of mass rearing cultures.	7	3 FTE (Grade 3) (1 FTE per state: VIC, NSW, SA) $90,000	$260,000
Agent distribution, monitoring and impact.	8	3 FTE (1 FTE per state: VIC, NSW, SA) $90,000	$390,000
Agent distribution, monitoring and impact.	9	3 FTE (1 FTE per state: VIC, NSW, SA) $90,000	$390,000
Agent distribution, monitoring and impact.	10	3 FTE (1 FTE per state: VIC, NSW, SA) $90,000	$390,000
Agent distribution, monitoring and impact.	11	3 FTE (1 FTE per state: VIC, NSW, SA) $90,000	$390,000
Agent distribution, monitoring and impact.	12	3 FTE (1 FTE per state: VIC, NSW, SA) $90,000	$390,000
Agent distribution, monitoring and impact.	13	3 FTE (1 FTE per state: VIC, NSW, SA) $90,000	$390,000
Agent distribution, monitoring and impact.	14	3 FTE (1 FTE per state: VIC, NSW, SA) $90,000	$390,000
Agent distribution, monitoring and impact.	15	3 FTE (1 FTE per state: VIC, NSW, SA) $90,000	$390,000

[A] Research costs based on two biocontrol agents

Appendix 5.3 Estimated Extra cost of Silver leaf nightshade in Victoria (Vic), New South Wales (NSW), and South Australia (SA), without Biological control by major Land Use, over 50 yrs (2006-2056)

	VIC		NSW		SA		
Year	Cropping	Pasture	Cropping	Pasture	Cropping	Pasture	**Total**
1	68,500	62,337	52,896	52,306	103,093	100,091	**439,222**
2	68,503	62,343	52,900	52,312	103,097	100,097	**439,251**
3	68,553	62,440	52,935	52,396	103,136	100,150	**439,609**
4	68,744	62,888	53,052	52,723	103,268	100,323	**440,998**
5	69,223	64,142	53,309	53,580	103,568	100,704	**444,526**
6	70,176	66,867	53,765	55,323	104,118	101,382	**451,632**
7	71,831	71,944	54,499	58,411	105,023	102,465	**464,173**
8	74,455	80,475	55,587	63,397	106,384	104,060	**484,358**
9	78,348	93,791	57,112	70,900	108,323	106,297	**514,771**
10	83,849	113,455	59,159	81,640	110,955	109,290	**558,347**
11	91,328	141,262	61,819	96,402	114,414	113,175	**618,400**
12	101,190	179,251	65,185	116,073	118,845	118,084	**698,626**
13	113,871	229,699	69,358	141,604	124,383	124,159	**803,073**
14	129,840	295,131	74,439	174,032	131,184	131,537	**936,163**
15	149,596	378,317	80,527	214,462	139,402	140,378	**1,102,682**
16	173,668	482,279	87,734	264,085	149,198	150,827	**1,307,791**
17	202,616	610,290	96,170	324,168	160,746	163,042	**1,557,031**
18	237,028	765,878	105,944	396,056	174,213	177,179	**1,856,297**
19	277,522	952,828	117,176	481,153	189,782	193,405	**2,211,865**
20	324,745	1,175,183	129,975	580,964	207,628	211,891	**2,630,387**
21	379,371	1,437,246	144,472	697,043	227,947	232,794	**3,118,872**
22	442,102	1,743,583	160,781	831,025	250,930	256,302	**3,684,723**
23	513,668	2,099,021	179,030	984,630	276,771	282,577	**4,335,697**
24	594,826	2,508,656	199,345	1,159,631	305,674	311,810	**5,079,941**
25	686,359	2,977,848	221,855	1,357,891	337,845	344,172	**5,925,970**
26	789,078	3,512,225	246,691	1,581,332	373,487	379,854	**6,882,666**
27	903,819	4,117,688	273,983	1,831,946	412,823	419,041	**7,959,299**
28	1,031,446	4,800,404	303,869	2,111,804	456,066	461,916	**9,165,505**
29	1,172,847	5,566,816	336,484	2,423,042	503,439	508,683	**10,511,312**
30	1,328,936	6,423,639	371,963	2,767,875	555,169	559,526	**12,007,107**
31	1,500,653	7,377,864	410,452	3,148,567	611,481	614,647	**13,663,664**
32	1,688,963	8,436,756	452,092	3,567,483	672,614	674,248	**15,492,155**
33	1,894,855	9,607,859	497,020	4,027,025	738,800	738,520	**17,504,079**
34	2,119,345	10,898,993	545,392	4,529,681	810,284	807,677	**19,711,371**
35	2,363,471	12,318,259	597,344	5,078,010	887,301	881,921	**22,126,305**
36	2,628,298	13,874,039	653,028	5,674,628	970,109	961,461	**24,761,562**
37	2,914,913	15,574,994	712,600	6,322,226	1,058,951	1,046,504	**27,630,189**
38	3,224,428	17,430,070	776,205	7,023,559	1,154,084	1,137,259	**30,745,606**
39	3,557,981	19,448,494	843,995	7,781,452	1,255,769	1,233,953	**34,121,644**
40	3,916,730	21,639,779	916,130	8,598,803	1,364,259	1,336,787	**37,772,488**
41	4,301,860	24,013,722	992,765	9,478,558	1,479,820	1,445,993	**41,712,718**
42	4,714,578	26,580,408	1,074,056	10,423,757	1,602,721	1,561,780	**45,957,299**
43	5,156,113	29,350,206	1,160,160	11,437,483	1,733,230	1,684,374	**50,521,566**
44	5,627,720	32,333,776	1,251,241	12,522,894	1,871,622	1,814,000	**55,421,253**
45	6,130,676	35,542,066	1,347,458	13,683,221	2,018,172	1,950,886	**60,672,478**
46	6,666,281	38,986,311	1,448,975	14,921,749	2,173,158	2,095,251	**66,291,725**
47	7,235,857	42,678,041	1,555,960	16,241,834	2,336,864	2,247,333	**72,295,889**
48	7,840,750	46,629,073	1,668,572	17,646,897	2,509,572	2,407,358	**78,702,222**
49	8,482,329	50,851,518	1,786,984	19,140,424	2,691,573	2,575,559	**85,528,387**
50	9,161,983	55,357,781	1,911,359	20,725,974	2,883,157	2,752,173	**92,792,426**

