Pathway risk analysis for weed spread within Australia (UNE61)

Appendix 3 – Review of literature

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Identifying and exploring pathways of weed spread within Australia: a literature review

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A component of UNE61 – Pathway Risk Analysis for Weed Spread within Australia

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Project UNE61 is part of the R and D component of the Australian Governments Defeating the Weed Menace Programme.

Photographs on cover page: B. Sindel (top left and bottom right); L. Tanner (bottom left); and R.D.B Whalley (top right).

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Glossary

Accidental spread: The inadvertent movement of weed propagules as a result of human activities. Such movement typically involves the transport of material (apparel, human or animal food, mulch) that has been contaminated with weed propagules.

Alien: Originating from outside of Australia.

Anemochory: Dispersal of plant propagules by wind. A species that is dispersed by wind is termed an anemochore.

Aquatic weed: A weed that grows in water. There are three kinds: 1) sub-merged growth beneath the surface; 2) emersed-growth above the water; and 3) floaters –plants that float on the water surface (Zimdahl 1999).

Deliberate: Intentional propagation of weeds for purposes such as gardening, revegetation, forestry, human or animal food production or herbal medicine. Such activities may or may not have a commercial benefit and may be carried out by industry, government or the community.

Diaspore: A reproductive unit of a plant, such as a seed, spore, or stem fragment.

Dispersal: The physical movement of seeds (or some other reproductive unit) from one place to another (Radosevich and Holt 1984).

Ecosystem: The system of ecological relationships upon which the life of any particular organism is based (Parsons and Cuthbertson 2001).

Exotic: see alien.

Feral: A naturalised alien species (Cronk and Fuller 1995).

Fruit: A structure formed from the flower ovary or receptacle and containing one or many seeds (Booth *et al.* 2003).

Frugivorous: Fruit eating; a frugivore (noun).

Genus: A taxonomic division of plants with common characteristics distinct from those of other groups, comprising one or more species (Parsons and Cuthbertson 2001).

Germinable: Capable of germinating.

Hydrochory: Dispersal of plant propagules by water. A species that is dispersed by water is termed a hydrochore.

Intentional: Deliberate.

Inadvertent: Accidental.

Introduced: see alien.

Introduction: The act of transporting a plant (or its propagule) across a major geographical barrier (Richardson *et al.* 2000). In the context of this review, humans are considered the major (if not sole) agent of introduction, and the term introduction is used in reference to the transport of alien plant flora into Australia. Introduction in this context may result from accidental or intentional human activities.

Invasion: Spread of an organism, without human assistance, into natural or semi-natural habitats to produce a significant ecosystem change (of composition, structure or processes) (Cronk and Fuller 1995).

Invasive: An organism that takes part in an invasion (noun).

Native: Originating from within Australia.

Naturalised: A non-native plant that forms self-sustaining populations but is not necessarily invasive (Booth *et al.* 2003).

Noxious weed: A species that is proclaimed by law (e.g. the NSW *Noxious Weed Act*, 1993) and is therefore subject to some form(s) of control.

Pappus: A group of hairs, bristles or scales (Parsons and Cuthbertson 2001).

Pathway: The means by which weed propagules are moved, often by wind, water, animals or through human activities.

Propagule: See diaspore.

Rhizome: A creeping stem, usually below-ground, from which new aerial shoots arise (Hussey *et al.* 1997).

Sleeper weeds: Non-native plants that have naturalised, but have not yet reached their potential to form large and widespread populations in Australia. They have the potential to

assume major significance if a change occurs allowing them to overcome current constraints on their population size and distribution (Australian Weeds Committee 2006).

Source: For this review, the term source is considered synonymous with pathway, and has been used interchangeably.

Species: A taxonomic division of plants with common characteristics distinct from those of other groups (the species ranks under the genus) (Parsons and Cuthbertson 2001).

Spore: A single celled reproductive organ characteristic of non-flowering plants such as ferns, fungi, and mosses (Parsons and Cuthbertson 2001).

Vector: The physical means or agent by which a species is transported. On land such agents are vehicles (trains, buses, cars, tractors). Over water, agents are vessels (ships, boats, barges) of many types and purposes (Carlton and Ruiz 2005).

Vegetative reproduction: Also known as clonal reproduction and vegetative growth, results in the formation of new individuals that are genetically identical to the parent plant. There are several types of clonal growth, including bulbs, tubers, and stem fragments (rhizomes) (Booth *et al.* 2003).

Weed: A plant that requires some form of action to reduce its harmful effects on the economy, the environment, human health and amenity (Australian Weeds Committee 2006).

Zoochory: Dispersal of plant propagules by animals or birds. There are two types: 1) endozoochory, involving the ingestion (and later excretion) of plant propagules; and 2) exozoochory, involving the transport of seeds attached to exterior parts (e.g. fur, feathers, wool, hooves).

Chapter 1: Introduction

Background

There has been considerable effort to determine the means by which weeds are introduced to Australia, and to assess and manage the risks associated with their importation. Weed risk assessment is a developing discipline that can assist to reduce the introduction and subsequent spread of plants in a region where they may become weeds. Australia is a world leader in the field, particularly with the implementation of the Weed Risk Assessment System (WRAS) (Pheloung et al. 1999) at Australia's border (Virtue *et al.* 2008).

The threat of weed spread can also be approached using a pathways-based analysis. There is not yet a generic process for assessing pathway risk, beyond combining risks of introducing each particular species (Simberloff 2005). A common approach is to identify a set of pathways, to assess the risk associated with each pathway, and also the ease with which that pathway may be managed. Risk is often assessed, at least in part, with respect to a particular group of plants that have known weed potential. The outcome of pathway assessment is a reduced set of pathways that represent considerable risk and can be managed with reasonable efficacy. This set of pathways can then be used to determine the allocation of resources and to inform policy and other management tools.

The United States Department of Agriculture has used a pathway-based analysis to conduct risk assessments associated with several commodities (Andow 2003). A pathways approach has also been used in New Zealand, to assess the risk to indigenous plant taxa and genetic material (Williams *et al.* 2000). Hulme *et al.* (2008) has developed a framework for integrating invasive species pathways into policy, using the European Union as a case study for the regulatory perspectives. The framework recognises six principal pathways for the introduction of invasive species: release (deliberate), escape, contaminant, stowaway, corridor and unaided (the natural spread of an alien species from one region into another). In each of these examples, pathway analysis facilitates the identification of priority areas for investment in weed prevention activities.

In Australia, a pathways-based approach to weed spread has been conducted in Victoria as part of the Tackling Weed Spread on Private Land initiative (Thomas *et al.* 2007; Wiess *et al.* 2006). This project has delivered a transparent and reproducible method for assessing the

relative weed spread risks of different industries and organisations. In this project, experts developed a comprehensive set of weed introduction pathways, and a list of organisations and industries whose activities might introduce and/or spread weeds in Victoria. This information was used to generate a matrix of industries and pathways. A set of weighted criteria were assigned an intensity rating, and used to generate a final 'risk assessment' score for each industry pathway. A confidence score was also calculated to indicate the level of uncertainty and availability of data for each criterion. It was determined that the industry pathways with both high risk scores and high/medium confidence scores were the most likely to pose serious problems for the distribution of the priority species. This process has assisted the government of Victoria to identify the industries with the highest potential for weed introductions, which can be actively engaged with to reduce the weed risk of their activities. Another outcome of the project is the identification of areas requiring further investigation, to generate information that will improve the reliability of the risk assessment scores (Thomas *et al.* 2007).

A national pathways-based assessment of weed-spread has been identified as a means of identifying high risk avenues of weed spread, so that appropriate management strategies can be devised. While the routes by which weedy species have entered Australia are generally well documented, information is needed to address the issue of weed spread within the country. This is especially important in the case of weeds that currently naturalised in small areas, so as to prevent their wider dispersal and establishment. The number of pathways of weed spread are vast, including contaminated fodder, seed, human apparel, machinery, animal manure, wind, and floodwater – in reality anything that moves or is moved (Panetta and Scanlan 1995). Given this vast array, there is no way of effectively sampling all these pathways in one project to quantify the level of weed ingress and therefore the relative risks imposed by each (J. Virtue, pers. comm.). The first and foremost requirement in this area is a desk-top study that brings together all the objective and anecdotal literature relating to weed spread within Australia, from which pathways of weed spread can be identified.

Objectives

The purpose of this literature review is to collate and analyse the scientific and other literature to identify:

1. the various sources and pathways of weed movement within Australia; and

2. management options to address weed spread via these sources and pathways.

We anticipate that the information yielded by this review will be useful in designing strategies to manage weed spread at the national, local and property scale. Also, by highlighting gaps in current knowledge, this research will assist to direct funding towards priority areas for scientific exploration. Finally, this work has implications for extension and communication to improve the public's understanding of ways in which they can assist to halt the spread of invasive plants.

Methodology

Pathways responsible for spreading weeds were identified and explored through a review of the related literature. Relevant literature was discovered through key word searches of catalogue options available through the University of New England (UNE) Library. This facility provides access to a wide variety of electronic databases (e.g. Journal Storage (JSTOR) 1995 onwards; SpringerLink 1996 onwards) as well as electronic and printed literature. A large number of useful publications were obtained from the extensive selection of weeds literature held within the Department of Agronomy and Soil Science (UNE). Key word searches were also performed using Google Scholar and Google search engines. Relevant websites were searched extensively, including Weeds Australia, the CRC for Australian Weed Management, and the various state and federal government agencies with responsibilities in weed management (e.g. New South Wales Department of Primary Industries). An email request for information was sent to subscribers on the Enviroweeds list server[1], and the email exchange between Enviroweeds subscribers was monitored and relevant discussion items noted. As a result of these processes, relevant information was discovered in scientific journals, conference papers, books, theses, reports, weed management guides and fact sheets. Unpublished or out-of-print sources were obtained upon request to the author(s). As this research is directed at understanding weed movement within Australia, literature was mostly

[1] The Enviroweeds list server was established by the Weeds CRC in 1998, and is used to exchange and discuss information relevant to the management of environmental weeds in natural ecosystems.

obtained from Australian sources, although some highly relevant international literature has also been included.

Context

This literature review is the first stage of Project UNE61 – Pathway Risk Analysis for Weed Spread within Australia. The University of New England (UNE) is conducting this research, by agreement with Land and Water Australia (LWA). Project UNE61 is part of the R and D component of the Australian Governments Defeating the Weed Menace Programme, which is being managed by LWA.

Once the literature review has identified all sources and pathways implicated in weed spread, experts will be surveyed by mail questionnaire to provide their experience of relative risks of weed ingress, the effects of changing trade patterns and environmental conditions, and effective management techniques. The information from the survey and the literature review will be subjected to focus group risk analysis (across weeds and industries) to refine and validate the findings and to brainstorm new and novel approaches to prevent weed movement, including institutional, regulatory, and policy approaches. The results of the survey and of the focus group risk analysis will be reported in later stages of the project.

Scope

The research questions that will be addressed in this review are as follows:

1. What pathways are involved in spreading weed propagules within Australia?
2. In what ways can these pathways be managed?

This literature review is not primarily concerned with:

- understanding how weeds enter Australia (i.e. international quarantine); or
- conducting a risk assessment of identified sources and pathways in terms of their capacity to spread weeds.

As this is a study of weed spread within Australia, the first issue is beyond the scope of this project. The last issue will be addressed in a later stage of the research (i.e. on the basis of expert survey and focus group findings). However, this literature review will discuss the

ability of each pathway to disperse weeds, and this will provide much of the information to conduct the risk analysis.

Structure

In this section we provide a brief overview of the information contained in the subsequent chapters of this review. A brief glossary is provided at the beginning of the document to define important terms that are used in ensuing chapters. In Chapter 2 we identify and discuss the deliberate spread of weeds that are valued by humans for ornamental, therapeutic, culinary, forestry, revegetation, or agricultural purposes. Chapter 3 is focussed on the main ways through which humans can accidentally spread weeds. Chapter 4 is concerned with weed spread by natural (non-human) dispersal agents, including wind, water, animals and birds. Chapter 5 contains three case studies, involving identification of weed spread pathways. In Chapter 6 we discuss management directions for research into, and prevention of, weed spread. Chapter 7 concludes the review, and contains a number of recommendations for future research. The reference section contains the details of literature cited in this review. Appendix 1 is the final section of this document, and contains the full list of 61 national priority weeds (Case study 3).

Chapter 2: Deliberate spread of weeds by humans

Although this literature review is not primarily concerned with the introduction of plants into Australia, an understanding of the introduction history of weeds provides insights into their spread once within the country. Virtue *et al*. (2004) have examined the sources of plant introductions to Australia. Plants have been introduced to, and distributed within Australia, for numerous reasons, including food, fodder, fibre, timber, herbal medicine, gardening, and environmental remediation. Table 1 presents the main industry sectors responsible for the introduction of exotic species. The three industries responsible for the majority of plant introductions are agriculture, forestry and gardening. From Table 1, it is clear that the gardening industry has been the major pathway for weedy species into Australia.

Table 1. Weed status by industry sector of exotic plant species introduced to Australia (source: Virtue *et al.* 2004).

	No. of species introduced	Naturalised[A]		Weeds[B]		Agricultural[C] weeds		Noxious[D] weeds		Natural ecosystem[E] weeds		Combined agricultural, noxious and natural ecosystem weeds[F]	
Industry sector	(*I*)	No.	*% of I*	No.	*% of I*	No.	*% of I*	No.	*% of I*	No.	% of I	No.	*% of I*
Food crops	221	85	*38*	105	*48*	26	*12*	8	*4*	55	*25*	58	*26*
Pasture (Poaceae)	490	150	*31*	180	*37*	82	*17*	7	*1*	116	*24*	124	*25*
Pasture (Fabaceae)	499	163	*33*	196	*39*	66	*13*	11	*2*	115	*23*	126	*25*
Pasture (the rest)	97	36	*37*	41	*42*	11	*11*	3	*3*	20	*21*	23	*24*
Total pasture	1,086	349	*32*	417	*38*	159	*15*	21	*2*	251	*23*	273	25
Forestry[G]	633	149	*24*	226	*36*	35	*6*	30	*5*	103	*16*	108	*17*
Gardening	25,360	1,831	*7*	2,520	*10*	660	*3*	273	*1*	1,279	*5*	1,366	*5*
Accidental[H]	207	186	*90*	185	*99*	84	*45*	24	*13*	121	*65*	141	*76*
Accidental and intentional[I]	1,051	776	*74*	828	*79*	443	*42*	137	*13*	592	*56*	640	*61*
Total introduced[J]	27,009	2,779	*10*	3,480	*13*	954	*4*	343	*1*	1,765	*7*	1,953	*7*

[A] Specimens lodged in Australian herbaria (Hosking 2003 and Randall 2004).
[B] Listed as weeds in Australia in various texts (Randall 2002 and Randall 2004).
[C] From Groves *et al.* (2003) and Randall (2004).
[D] From www.weeds.org.au
[E] Species cited as 'Environmental Weeds' in Randall (2004).
[F] This is less than the sum of all weed types as some species occur as more than one type.
[G] This includes species used for forestry purposes overseas but not currently in commercial production in Australia (Randall 2004).
[H] Species cited as 'Contaminants' (e.g., of imported grain, fodder, ballast, packing materials, livestock) in Randall (2004).
[I] This is the upper limit of accidental introductions. Species are likely to have been introduced to Australia as contaminants, but are also known to have been deliberately cultivated in Australia (Randall 2004).
[J] This is less than the sum of all industry sectors as some species occur in more than one sector.

Figure 1 further illustrates the historical importance of the garden industry, based on the findings of Groves (1997). Of the 290 species thought to have naturalised in Australia between 1971 and 1995, the majority (65%) were introduced as ornamental plants. Only 7%

were introduced for agricultural use, and 2% through seed contamination. The remaining 26% are of unknown origin or from 'other' sources.

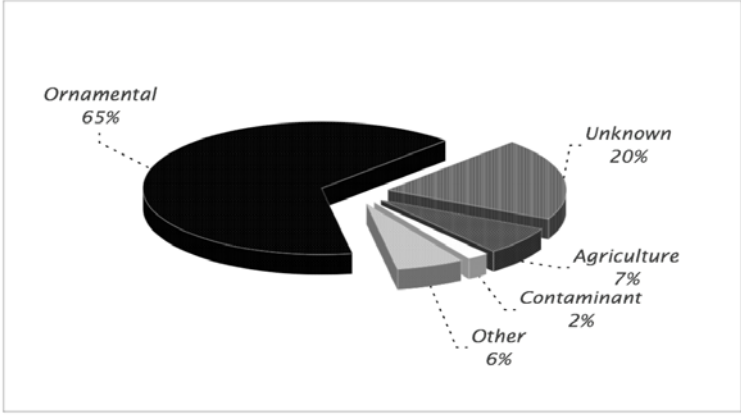

Figure 1. Pathways for introduction of environmental weeds into Australia (source: Groves 1997).

Ornamental plants

Over the last 20 years, all but three of the 281 garden species that have been identified as potential threats to Australian grazing industries have been available in Australian nursery stock publications (Barker *et al.* 2006). Of these species, 67 per cent were available from Australian nurseries in 2004 (Barker *et al.* 2006). According to Coutts-Smith and Downey (2006) garden escapes accounted for 65% of the 127 weeds threatening biodiversity in New South Wales. At the time their paper was written, just under half (43%) of these species were available for purchase within Australia, and 28% were available for sale in New South Wales. Table 2 provides further detail on the sale of invasive garden plants in NSW. These figures may no longer be accurate due to subsequent changes in state legislation and self-regulation of the nursery industry.