Appendix 5.4 Estimated Distribution of Present Value of Benefits of Biological control of Silver Leaf Nightshade over a 30-year period



Appendix 6 Victorian Farmer Experiences with PGC Management

Workshop Outcomes

An ‘Integrated Management of Prairie Ground Cherry” workshop, facilitated by the Victorian Department of Primary Industries was conducted on 31 July 2003 at Tatura, Victoria. The aims of the workshop were to bring together Victorian farmers affected by the weed and to gather their experiences in dealing with PGC control. This information was distilled into a series of Integrated Weed Management Plans providing real-life examples of the management of PGC on an organic farm (ie no chemical use), and for the management of scattered and widespread infestations (Moerkerk and Snell 2003).

Best Practice Management

The workshop identified the following issues and requirements to achieve best management practice of PGC:

3. Awareness and education
   - Education of farmers of methods of spread (stock, hay, fodder, and birds) and the importance of hygiene to prevent seed movement in spoil via cultivation equipment and vehicles.
   - Improve farmers’ knowledge of how to spot new or existing infestations (ie look under bird roosts such as fence lines, power lines, trees).
   - Community awareness and greater involvement from Landcare is needed to increase awareness and prevent further spread.
   - Awareness that there may be programs in some areas where reimbursement of herbicide costs for PGC control is offered (consult local DPI/DSE office).

4. Best Control Strategies – Integrated Control
   - Cultivation is generally not recommended as the only method of control as it aids in the spread of root fragments.
   - Cultivation or slashing prior to herbicide application may enhance the effectiveness of chemicals. The regrowth of the shoots will ensure that all plants are uniform in growth allowing them to be ‘hit’ all at once at the optimum time, increasing chemical translocation to the roots.
   - Chemical fallowing and grazing in late spring reduces other vegetation allowing PGC to be easily spotted in summer for spot spraying.
   - After herbicide application of PGC, plant competitive summer growing crops and pastures to compete with PGC regrowth and seedling emergence.
   - Prevent seed spread by not moving stock when mature seed is present, or use containment areas.

- Clean all machinery and vehicles used in infested paddocks.
- Cut crops early to prevent seed contamination.
- Manage vermin foxes and rabbits as these could spread seeds.
- It is essential to follow-up chemical treatments to control regrowth.
- Monitoring for new infestations is critical and must be controlled before they become well established.

Research required for optimum management

Snell (2003) summarised from the workshop discussions that “Prairie ground cherry is currently poorly researched and there is little information available on its biology and ecology, and therefore a lack of knowledge of best management practices”. Important aspects for better management, as derived from current knowledge (ie the workshop) include:

- Most effective chemicals and chemicals that produce longer-term results.
- Biology and ecology: growth stages and optimum time/s for spraying.
- Competitive summer-growing crops and pastures species.
- Management of mature plants with established root systems.
- Better management with non-chemical methods (eg biological control).
- What are the seed bank and dormancy conditions/duration?

Appendix 7 Benefit-Cost Analyses of PGC

Benefit Cost Analysis of Biological Control Program for Prairie Ground Cherrry

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March 2006

Executive Summary

A feasibility study on the biological control of prairie ground cherry (*Physalis viscosa*) has been conducted by the Victorian Department of Primary Industries (DPI) for Meat and Livestock Australia (MLA). As part of this study, an *ex ante* economic analysis was undertaken to estimate the monetary value of expected benefits of the biological control research program to the grazing and cropping industries in south eastern Australia.

To estimate the impact of a biological control program targeted against prairie ground cherry, the standard benefit cost analysis (BCA) technique of economic analysis was employed. The economic model applied in this study was the BCA spreadsheet of the Victorian Department of Primary Industries (DPI) dubbed 'appraisal'. This model has been designed and applied in the economic analysis of agricultural research and development projects at regional or state- wide scale.

This analysis examined the benefits and costs of a reduced dependence on current technology for the control of prairie ground cherry, with biological control. The net economic benefit was calculated by comparing the benefits and costs of the current control technology with the benefits and costs with biological control. The benefits that may accrue to agriculture were estimated in terms of expected savings in future control costs to grazing and cropping industries, with biological control.

Positive returns on investment were obtained at all discount rates applied (8, 10, & 12%) with close to $38 million savings in future control costs and a return of $26.30 for every one dollar investment, at 10% discount rate over 30 year period. Meanwhile, if other benefits were quantified e.g., control cost savings to horticulture and other possible minor land use types, higher return on investment could be expected. However, due to the limitations of available data sets, the benefits to these other industries have not been quantified. Also, because of the lack of reliable data, beneficial impacts of biological control of this weed on quantity and quality improvements in agricultural production were not taken into account in this benefit cost analysis. Therefore, the estimated total benefits in this analysis may be under estimated.

To address uncertainties about the data and assumptions applied in the study, sensitivity analysis was performed. The probability of success of the research program, discount rate, and the adoption rate of the technology by graziers and growers, are the key parameters tested. A 10% change in adoption rate was found to lead to 19% change in the return on investment whilst a 10% change in

the rate of research success resulted in a slightly lower (17%) percentage change in the return on the same investment. This suggests that the likelihood of success of the research program is as critical as the rate of adoption of biological control as a new technology.

The impacts of lower gross margin value savings and slower rate of weed spread were also separately tested and analysed. With a 20% reduction in the gross margin value savings for grazing and cropping enterprises, the return on investment remained positive at $21.00 for every dollar of research investment. Meanwhile, a similar 20% reduction in the rate of weed spread was found to yield a return of $21.20 for every dollar investment. Results indicate that the proposed research investment in the biological control program for prairie ground cherry is economically viable. Finally, the grazing industries in Victoria, New South Wales and South Australia are likely to capture approximately 35% of the total expected benefits.

1. Introduction

A feasibility study on the biological control of prairie ground cherry (*Physalis viscosa*) has been conducted by the Victorian Department of Primary Industries (DPI) for Meat and Livestock Australia (MLA). As part of the feasibility study, an *ex ante* economic analysis was undertaken to quantify, in monetary terms, the expected benefits of a biological control program for this weed, to the grazing and cropping industries in south eastern Australia.

2. Methodology

The standard benefit cost analysis (BCA) technique of economic analysis was used in estimating the impact of a proposed biological control program targeted against prairie ground cherry. The model applied is the 'appraisal' BCA spreadsheet of the Victorian Department of Primary Industries (DPI). This model has been designed and applied for the economic evaluation of agricultural research and development projects at the regional or state- wide scale in Victoria (1).