Table 2. The most invasive garden plants in each state, territory and the whole of Australia that were available for sale in NSW in 2006 (source: Coutts-Smith and Downey 2006).

The most invasive garden plants available for sale in Australian and in each state and territory	State in which the species is identified in top 10 garden escapes [ab]	Available for sale in NSW as of July 2006 [c]
Acacia saligna (golden wreath wattle)	SA	Yes
Coprosma repens (looking glass bush)	Tas	Yes
Coreopsis lanceaolata (coreaopsis)	Qld	Yes
Conteaster spp.	ACT	No
Cytisis spp.	Aust., NSW, Tas., ACT	Yes
Eragrostis curvula (African lovegrass)	Vic.	Yes
Genista spp. (broom)	ACT	No
Gloriosa superba (glory lily)	Aust., NSW, Qld	Yes
Lonicera japonic a (Japanese honeysuckle)	Aust., Qld, ACT	Yes
Ochna serrulata (mickey mouse plant)	Qld	No
Olea europaea (olive)	SA, ACT	Yes
Opuntia spp. *(prickly pear)*	Vic.	No
Pennisetum clandestinum (kikuyu)	SA	Yes
Pinus radiata (radiata pine)	Tas, ACT	Yes
Pittosporum undulatum (sweet pittosporum)	Aust, Tas, WA	Yes
Pyracantha spp.	ACT	No

a) These weed species were identified by Groves et al. (2005) as the 10 most invasive garden escapes that were available for sale in Australia.

b) Aust. = Australia, SA = South Australia, Tas. = Tasmania, Vic. Victoria, NSW = New South Wales, Qld = Queensland, ACT = Australian Capital Territory, WA = Western Australia.

c) Based on the list of prohibited species under the NSW Noxious Weeds Act 1993.

The availability of plants for sale in states where they are not considered invasive is of concern because propagules could easily be transported, accidentally or otherwise, across the borders into states in which the plants are considered invasive.

When discussing the spread of weeds through the ornamental industry, it is important to consider that Australian native plants can become weedy when introduced outside their original range. According to Low (2001), the weedy potential of Australian plants has not received adequate attention. Low (2001) states that very few native plants were genuinely popular in gardens in the past, but those that were include many of today's worst weeds, such as golden wreath wattle (*Acacia saligna*) and sweet pittosporum (*Pittosporum undulatum*). Each of these species were available for sale in New South Wales in 2006 (see table 2).

Aquarium plants

The trade in ornamental plants includes those used in aquariums and water gardens. According to Mitchell (Mitchell 1978), the international trade in ornamental plants for fresh water aquaria has been the most important agency for the spread of exotic aquatic plants into and within Australia. Virtually all of Australia's major aquatic weed species were originally imported for use in garden ponds or as ornamental aquarium plants (Csurhes and Edwards 1998). The 'seeding' of waterways for wild harvesting, to meet consumer demand for aquatic species, has resulted in many aquatic weed infestations. For example, the spread of Cabomba (*Cabomba caroliniana*), a WONS species, has been facilitated by this practice (ARMCANZ 2000).

Stopping the spread of invasive plants in the garden industry

Moss and Walmsley (2005) explored the use of voluntary approaches as an option for controlling the sale of invasive plants. They conclude that, while there is certainly a role for industry-led voluntary approaches to raise awareness of weed impacts and risks associated with garden plants, there are inherent constraints that prevent a national voluntary approach being effective on controlling the sale of invasive species. These include:

- The structure of the garden industry, which is dispersed and consists of many small to medium sized businesses. This impedes the successful implementation and monitoring of voluntary measures.
- Limited coverage by the national industry body. Not all nursery and garden industries are members of the national industry body, Nursery and Gardening Industry Australia (NGIA), including some major retailers such as supermarket and hardware store chains.
- A national voluntary measure could create an un-level playing field where those businesses that do voluntarily remove invasive garden plants from sale may be at a commercial disadvantage compared to those that continue to sell these species.
- Size of the industry body. Self-regulatory schemes may be very costly to run and administer, and the presence of a large industry association appears to be a crucial factor to ensure a workable scheme. According to Moss and Walmsley (2005), the

NGIA and related bodies are too small to provide confidence that cost advantages would occur.

The owners of gardens, including community members, government agencies and developers, also have a role in preventing the sale of weedy plants. Plant buyers can influence gardening and landscaping businesses through their purchase choices, thereby providing a commercial incentive for dealing in non-invasive garden species.

A note on e-commerce in the trade of invasive species

While humans have transported plant species between countries for many centuries, the event of e-commerce has increased the speed and scale at which this exchange may occur. It is therefore appropriate that this avenue should be considered in any efforts to curb the spread of invasive species within Australia. King (2005) has highlighted the ease with which declared weeds and invasive plants can be imported into Australia via e-commerce and then moved from State to State. According to this report, the Australian Quarantine and Inspection Service (AQIS) has observed an increase in non-compliance since the introduction of eBay and internet sales in general. King (2005) has identified the various weaknesses in National and State legislative frameworks and border controls, and provides recommendations to tighten these controls. These recommendations are based on a review of the relevant literature, and range from short-term strategies, such as implementing the USA's internet surveillance system (AIMS), through to longer-term, more far reaching national policy and legislation reforms.

Text box 1. A note on e-commerce in the trade of invasive species.

The Nursery and Garden Industry is actively working to reduce the number of invasive plants that are grown and sold in Australia. It has released a national position paper on invasive plants, which sets out the nursery and garden industry's commitment to tackling the issue of invasive plants. A set of national labelling guidelines has been developed, including a section on invasive and potentially harmful plants. These guidelines cover correct botanical nomenclature, warnings about invasiveness, and poisonous plant warnings. The guidelines are recommended for adoption by all plant producers, suppliers of plant material, plant retailers and label manufacturers. The National 'Grow Me Instead' program is an educational program for industry and consumers. It is co-funded by NGIA, industry members, and the Federal Government's Defeating the Weed Menace program. The program aims to promote a number

of key messages, including encouraging gardeners to remove problem plants and replace them with low risk alternatives, adopt responsible gardening practices to reduce weed spread, and seek advice from a local expert on local problem species. Mediums used to communicate these messages include Regional 'Grow Me Instead' booklets, posters and other in-store promotional material, as well as industry workshops for retailers and presentations tailored for consumers in garden centres (Chin 2008).

The National Aquatic Weeds Management Group, in partnership with state governments, aquatic plant trade industries and New Zealand's National Institute of Water and Atmospheric Research, have initiated a Weed Risk Assessment (WRA) of aquatic plants within the ornamental plant trade (Petroeschevsky and Champion 2008). The process ensures declarations will be based on research conducted under Australian conditions and made in consultation with industry. So far, the process has used data on historic and current sales to identify 25 high-risk aquatic plant species that are recommended for national ban. *Limnocharis flava* is among the 25 species recommended for a national ban. It is one of 6 species targeted in a national cost sharing weed eradication program, the 'Four Tropical Weeds Eradication Program' (Petroeschevsky and Champion 2008).

Therapeutic plants

Some important weeds have been spread within Australia, at least in part, because of their value for therapeutic or medicinal purposes. Horsetails (*Equisetum* spp.) are among the world's worst weeds for agriculture and are on the Alert List for Environmental Weeds (CRC for Australian Weed Management 2003). It has been retailed as a medicinal plant and traded among alternative medicine enthusiasts (Blood 2001). Orange hawkweed (*Hieracium aurantiacum*) is another species on the Environmental alert list (CRC for Australian Weed Management 2003) that has been grown and sold for its herbal properties (Rudman and Goninon 2002). St John's wort (*Hypericum perforatum*) is well known weed and is also well known as a medicinal plant. The history of its introduction to Australia is not clear, but its use as a medicinal plant goes back as far as the 1860s, when it was planted in the gold-mining town of Bright (Victoria) for its medicinal properties, including the induction of human abortions (Parsons and Cuthbertson 2001). It has since been declared a noxious weed in NSW, Victoria, WA and Tasmania. There is now a resurgence of interest in the therapeutic properties of this herb, particularly as an antidepressant (Peacock *et al.* 2005).

Dwyer (2006) has uncovered substantial, albeit circumstantial, evidence to support the view that many plants introduced to Victoria for medicinal use, escaped gardens and became weeds. Species he considers likely to have originated from medicinal plantings include variegated or milk thistle (*Silybum marianum*), sorrel (*Rumex acetosella*), and horehound (*Marrubium vulgare*). As with any plant that is valued by humans for some purpose, the benefits of plants with medicinal properties need to be weighed against their negative impacts. Where it is deemed viable for these plants to be propagated, growers should be advised of their weed risk and also of strategies to reduce the spread of these species into new areas.

Culinary plants

Plants promoted as food for humans can become invasive. For example, the European olive (*Olea europaea* spp. europaea) is the focus of an expanding industry in Australia. The olive is now naturalised in South Australia, NSW, Victoria and Western Australia. In South Australia it is a proclaimed plant, when not planted and maintained for domestic or commercial use (Weeds Australia 2008a). The species provides a striking example of colliding economic and environmental priorities (Hanson 2002). Current estimates of olive production in Australia are shown below in table 3. While it is recognised that olives are a valuable tree crop, the costs of controlling wild olives also needs to be taken into consideration. Control of feral olives by poisoning the trees, together with follow-up spraying of emerging seedlings, will typically cost $500/ha/year. The felling and removal of dead olive trees is often also required, and this can cost an additional $15,000 to $20,000 per hectare for dense infestations of mature trees (Interdepartmental Taskforce on Feral Olives 2003).

Table 3. Olive production statistics for Australia in 2008 (Source: Australian Olive Association 2008).

	Production Estimates for Australia (tonnes)								EVOO		Table Olives	
Year	Table Olives	Olive Oil	NSW	QLD	SA	VIC	TAS	WA	Imports (tonnes)	Exports (tonnes)	Imports (tonnes)	Exports (tonnes)
2001		500	-	-	-	-	-	-	27,680	385	11,545	74
2002		750	-	-	-	-	-	-	28,987	300	12,618	199
2003		1,500	11.0%	12.0%	39.0%	28.0%	1.0%	9.0%	28,447	278	14,483	138
2004	2,000	2,500	12.0%	8.0%	16.0%	47.0%	1.0%	16.0%	32,657	501	13,711	265
2005	2,700	5,000	12.1%	5.0%	16.2%	40.1%	0.4%	26.2%	29,062	1,652	15,143	215
2006	3,200	8,650	8.3%	4.0%	18.2%	53.9%	0.2%	15.4%	34,511	2,988	15,608	230
2007	2,500	9,250	8.0%	4.1%	14.6%	49.2%	0.2%	23.9%	43,404	2,502	16,364	207
2008	2,200	12,000										

Sources:

Olive oil: Leandro Ravetti, Modern Olives - AOA National Conference

Table olives: Jim Smyth, Olive Skills

Imports and exports: Australian Bureau of Statistics

Alligator weed (*Alternanthera philoxeroides*) is a WONS species (CRC for Australian Weed Management 2003) and is considered one of the worst aquatic and terrestrial weeds in the world. The weed has been cultivated as a green leafy vegetable by the Sri Lankan community, in the mistaken belief that it is another plant sessile joy weed (*Alternanthera sessilis* (L.) R. Br. ex DC.). The Department of Natural Resources and Environment in Victoria, Australia has worked in partnership with the Sri Lankan community to eradicate, manage and prevent reinfestation of the alligator weed. As results of this program, 775 alligator weed infestations have been located including 13 naturalized sites. An Australian native species, common joy weed (*Alternanthera denticulata* R. Brown), has been tested for nutritional value and distributed to Sri Lankan families. This alternative species appears to be very popular and has since been sold in a number of shops around Melbourne (Gunasekera and Bonila 2001).

Pond apple (*Annona glabra*) is a major environmental weed of the Wet Tropics bioregion of North Queensland and is a WONS. This small to medium-sized tree invades fresh, brackish and saltwater areas and its thickets are capable of replacing whole ecosystems. The species was imported into Australia in 1912 as grafting or root-stock for the commercial production of custard apple. This practice has now ceased (R. Cobon 2008, pers. comm.), but a large number of existing infestations can be traced back to farms and orchards (Department of Natural Resources, Mines and Water 2006).

Fodder plants

As shown in Figure 1, of the 290 species thought to have naturalised in Australia between 1971 and 1995, 7% were introduced to Australia for agricultural reasons (Groves *et al.* 2005a). Cook and Dias (2006) have reviewed the history of deliberate plant introductions by Australian government agencies during the 20th century. According to this work, Commonwealth Plant Introductions comprised more than 2200 grass (Poaceae) and 2200 legume species (Fabaceae *sensu strictu*); approximately twice the indigenous flora in those families.

These introductions have left a legacy of unwanted species. Five of the WONS species are legumes that were planted intentionally on livestock grazing properties, as browse or fodder plants, and/or for shade or shelter. These species are: gorse (*Ulex europaeus*), mesquite (*Prosopis* spp.), mimosa (*Mimosa pigra*), parkinsonia (*Parkinsonia aculeata*) and prickly acacia (*Acacia nilotica* ssp. *indica*). Paynter *et al.* (2003) reviewed the literature on the topic of weedy legumes. According to this source, most serious legumes are exotic thicket-forming species that were deliberately introduced for shade, fodder, or as garden ornamentals. One species, Tagasaste (*Cytisus proliferus)*, is of the tribe Genisteae, subtribe Cytisus-Genista, which includes other noxious weeds (e.g. brooms and gorse). Tagasaste is an environmental weed in south-eastern Australia, and has been available commercially and widely planted for fodder (Blood 2001). Another species, Coffee bush (*Leucaena leucocephala)* has been promoted as fodder for cattle, even though it can form dense thickets that exclude native vegetation (Smith 2002).

The issue of perennial grass weeds has received particular attention in the weed literature, being the focus of an entire special edition of Plant Protection Quarterly (for more detail, see Grice 2004). The Poaceae are one of the major plant families represented in the flora naturalising in Australia between 1975 and 1995 (Groves 1997). Amongst Randall's (2001) list of 358 'garden thugs', there are 46 Poaceae that are either invasive or potentially invasive, and 26 that are classified as significant environmental weeds in Australia (Grice 2004). Three species, serrated tussock (*Nassella trichotoma*), Chilean needlegrass (*N. neesiana*), and olive hymenachne (*Hymenachne amplexicaulis*) are amongst the 20 WONS species. The means by which Chilean needle grass and serrated tussock entered Australia has been described as unknown (CRC for Australian Weed Management 2003). However, Cook and Dias (2006)

have pointed out that a large number of *Nassella* species were introduced and trialled as pasture grasses in Australia, and a trade in *N. trichotoma* as a forage plant has been documented. Olive hymenachne was originally introduced to Queensland and the Northern Territory as a ponded pasture species, and according to Smith (2002), some pasturalists continue to sow it for this reason.

Buffel grass (*Cenchrus ciliaris*) is valued for its drought resistance and ability to withstand persistent heavy grazing (Lazenby 1997) and is an important pasture grass in low-rainfall regions of Australia. It is also considered a major environmental weed of northern Australia, where it increases ground fuel loads in native woodlands. Invasion by the species is facilitated by burning, producing a positive feedback between Buffel Grass and fire. As a result, the rate of degradation in native remnant vegetation is accelerated (Butler and Fairfax 2003).

The *Eragrostis curvula* complex comprises numerous varieties, some of which have been used as pasture species, to control erosion in waterways, and as a nematode break in maize crops (Silcock 2005). *Eragrostis curvula* has been described as weed of road verges that may form dense swards crowding out more desirable species in pasture or environmental areas (Weeds Australia 2008b). It is difficult to obtain information regarding the invasiveness of the different varieties of this species. A variety, 'Consol' is commonly recommended as a pasture species and has been shown to provide control over spiny burrgrass (*Cenchrus* spp.) (Johnston 1989).

Gamba grass (*Andropogon gayanus*) is another example of a pasture species that has gone on to become invasive. Csurhes (2005) has reviewed the introduction history of this plant in Queensland and assessed its economic, social and environmental impacts. According to Csurhes (2005), the CSIRO Division of Land Research introduced gamba grass seeds to the Northern Territory in 1931. It was released through the NT Herbage Plants Liaison Committee in 1978 and listed in the Register of Australian Herbage Cultivars in 1986. Commercial quantities of gamba grass seeds first became available in 1983, and the species was afterwards sown for pasture in the Northern Territory. Csurhes (2005) considers that Gamba grass has the potential to become one of Queensland's worst weeds of tropical savannas (tropical woodland and open forest ecosystems) because of its ability to replace native grasses, increase fuel loads, and reduce available soil nitrate levels. In the Northern Territory is has been claimed to cover an estimated area of 10,000 km^2 to 15,000 km^2, and has the potential to occupy up to 380,000 km^2 (Natural Resources, Environment, The Arts and

Sport, undated). Gamba grass is not currently a declared weed in the Territory, but it is being considered for declaration under the Weeds Management Act 2001 (NRETA 2007).