This analysis examined the future benefits and costs that could accrue to graziers and growers in Victoria, New South Wales and South Australia, due to a reduced dependence on current technology for the control of prairie ground cherry, with biological control. Because of the non-availability of required data on possible beneficial impacts of biological control of this weed on quantity and quality of agriculture production, the net economic benefit was calculated based only on future control cost savings, with biological control.

The net present value (NPV[1]) benefit cost ratio (BCR[2]) and internal rate of return (IRR[3]) are three investment decision criteria estimated. These decision criteria allow the determination of whether or not the investment is economically viable as well as the level of expected benefits from the investment program (2). To address uncertainties about the data and assumptions applied in the study, sensitivity analysis was performed. Sensitivity analysis is a technique for examining how parameter values lower or higher than the assumed 'most likely' value would impact on the results.

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1 Net present value (NPV) is the difference between the present value of future benefits and costs associated with the program. A positive NPV means the program is economically viable.

2 Benefit cost ratio (BCR) is the ratio of the present value of program benefits to the present value of program costs. A BCR greater than one means the program is economically viable. For example, a BCR of 1.50 means that one-dollar investment in the program, generates $1.50 worth of benefits.

3 Internal rate of return (IRR) is the break-even discount rate. This is the rate at which the present value of program benefits equals the present value of program costs. The higher the IRR, the more economically attractive the program.

Sensitivity analysis helps decision-makers to assess and identify the uncertain variables to which the return on investment is most sensitive. The probability of success of the research program, discount rate, and the adoption rate of the technology by graziers and growers, are the key parameters tested. The impacts of lower gross margin[4] value savings and slower rate of weed spread were also separately tested and analysed.

3. Data and assumptions

One key information required in estimating the future impact of the weed is the total area of grazing and cropping lands potentially at risk from prairie ground cherry infestation. In order to determine potential distributions in Victoria, New South Wales and South Australia over the evaluation period (between 2006 and 2038), a logistic-type weed spread model was applied.

Meanwhile, the rate of weed spread is exceedingly difficult to accurately predict because of a number of environmental factors that influence it. Expert opinion is that prairie ground cherry will take between 100 and 200 years to reach its potential maximum geographical distribution. This rate of spread would depend on key variables including present distribution, potential distribution as predicted using climatic factors and land use, number of current infestations, and invasiveness rating (3). Table 1 shows the inputs to the weed-spread model applied in this study. Present distribution data for Victoria was based on a survey conducted in 2004 (David McLaren, DPI Victoria, *personal communication*). In the Riverina region of New South Wales, meanwhile, some 'low' to 'medium' density infestations were reported in 2004 (4). Because infestation records for prairie ground cherry in New South Wales and South Australia were not available to us at the time, estimates of present distribution in these states were assumed to be less than that in Victoria. Potential distribution data were estimated using CLIMATE software (5).

Table 1. Weed spread model inputs

Present distribution estimates, ha	
Victoria	12 427
New South Wales [A]	8 200
South Australia [A]	8 200
Potential distribution, ha million (%) [B]	
Victoria	13.2 (77%)
New South Wales	60.4 (91%)
South Australia	51.8 (94%)

[A] Estimates for New South Wales and South Australia were assumed to be 66% of that in Victoria.

[B] Figures in parentheses are percentages referring to proportion of predicted infestations likely to occur on pastures

The state most susceptible to prairie ground cherry invasion is New South Wales (60.4 million ha) followed by South Australia (51.8 million ha) and Victoria (13.2 million ha). The potential distributions

[4] Gross margin (GM) is the difference between farm revenue less variable costs of production, calculated per unit of land ($/ha).

of prairie ground cherry, over 50 years, in cropping and grazing areas of these south- eastern Australian states are shown in Appendix 7.1.

Few necessary assumptions were made as inputs to the BCA model. These include:

- Year biological control is first adopted – 8
- Maximum rate of adoption – 60%
- Year maximum adoption is obtained – 18
- Probability of research success – 60%
- Discount rate – 10%
- Extra cost of control on cropping areas, no biological control ($/ha) - $8.75
- Extra cost of control on pasture areas, no biological control ($/ha) - $4.10

Weed research scientists based at DPI Frankston, using currently available knowledge, provided the estimates for the first four dot points. Meanwhile, to reflect the high degree of uncertainty about the estimated future cost of control, a preferred discount rate of 10% was chosen. The estimates of control costs were based on a survey conducted in 2004 involving respondents from Victoria (David McLaren, DPI Victoria, *personal communication*).