Biofuels

Biofuels are liquid hydrocarbons derived from organic matter, and can be used directly or blended with petroleum products to provide energy (Pyke *et al.* 2008). Biofuels may benefit the environment through the reduction of greenhouse gas emissions, but there are also significant risks associated with the selection of potentially invasive cultivars (Pyke et al. 2008). The Invasive Species Council has assessed the weed threat posed by biofuels and provided recommendations to reduce the weed risk associated with the biofuels industry (Low and Booth 2007). This report summarises the weed risks of 18 proposed biofuel plants that are receiving interest in Australia and overseas. Of these plants, the report recommends that 16 should not be cultivated in Australia because of their weeds risk. *Jatropha curcus* is among the 16, and is perhaps the most notorious example. This species is already being cultivated in South East Asia, Southern Africa, Central and South America and India for the production of biodiesel (BP Press Office 2007). As with any plant industry, there is the need to ensure that industry and government stakeholders work together to reduce the weed-risk associated with cultivating potentially invasive species for the production of biofuels. The advantage in this case is that the biofuels industry is relatively young and Australia has the opportunity to take pre-emptive action to minimise weed risks, thus avoiding the damage that has occurred through previous deliberate plant introductions.

Revegetation and forestry

Revegetation using exotic and native species has occurred for a number of reasons, including stabilisation of disturbed areas, rehabilitation of degraded soils, to provide shelter or shade for stock and humans, and to produce timber. As in other cases of intentional plant introductions, conflicts of interest may arise in relation to species introduced for revegetation purposes. Such conflicts may involve pastoralists that seek to maintain or improve production, and conservationists concerned about the integrity of natural vegetation. Conflict could also arise on the basis of competing environmental interests. For example, landscape stability versus composition of natural plant communities (Grice 2004).

Perhaps one of the most well-known example of a revegetation plant-turned-weed is that of bitou bush (*Chrysanthemoides monilifera* subsp. *rotundata* (DC.) T.Norl.). According to the NSW bitou bush strategy (Ray 2001), from 1946 to 1968, bitou bush was planted along the coast by the NSW Soil Conservation Service to reduce dune erosion and assist in post-mining rehabilitation. Mapping surveys conducted in 2000 showed that over 80 percent of the NSW coastline was infested with bitou bush.

Cook and Dias (2006) discuss the role of soil conservation authorities and the CSIRO in introducing species for soil erosion and rehabilitation. Starting in the late 1930s, a range of exotic species were introduced for soil stabilisation and rehabilitation of the arid zone, including species from genera such as *Stipa, Parkinsonia, Salix, Genista, Nassella, Senecio, Retama* and *Sporobolus.* Species in these genera have now become weeds. For example, most of the *Salix* spp. (willows) are listed as WONS (CRC for Australian Weed Management 2003). Willows have been planted widely in the southern half of Australia for protection of riverbanks and for aesthetics, shade and shelter. However willows are spreading into Australia's waterways (Cremer 2003). While many species of willow are now banned in Australian states and territories, some species remain undeclared. It is important that the invasiveness of these undeclared species is fully explored, resulting in legislative changes where invasiveness is demonstrated. For example *Salix reichardtii* is not among the willow species listed as WONS. However, it has recently been recognised as invasive along watercourses within the Mount Lofty Ranges (Coles and Cramond 2008).

Virtue and Melland (2003) have assessed the environmental weed risk of a range of trees, shrubs and grasses that have been planted for use in broad scale rural revegetation and farm forestry in South Australia. Their report provides comprehensive evidence of the significant weed risk of some species, both exotic species and Australian native species. Exotic pines (*Pinus brutia, P. halepensis* and *P. radiata*) ranked as high to very high environmental weed risks in various southern SA regions, readily establishing in relatively undisturbed native vegetation and forming high-density monocultures in the long-term. The native sugar gum (*Eucalyptus cladocalyx*), which is indigenous to nearby regions of southern SA, was able to establish readily in native vegetation and represented a high weed risk in the Mt Lofty Ranges and a medium weed risk in South East regions. Other native species with medium to very high weed risk were perennial veldt grass (*Ehrharta calycina*), western coastal wattle (*Acacia*

cyclops) and golden wreath wattle (*A. saligna*). At this time this assessment was conducted, the later two species had already formed high-density infestations in the region.

A note on deliberate introductions

The definition of a weed is both time and location specific (Sindel 2000). Many plants have been intentionally planted because of some benefit to humans, and would not be a problem if their population had remained within the confines of its original location. However, as this chapter has demonstrated, many deliberately introduced plants 'jump the garden fence' to become invasive species that cause substantial damage to agriculture and the environment.

Human agency in deliberately introducing weeds into a new range opens, in turn, the potential for these species to be inadvertently spread by humans and natural dispersal agents (Mack and Lonsdale 2001). Kowarki (2003) studied the role of human agency in biological invasions. This work has a number of important implications for deliberately introduced plants. Firstly, the rate of naturalisation is higher in deliberately introduced plants as compared to accidental introductions. Further, secondary releases of alien species may mimic demographic and dispersal processes that lead to population growth and range expansion. They also offer a pathway to overcome spatial isolation in species whose propagules are not naturally moved long distances. Thus, secondary releases may promote invasions even beyond the threshold of naturalisation. The author concludes that attempts at prevention should focus on secondary releases as well as on initial introductions.

Deliberate human introductions of plants also affects invasiveness because, the more often an introduction is repeated in time or space, the greater will be the variety of release sites and the greater the chance of release into environmental conditions suitable for establishment. This phenomenon is referred to as introduction pressure, and has been shown to be a major factor in the naturalization of woody species in south-eastern Australia (Mulvaney 2001). Invasiveness is also strongly related to the time that the species has been present within Australia. That is, the earlier the plant was introduced, the longer it has had to establish and spread. This phenomenon has been shown by Richardson (1994) for *Pinus* spp. in the southern hemisphere, and by Scott and Panetta (1993) for southern African plants introduced to Australia.

Chapter 3: Accidental spread of weeds by humans

Human apparel and equipment

Humans themselves can inadvertently spread weed propagules that cling to their hair, clothing and equipment, and within mud on their footwear. A number of studies illustrate the importance of this pathway as an agent of weed spread within Australia. For example, Chaloupka and Domm (1986) studied the role of anthropochory (human dispersal) in the alien plant invasion of coral cays in the southern Great Barrier Reef region of Australia. Inadvertent human visitor dispersal of alien diaspores was indicated as the principal dispersal syndrome responsible for the alien species invasion of these cays. Moreover, the geographic distribution of the alien flora was clearly a function of visitor traffic, and the percentage of alien species was associated directly and significantly with the extent of visitor traffic.

Whinam *et al*. (2005) examined human agency in the introduction of alien organisms to two subantarctic islands, Heard Island and Macquarie Island. This study reported a range of cargo inspections, expeditioner surveys, vacuuming of clothing and equipment, and inspection of transport vehicles. All cargo items were found to have the potential to act as vectors for alien species introductions, harbouring both plant material and seeds. Propagules from a total of 90 plant species and 15 families were collected from the clothing and equipment of 64 expeditioners. Equipment identified as high-risk vectors included equipment cases, daypacks, and the cuffs and Velcro closures of outer clothing.

Further evidence of the capacity of human clothing to spread weeds is provided by Mallen and Wimbush (1985). This study involved two groups of hikers in Kosciusko National Park, both of which were provided with new socks before commencing hikes. From the socks of 30 hikers who walked 5 km cross-country through subalpine vegetation, 420 seeds of non-native plant species were collected. In comparison, only nine seeds of non-native species were found on the socks of 40 walkers who walked 20km along tracks through alpine vegetation.

The photograph below (Figure 2) provides an illustration of the ability of weed seeds to cling to footwear. In this case, the species is spiny burr grass (*Cenchrus incertus*), which has barbed seeds that adhere to wool, fur, clothing, bags and any other fibrous material (Parsons and Cuthbertson 2001).

Figure 2. Seeds of spiny burr grass attached to shoelaces (photo courtesy of B. Sindel, UNE).

In Britain, Clifford (1956) examined seed spread on human footwear by scraping the mud off shoes, and then counting and identifying the recovered seeds. The results revealed that humans can transport many and varied types of plant seeds on their footwear over long distances. In Australia, Carter (1993) has reported that the seeds and pods of rampion mignonette (*Reseda phyteuma*) have been carried in mud on the boots of workers travelling between vineyards in South Australia. Smith and Harlen (1991) provide evidence that human footwear is involved in the spread of broom (*Cytisus scoparius*) in the Barrington Tops region of New South Wales. They recovered a total of 39 broom seeds from 13 boots, 50% of which were viable.

Machinery and vehicles

Research by Clifford (1959), conducted in Africa, confirmed the ability of motor vehicles to transport seeds. The first Australian study of this kind was conducted by Wace (1977). It revealed that cars have the ability to transport large numbers of seed from a diverse range of species. Barwick (1999) identifies a number of ways in which traffic contributes to weed spread. Speeding vehicles pick up seeds and other material that is carried temporarily in the air suction currents they generate. Propagules are also collected in mud on tyres and elsewhere. When seed-containing mud later falls off or is removed, it creates a seed reservoir from which further infestations can develop. Work vehicles engaged in maintenance of

pavements, drains and vegetation were also identified as agents of weed spread and need to be regularly cleaned before moving from one area to another.

A discussion paper by Good (1987) highlights the importance of vehicles and other machinery in spreading weeds within national parks and conservation areas of New South Wales. According to this paper, weeds in national parks are concentrated along access systems (roads, tracks), picnic areas and sites of park infrastructure. Park infrastructure sites are often used by utility companies, such as water, electricity, and hydroelectric services. Unfortunately, many of these utility sites are linear areas of disturbed vegetation (e.g. power line easements) with considerable weed presence, and traffic through these areas can spread the weeds to other parts of the parks.

A study by Lonsdale and Lane (1994) shows the importance of tourist vehicles as vectors of weed seeds in national parks. In this study, which was carried out in Kakadu National Park, the radiators and outer surfaces of car bodies were vacuumed, and vehicles were searched for mud in wheel arches and tyres. The results revealed that tourist vehicles were responsible for introducing new weeds into the park. One particularly dangerous grass, *Pennisetum polystachion*, was among the most common species recorded from tourist vehicles. The study also revealed that type of vehicle is an important predictor of seed dispersal ability. Four-wheel drive (4WD) vehicles carried significantly more seeds than two-wheel drive (2WD) vehicles, presumably because of the increased likelihood that 4WD vehicles will be driven off-road.

The importance of vehicles and machinery as agents of weed spread is further confirmed by Moekerk (2006), who conducted a study in Victoria to assess the risk of noxious weed movement through vehicles, plant and equipment. The results suggest that vehicles and machinery can carry a large quantity of seeds in a number of locations on the vehicles. Over 230 contaminant species or taxonomic groups were identified, including 23 Victorian noxious weeds. Cabins were the most likely place to find seeds, followed by the engine bay, but noxious weeds were found in all the locations assessed. Vehicle type again emerged as an important predictor of capacity to carry seeds. Utility vehicles carried larger numbers of weed seeds than wagons, and 4WD vehicles were more likely to carry weed seeds than 2WD vehicles. Interestingly, passenger vehicles were more likely than machinery to carry weed seeds, which, as Moekerk points out, is somewhat contrary to popular belief that machinery is more likely to spread noxious weed species. Contaminant species on passenger vehicles

differed to those of machinery, reflecting the environment in which the equipment has been used. Passenger vehicles were more frequently contaminated by species such as *Lolium* spp. and *Avena* spp., while machinery was more frequently contaminated with species such as *Poa annua* and *Plantago* spp. *Plantago* spp. are common weeds of turf, roadsides, drains and ditches and are more likely to be found on machinery that is used in these locations.

Agricultural machinery is often implicated in the spread of weeds within and between agricultural districts. Evidence of weed spread by farm machinery is documented by Blanco-Moreno *et al*. (2004), who showed that the dispersal pattern of annual ryegrass (*Lolium rigidum*) was strongly affected by combine harvesters. The authors point-out that this mechanism could potentially spread the species over great distances. Secomb (2006) provides further evidence of the involvement of farm machinery in weed spread. This study investigated the possible movement of branched broomrape (*Orobanche ramosa*) by tracing the movement of potential vectors for the spread of seed. The results revealed that farm machinery, particularly ground-penetrating equipment, represents the highest risk for spreading this species (see Figure 3).

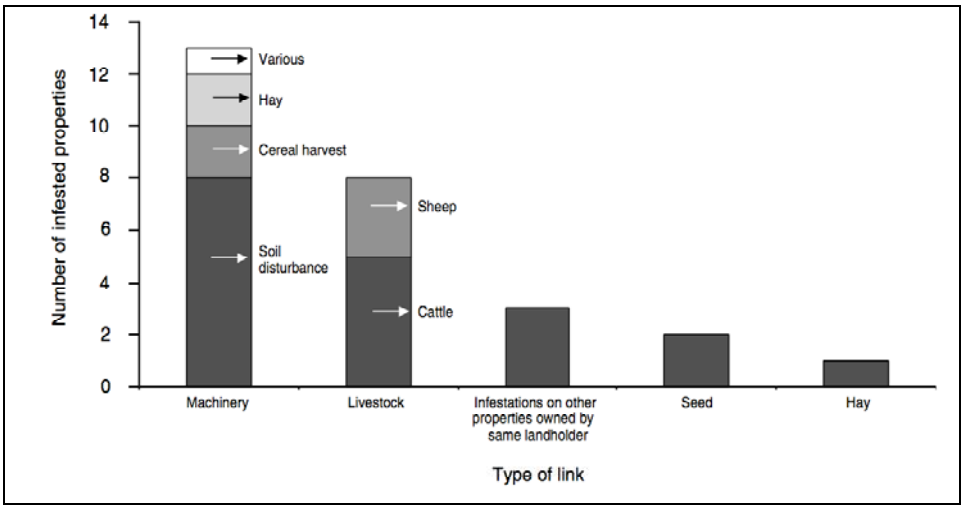

Figure 3. Types of links between properties producing positive recordings of branched broomrape (Secomb 2006).

Parthenium weed (*Parthenium hysterophorus*) is commonly observed along roads and tracks, has been attributed to the movement of harvesting machinery, cattle, hay, grain and vehicles (Parsons and Cuthbertson 2001). As is shown in Figure 4, contract harvesters are particularly associated with the spread of this weed.

Figure 4. Sign warning contract harvesters of the possibility of machinery inspections by police or weed officers (photo courtesy of B. Sindel, UNE).

The spread of parthenium weed was mapped in Queensland for the years 1975, 1979, and 1981 (see Figure 5). The association between infestations and roads strongly suggests that vehicles have played a role in dispersing the seeds.

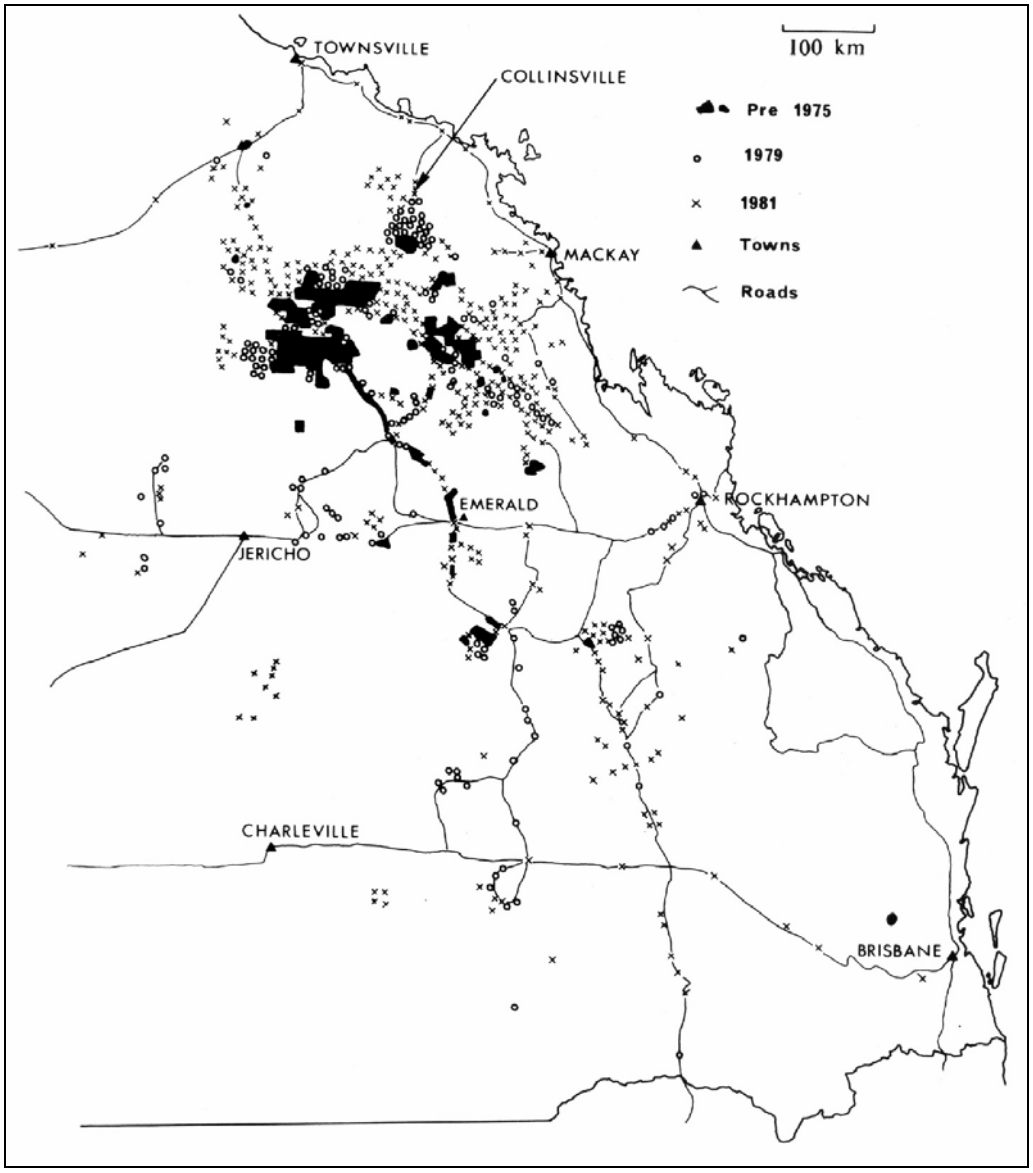

Figure 5. Spread of Parthenium weed in Queensland (source: Auld *et al.* 1982).