4. Project costs

The projected estimates of annual investment cost of a biological control program for prairie ground cherry are shown in Table 2. Details of the cost estimate for each research activity to be undertaken over the first seven years, and the subsequent release, distribution and monitoring of the agents' impact from the 8th to the 12th year are presented in Appendix 7.2.

Table 2. Projected annual investment cost, un-discounted

Year	Investment ($ '000)
1	195
2	255
3	255
4	210
5	210
6	210
7	210
8	210
9	210
10	210
11	210
12	210

5. Results and analysis

Environmental factors could influence the rate of weed spread as well as the effectiveness of biological control agents to reduce such rate. Figure 1 illustrates a conservative 60% reduction in the rate of spread of prairie ground cherry on pasture land in south-eastern states of Australia, with the successful biological control program between 2006 and 2044, or 30 years after the target initial release of the biological control agents.

Meanwhile, due to currently available knowledge being limited and other uncertainties associated with *ex ante* analysis, sensitivity analysis was performed particularly on the rate of research success, adoption rate for the biological control technology and the applied discount rate. Table 3 presents the results of the sensitivity analysis.

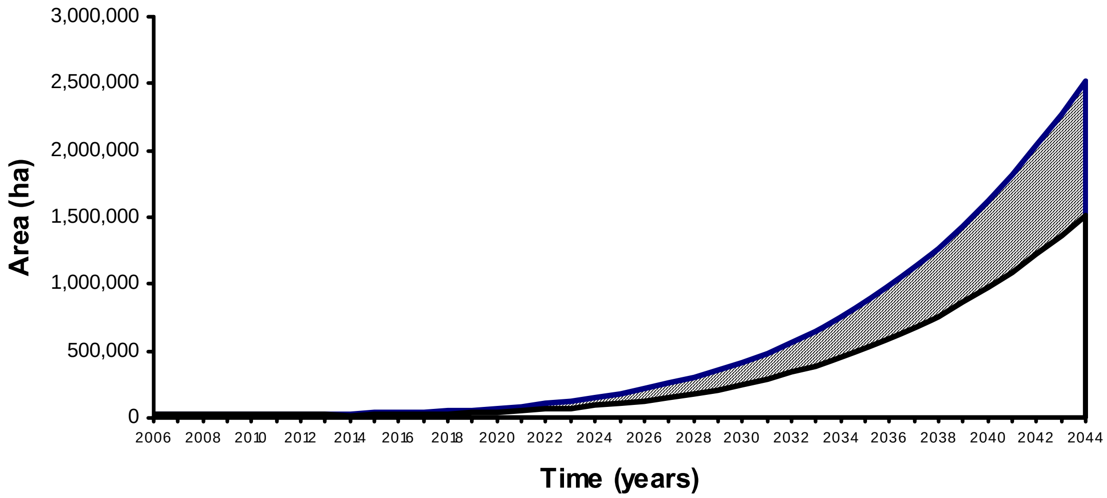

Figure 2. Illustrates a 60% reduction in the rate of spread (hatch area) of prairie ground cherry on pastureland in New South Wales, South Australia, and Victoria with biological control, between 2006 and 2044 or 30 years after the target initial release and distribution of agents.

Graziers and growers in Victoria, New South Wales and South Australia may receive a return of $26.30 for every dollar investment, at 10% discount rate, if a successful biological control program for prairie ground cherry were implemented. Positive returns on investment were estimated at all discount rates applied (8, 10 and 12%).

Table 3. Sensitivity analysis [A]

Investment decision criteria	NPV ($ million)	BCR	IRR (%)
(a) Discount rate			
8%	55.2	34.60	48.1
10%	37.6	26.30	48.1
12%	26.4	20.50	48.1
(b) Research success			
50%	31.1	21.90	45.3
60%	37.6	26.30	48.1
70%	44.2	30.60	50.6
(c) Adoption rate			
50%	30.1	21.20	45.3
60%	37.6	26.30	48.1
70%	45.2	31.40	50.6

[A] Base model (most likely) values are highlighted

A 10% change in adoption rate was found to lead to 19% change in the return on investment whilst a similar 10% change in the rate of research success resulted in a slightly lower (17%) percentage change in the return on the same investment. This indicates that return on investment is almost equally sensitive to adoption rate and the rate of research success. This suggests that the adoption of biological control as a new technology is as critical as the likelihood of success of the research program.