Trains are also implicated in weed spread. Sindel (2001) provided a theoretical framework for the colonisation of weeds along railway tracks based on a general understanding of weed ecology. He has theorised that train movement, often at high speeds, creates air turbulence that promotes the movement of wind-dispersed weed seeds from beside the track area. Sindel (2001) suggests that the conveyance of materials for track construction, and the trains themselves, particularly freight trains, have played a role in weed spread in the past. Whether this is still the case, considering changes to train design and patterns of freight transportation, needs to be assessed.

Cuthbertson (1967) has observed an association between advanced skeleton weed (*Chondrilla juncea*) infestations and the movement of stock and other agricultural products by rail. According to this source, the pappus and seed of skeleton weed were commonly observed floating in carriage corridors during summer, indicating that direct transport by railway may play a role in dissemination of the species. Figure 6 shows the association between infestations of skeleton weed and with the railway network in New South Wales.

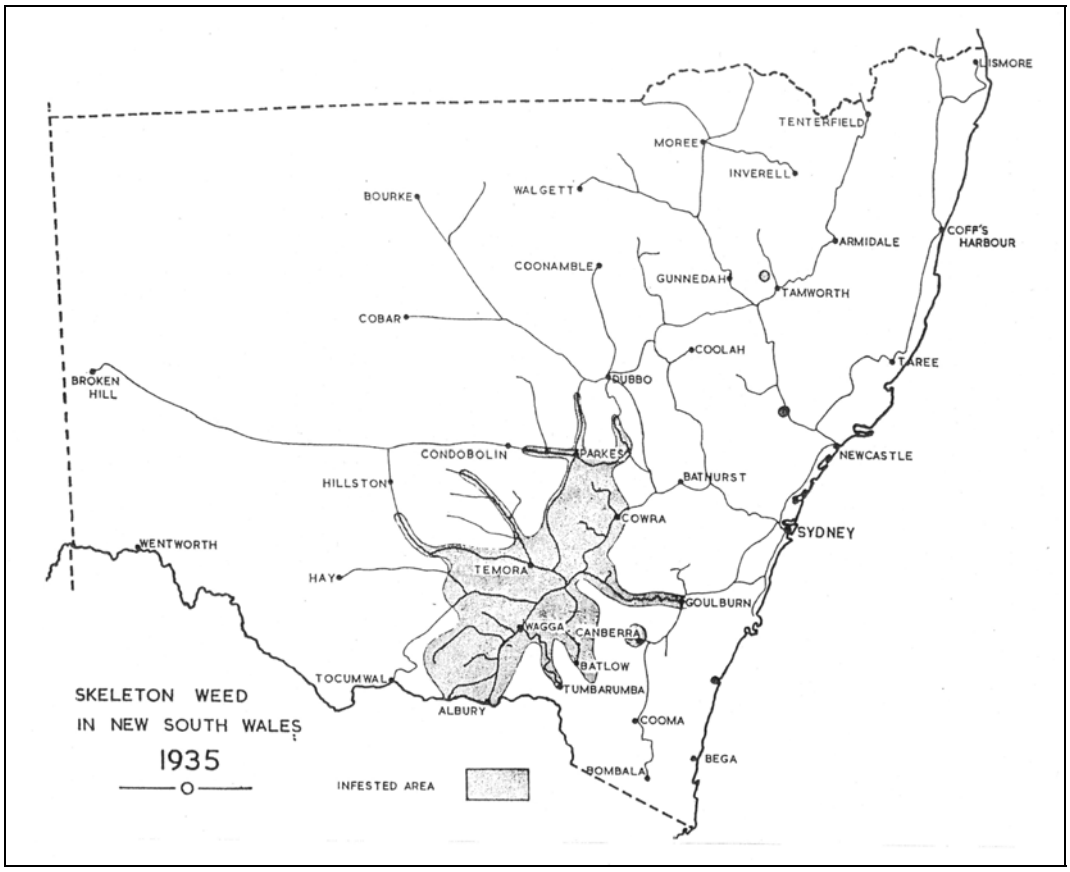

Figure 6. Skeleton weed infestations associated with the railway network in southern NSW in 1935 (source: Cuthbertson 1967).

Watercraft are other vectors of weed propagules, particularly of aquatic species. For example, the transportation of boats between water bodies appears to have resulted in infestations of alligator weed (*Alternanthera philoxeroides*) in lakes hundreds of kilometres distant from existing infestations (Sainty *et al.* 1998).

Aircraft have been shown to transport invertebrates (e.g. Dobbs and Brodel 2004; Tatem *et al.* 2006), but we could not uncover evidence that aircraft are involved in weed spread. It is worth mentioning that fireweed (*Senecio madagascariensis*) has been observed growing beside runways at the Sydney Kingsford Smith airport (B. Sindel, pers. comm.), although this does

not provide hard evidence that aircraft were the vector in this situation (i.e. seed could have been spread through aircraft construction or maintenance operations).

Construction and landscaping materials

The literature furnishes a number of examples that demonstrate the potential of construction and landscaping materials to spread weeds. In the Australian Alps, the construction and maintenance of roads has caused profound disturbance to the existing soil and vegetation, as well as the introduction and proliferation of exotic plant species (Johnston and Johnston 2004). One exotic species, *Achillea millefolium,* is thought to have been spread throughout the region by the use of gravel from weed-contaminated dumps (Sanecki *et al.* 2003).

The transportation of contaminated turf, soil and sand from infested to un-infested locations are strongly implicated in the spread of alligator weed within Australia (Sainty *et al.* 1998). Nurseries may also accidentally spread weeds that are a contaminant of other gardening products. For example, Mikania vine (*Mikania micrantha*) has been inadvertently spread through the sale of contaminated pots by a nursery at Speewah, in Queensland (Brooks and Galway 2006). In another case, home growers and commercial cut-flower nurseries in Tasmania were supplied with bulbs contaminated with *Rorippa sylvestris* (creeping yellowcress), one of 17 potential sleeper weeds for which eradication is being considered (Cunningham and Brown 2006).

Agricultural produce

Many common agricultural weeds are spread as contaminants in fodder, pasture seed and seed crops. For example, fireweed can be dispersed in hay and grain products (Sindel *et al.* 1998). Contaminated hay is important in spreading variegated thistle (*Silybum marianum*) because plants are generally flowering when hay is cut (Parsons and Cuthbertson 2001). Paterson's curse (*Echium plantagineum*) has most often been introduced to a district in consignments of fodder (Peirce 2004). This species has also been reported as a contaminant of harvested grain and is a common volunteer in and around cereal and pasture crops (Piggin and Sheppard 1995). There are numerous other examples of weeds that are spread this way. Examples from Smith (2002) include: spinyhead sida (*Sida acuta*), spread as a contaminant of hay and seed crops; snakeweeds (*Stachytarpheta* spp.), spread in fodder, hay and contaminated pasture seed; and Caltrop (*Tribulus* spp.), spread in hay and straw.

Thomas *et al.* (1984) recorded and analysed the types, amounts and origins of fodder moving into and out of Yass, Young and Gundagai (NSW). Approximately 42 000 t of fodder was involved, transported from districts up to 1000 km away. Viable seeds of weeds, including 'noxious' species, were found in samples of hay and grain imported into the Yass district. In another paper, the aforementioned study by Secomb (2006), a small number of branched broomrape infestations were traced to the movement of hay and cereal seed. Erkelenz *et al*. (1990) recorded that, in separate incidents, *Amsinckia lycopsoides* and *A. calycina* yellow burrweed) were dispersed over 300km in drought fodder (hay).