With respect to a change in discount rate, the return on investment in research for the biological control of prairie ground cherry ranges from $20.50 (12%) to $34.60 (8%) per dollar of investment, all other things remaining equal.

Meanwhile, when the expected gross margin value savings of $8.75 and $4.10 per ha respectively, for cropping and grazing enterprises were reduced by 20, 40 and 60%, positive returns on investment were still obtained. The expected returns on investment are $21.00 (20% reduction), $15.80 (40%) and $10.50 (60% reduction). A 20% reduction in the rate of weed spread yielded $21.20 return for every dollar investment.

The benefits estimated were limited to agriculture alone, that is, in terms of future control cost savings to grazing and cropping industries following the targeted release of biological control agents in south eastern Australia. A higher return on investment could be expected if other benefits would be quantified e.g. control cost savings in horticulture and other possible land uses. However, due to data limitations, the benefits to these other industries have not been included. It is recommended that a detailed economic study should be conducted as a part of this research program when more accurate cost and weed spread information become available.

Results indicate that the proposed research investment in the biological control program for prairie ground cherry is economically viable. Prairie ground cherry has been identified as one of the weeds significant to Australia's grazing industries (6). In this analysis, the grazing industries in Victoria, New South Wales and South Australia are likely to capture approximately 35% of the total expected benefits. However, this proportion could be higher if the actual rate of weed spread on grazing areas of the three states were higher than what was assumed in this analysis.

References

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4 New South Wales Agriculture. (2004). Riverina prairie ground cherry management plan: final draft. (NSW Agriculture, Wagga Wagga).

5 Pheloung, P.C. (1996) CLIMATE: a system to predict the distribution of an organism based on climate preferences. (Agriculture Western Australia: Perth).

6 Grice, T. (2004). Weeds of significance to the grazing industries of Australia. Meat & Livestock Australia, CSIRO and the Weeds CRC.

Appendix 7.1 Estimated Potential Distribution of Prairie Ground Cherry (PGC) in Victoria (Vic), New South Wales (NSW), and South Australia (SA), by Land Use in Ha (2006-2056)

VIC	Yr	Cropping	Pasture	**NSW**	Yr	Cropping	Pasture	SA	Yr	Cropping	Pasture
	0	8038	4389		0	5305	2897		0	5305	2897
	1	8039	4390		1	5306	2898		1	5306	2898
	2	8047	4397		2	5314	2907		2	5315	2907
	3	8072	4417		3	5339	2937		3	5341	2936
	4	8123	4457		4	5390	3003		4	5395	2999
	5	8211	4523		5	5479	3121		5	5491	3113
	6	8348	4623		6	5617	3311		6	5642	3294
	7	8545	4763		7	5816	3592		7	5861	3562
	8	**8,816**	**4,950**		**8**	**6,088**	**3,986**		**8**	**6,163**	**3,936**
	9	9172	5192		9	6448	4516		9	6562	4437
	10	9627	5496		10	6906	5205		10	7075	5087
	11	10194	5868		11	7478	6077		11	7718	5908
	12	10887	6317		12	8177	7158		12	8506	6923
	13	11719	6849		13	9017	8474		13	9456	8157
	14	12704	7472		14	10012	10053		14	10586	9635
	15	13857	8192		15	11177	11922		15	11912	11381
	16	15193	9018		16	12526	14110		16	13453	13423
	17	16725	9956		17	14074	16645		17	15226	15786
	18	18470	11014		18	15837	19560		18	17250	18497
	19	20441	12199		19	17830	22883		19	19543	21585
	20	22654	13519		20	20067	26646		20	22124	25078
	21	25125	14980		21	22565	30881		21	25013	29004
	22	27869	16592		22	25340	35620		22	28227	33393
	23	30901	18360		23	28407	40897		23	31788	38275
	24	34238	20292		24	31783	46744		24	35714	43680
	25	37896	22397		25	35483	53197		25	40025	49638
	26	41890	24680		26	39525	60290		26	44742	56181
	27	46237	27151		27	43924	68057		27	49885	63341
	28	50954	29815		28	48697	76535		28	55475	71148
	29	56056	32682		29	53862	85759		29	61532	79636
	30	61560	35757		30	59434	95767		30	68077	88838
	31	67483	39050		31	65431	106594		31	75131	98786
	32	73843	42567		32	71870	118280		32	82716	109514
	33	80655	46316		33	78768	130861		33	90853	121057
	34	87937	50305		34	86143	144375		34	99563	133447
	35	95706	54541		35	94012	158863		35	108869	146721
	36	103979	59031		36	102393	174363		36	118792	160912
	37	112774	63784		37	111302	190914		37	129355	176057
	38	**122,108**	**68,807**		**38**	**120,759**	**208,557**		**38**	**140,579**	**192,191**
	39	131999	74107		39	130780	227332		39	152488	209349
	40	142464	79693		40	141385	247279		40	165103	227569
	41	153521	85572		41	152590	268441		41	178447	246886
	42	165188	91751		42	164414	290858		42	192543	267339
	43	177483	98238		43	176875	314573		43	207414	288963
	44	190423	105041		44	189992	339628		44	223084	311797
	45	204027	112167		45	203782	366065		45	239575	335878
	46	218313	119625		46	218265	393927		46	256910	361245
	47	233300	127421		47	233460	423258		47	275114	387936
	48	249005	135565		48	249383	454102		48	294210	415989
	49	265447	144062		49	266055	486502		49	314221	445445
	50	282,644	152,921		50	283,494	520,503		50	335,172	476,341

Appendix 7.2 Estimated Research and Development Cost for Biological Control of Prairie Ground Cherry (PGC)

Research Activity	Year	Cost	Total Research Costs [A]
Genetic variability studies of PGC populations in Australia and comparisons with populations in South America. Survey organisms associated with PGC populations in Australia to determine what faunas (native and exotic) are already attacking the weed and to determine if any of these have potential as biocontrol agents. PhD project on PGC population ecology commences.	1	1 FTE (Grade 4) $70,000 operating ($50,000 molecular studies, $20,000 fauna surveys) 1 PhD student ($25,000 stipend)	$195,000
Overseas surveys in Argentina. PhD project (PGC population ecology continued).	2	1 FTE (Grade 4) 0.5 FTE (Grade 3) $80,000 1 PhD student ($25,000 stipend)	$255,000
Selection of potential agents and submission of applications for host test list and importation. PhD project (PGC population ecology completion).	3	1 FTE (Grade 4) $30,0001 PhD student ($25,000 stipend)	$255,000
Development of agent cultures, preliminary impact studies and host testing conducted in Argentina.	4	1 FTE (Grade 4) 0.5 FTE (Grade 3) $60,000	$210,000
Development of agent cultures, preliminary impact studies and host testing conducted in Argentina. Importation of cultures into quarantine in Australia.	5	1 FTE (Grade 4) 0.5 FTE (Grade 3) $60,000	$210,000
Completion of host testing of Australian native Solanaceae in Australia quarantine. Application for release.	6	1 FTE (Grade 4) 0.5 FTE (Grade 3) $30,000	$210,000
Release from quarantine and development of mass rearing cultures.	7	1 FTE (Grade 3) $30,000	$210,000
Agent distribution, monitoring and impact.	8	1 FTE (Grade 3) $30,000	$210,000
Agent distribution, monitoring and impact.	9	1 FTE (Grade 3) $30,000	$210,000
Agent distribution, monitoring and impact.	10	1 FTE (Grade 3) $30,000	$210,000
Agent distribution, monitoring and impact.	11	1 FTE (Grade 3) $30,000	$210,000
Agent distribution, monitoring and impact.	12	1 FTE (Grade 3) $30,000	$210,000

[A] Research costs based on two biocontrol agents

Appendix 7.3 Estimated Annual Extra Cost of Control of Prairie Ground Cherry (PGC) in Victoria, New South Wales and South Australia, by cropping and Pasture land use type ($)

VIC Yr	Cropping	Pasture	NSW Yr	Cropping	Pasture	SA Yr	Cropping	Pasture
0	70,333	17,995	0	46,419	11,877	0	46,419	11,877
1	70,341	17,999	1	46,428	11,881	1	46,428	11,881
2	70,413	18,029	2	46,500	11,919	2	46,503	11,918
3	70,627	18,111	3	46,715	12,042	3	46,730	12,038
4	71,073	18,274	4	47,163	12,311	4	47,209	12,297
5	71,844	18,545	5	47,939	12,796	5	48,050	12,763
6	73,043	18,953	6	49,146	13,574	6	49,367	13,506
7	74,772	19,527	7	50,888	14,728	7	51,283	14,604
8	**77,140**	**20,296**	**8**	**53,274**	**16,344**	**8**	**53,923**	**16,137**
9	80,257	21,288	9	56,417	18,516	9	57,421	18,191
10	84,238	22,533	10	60,432	21,339	10	61,910	20,855
11	89,199	24,061	11	65,437	24,915	11	67,530	24,221
12	95,259	25,900	12	71,552	29,347	12	74,425	28,385
13	102,539	28,081	13	78,901	34,744	13	82,740	33,445
14	111,162	30,634	14	87,607	41,216	14	92,624	39,503
15	121,253	33,587	15	97,799	48,879	15	104,230	46,664
16	132,938	36,972	16	109,603	57,849	16	117,713	55,033
17	146,347	40,818	17	123,151	68,246	17	133,229	64,721
18	161,610	45,156	18	138,575	80,194	18	150,938	75,838
19	178,857	50,015	19	156,009	93,818	19	171,004	88,499
20	198,224	55,427	20	175,587	109,247	20	193,589	102,819
21	219,843	61,420	21	197,446	126,610	21	218,861	118,917
22	243,851	68,026	22	221,725	146,041	22	246,988	136,913
23	270,386	75,276	23	248,562	167,676	23	278,141	156,928
24	299,585	83,199	24	278,099	191,652	24	312,493	179,088
25	331,589	91,826	25	310,478	218,108	25	350,218	203,517
26	366,538	101,189	26	345,841	247,187	26	391,493	230,343
27	404,576	111,318	27	384,333	279,034	27	436,495	259,697
28	445,844	122,243	28	426,100	313,792	28	485,404	291,708
29	490,487	133,995	29	471,288	351,612	29	538,401	326,509
30	538,650	146,606	30	520,045	392,643	30	595,670	364,236
31	590,480	160,105	31	572,520	437,036	31	657,396	405,023
32	646,124	174,525	32	628,862	484,946	32	723,764	449,009
33	705,731	189,897	33	689,223	536,528	33	794,962	496,332
34	769,448	206,250	34	753,753	591,939	34	871,179	547,134
35	837,428	223,617	35	822,606	651,339	35	952,605	601,555
36	909,819	242,028	36	895,935	714,888	36	1,039,433	659,740
37	986,776	261,515	37	973,895	782,748	37	1,131,857	721,834
38	**1,068,449**	**282,108**	**38**	**1,056,640**	**855,083**	**38**	**1,230,069**	**787,981**
39	1,154,993	303,840	39	1,144,328	932,060	39	1,334,267	858,331
40	1,246,562	326,741	40	1,237,116	1,013,846	40	1,444,647	933,032
41	1,343,311	350,843	41	1,335,160	1,100,609	41	1,561,409	1,012,234
42	1,445,396	376,177	42	1,438,621	1,192,519	42	1,684,751	1,096,088
43	1,552,974	402,775	43	1,547,656	1,289,750	43	1,814,875	1,184,748
44	1,666,202	430,667	44	1,662,428	1,392,473	44	1,951,983	1,278,366
45	1,785,239	459,886	45	1,783,096	1,500,865	45	2,096,278	1,377,100
46	1,910,243	490,462	46	1,909,823	1,615,100	46	2,247,964	1,481,104
47	2,041,374	522,428	47	2,042,771	1,735,358	47	2,407,248	1,590,536
48	2,178,793	555,815	48	2,182,103	1,861,817	48	2,574,335	1,705,556
49	2,322,660	590,654	49	2,327,983	1,994,658	49	2,749,434	1,826,323
50	2,473,137	626,978	50	2,480,577	2,134,062	50	2,932,753	1,952,998

Appendix 7.4 Estimated Distribution of Present Value of Benefits of Biological control of Prairie Ground Cherry over a 30-year period