Jones *et al.* (2000) has reported that the Australian winter cropping system looses $25 million per annum due to price penalties from weed-contaminated grain. Wheat incurred by far the largest loss, ($11 million), followed by pulses ($5 million) and malting barley ($5 million). Two studies from Victoria provide evidence of crop seed contamination. Moekerk (2002) recorded significant levels of foreign seed contamination in seed used for sowing dry-land crops in Victoria during 1996 and 1997. Average quality of sowing seed did not meet certification standards due to volunteer crop contamination levels, because in ninety nine percent of cases, the seed was farmer-saved or purchased 'over the fence'. Niknam *et al.* (2002) recorded a wide range of weed species in farmer-saved seed and showed that this kind of seed contained more weed seeds than certified seed.

King (2006) used the findings from other studies to model potential levels of weed seed in feed grains in Victoria. The model showed that 65.4 ktonnes of feed grain contaminated with weed seeds is potentially moved into and used in Victoria annually. The report states that, whilst feed grain presents the highest risk for weed spread, weeds are still spread by other classes of grain, particularly during transport along road and rail systems. At the time this report was written, no enforcement under the Catchment and Land Protection Act (CaLP Act) had occurred in Victoria in relation to grains, and it was recommended that the logistics of doing so should be determined. The author also recommended that, as a minimum, there should be discussions with grains industry peak bodies into modifying the existing receival standards to reflect the zero tolerance for declared weeds proscribed by state legislations.

Research

Plants introduced for agricultural research purposes have been known to escape from trial sites and invade surrounding areas. McLaren *et al*. (2004) documents the distribution, impacts

and identification of exotic stipoid grasses in Australia. This work identified escape from research facilities as the means of entry for two species: short-spined needle grass (*Nasella megamotamia*), and plumerillo (*Jarava plumosa*). *Nasella megamotamia* is reported to have escaped from CSIRO plant introduction plots near Black Mountain in Canberra. This grass is a member of the same genus as the WONS species *N. trichotoma* and *N. neesiana*, and could be considered a potential environmental weed. *Jarava plumosa* was, according to McLaren *et al*. (2004) imported as a potential pasture plant by the Waite Agricultural Research Institute, South Australia, and has since been found naturalised in the vicinity of this institute.

Pannicle jointvetch (*Aeschynomene paniculata*) is one of the 17 'sleeper weeds' identified for eradication before they become major agricultural weeds in Australia (Cunningham and Brown 2006). It was introduced to north Queensland as a potential pasture species and has spread from the trial site and naturalised in grazing woodland (Cunningham *et al.* 2003; Groves *et al.* 2002).

Because of the risk of escape and spread from research facilities, the World Wildlife Fund (WWF Australia 2003) urged that a National Action Plan to include an audit and/or retrospective weed risk assessment of all species located in botanic gardens, research centres, and especially old agricultural research farms, to identify and eradicate any potentially invasive species. Cook and Dias (2006) echo this call for a thorough investigation of old plant-introduction trial sites to prevent further naturalisations of unwanted species from these areas.

Livestock

Zoochery, or seed dispersal by animals, occurs in 50% of all plant species (Tiffney and Mazer 1995). Animals can disperse weeds by exozoochory, where weed propagules are attached to their bodies, or by endozoochory, where weed seeds are ingested and passed through the gut (Stanton 2006). Some examples of both types of zoochory by livestock are discussed below.

Lolium rigidum is a major grass weed of the cropping zone of south-eastern Australia. The seed is palatable to stock, and stock grazing is commonly used to control the weed. However, there is experimental evidence that, while grazing achieves a reduction in the available seed, a significant proportion of germinable seed is excreted by both sheep and cattle, and the time taken for seed passage through the gut could provide a mechanism for spread beyond the area of infestation (Stanton *et al.* 2002).

It is not only palatable species that are spread by grazing livestock. The seed heads of giant Parramatta grass (*Sporobolus fertilis*) are extremely unpalatable, yet one study has recorded large numbers of viable seeds from the faeces of grazing stock (Andrews 1995), indicating that the species could be dispersed in this way. It was suggested that ingestion of the seeds might occur when stock accidentally swallow seeds attached to palatable leaves or to their coats (i.e. to be licked off during grooming). However, the adherence of seeds to the hair of animals was thought to be more important in spreading the weed. Similarly, Chilean needle grass, which is also highly unpalatable, does not spread to any great extent through ingestion by livestock, but seeds adhering to wool are spread effectively (Gardener *et al.* 2003). It has been reported that seeds attached to sheep can be transported over extremely long distances, up to several hundred kilometres (Manzano and Malo 2006).

Horses and goats can also disperse weed seeds. Viable seeds of gorse (*Ulex europaeus*), broad-leaved dock (*Rumex obtusifolius*), variegated thistle (*Silybum marianum*), and perennial ryegrass (*Lolium perenne*) have been recovered from goat pellets, even up to 72 hours following ingestion (Beskow *et al.* 2006). In another study (St John-Sweeting and Morris 1990), pasture and weed seeds were fed to horses and were mostly recovered in a viable condition. Horses were able to disperse seeds for 10 days after ingestion; a result that has been confirmed by Weaver and Adams (1996). In comparison, goats, cattle, and sheep will tend to excrete most seeds within the first three days, but withholding periods of up to one week are recommended before moving animals to uninfested areas (Neto *et al.* 1987). Failure to observe withholding periods could lead to infestations in new locations on the same property, or even to beyond the farm gate when stock are sold.

Livestock have played important roles in the dispersal of important weeds within Australia. For example, Anderson *et al.* (2006) have suggested that an under-estimation of the viability of mesquite seeds post excretion by animals has been a major factor in the weeds expansion (Anderson *et al.* 2006). Sheep can excrete viable seed of Paterson's curse, and it is probable that this has been responsible for much of its spread within Australia (Piggin 1978). Brown and Carter (1998) have identified that a large increase in the population of prickly acacia (*Acacia paradoxa*) from 1974 to 1994 paralleled a shift from sheep to cattle (a more effective dispersal vector) as the dominant livestock species.

Waste

Disposal of garden and aquarium waste, either through council green waste collection, illegal dumping along roads, or emptying aquariums into drains and waterways, can spread weeds by movement of propagules, such as seeds, bulbs, and rhizomes. Porter *et al.* (1995) review the literature on the risk of spreading pests, diseases and weeds through council green wastes. This work identified 31 common weeds that are likely to occur in green wastes, including 10 grasses and 21 herbaceous species. A two-year botanical survey of Melbourne's green waste stream (Tymms *et al.* 1999) established that weeds made up 28% (by volume) of plants recorded. Most of the weed material was from evergreen shrubs, followed by evergreen trees, vines and climbers, and grass clippings. A total of 318 plant species were recorded, of which 73 were weeds. It was determined that the risk of weed spread through using chipped uncomposted green waste is considerable at any time of year, because the 73 weed species set fruit and seed at varying times. Also, grass clippings are likely to contain weed seeds at all times, and vines and climbers can reproduce vegetatively in most seasons. Composting processes were also investigated in the study, and revealed that weed spread via the final composted product could be minimised under controlled compost management.

Inappropriate disposal of garden waste has been identified as a common source of environmental weeds (Blood 2002). In eastern Northland, New Zealand, a team of ecologists recorded the exotic plant species present in coastal forests and their neighbouring settlements, to investigate how subdivisions affect the weediness of forests. Gardeners in the area were growing 87% of the plants listed by the Northland Regional Council as the worst invaders of forests. In the reserves, the researchers often reported piles of freshly dumped garden waste containing these invasive weeds.

Improper disposal of pond and aquarium waste is also implicated in weed spread. In 1983, *Hydrocotyle ranunculoide* was first observed growing in the urban drainage network in the Canning River Regional Park, Western Australia. By 1991 the plant had extended throughout the drainage network into the river and adjacent wetlands (Ruiz-Avila and Klemm 1996). In another example, every infestation of Water hyacinth (*Eichhornia crassipes*) in southern Australia has been attributed to deliberate plantings or the inappropriate disposal of surplus plant material (Parsons and Cuthbertson 2001).

Chapter 4: Weed dispersal by natural agents

Dispersal between continents, across oceanic dispersal barriers, must rely largely on human intervention (Cousens and Mortimer 1995). In comparison, natural forces represent a small threat as vectors for the transoceanic movement of weedy species. However, natural dispersal agents are important in facilitating a weed's occupation of a new range that was originally reached through human dispersal, and extreme events, such as storms and floods, can spread a new species over considerable distances (Mack and Lonsdale 2001).

Animals and birds

Research conducted in Australia has demonstrated the dispersal potential of both native and feral animals. Rabbits have been shown to increase the weed component of pastures at Cowra in New South Wales (Croft *et al.* 2002). In Britain, a study of rabbit endozoochory in acidic grasslands found that rabbit pellets contained germinable seeds of 37 plant species (e.g. Pakeman *et al.* 1999).

Grice (1996) determined that Chinese date (*Ziziphus mauritiana*), an exotic shrub that is invading tropical woodlands of northern Australia, is eaten and dispersed by several mammalian vectors, including wallabies and feral pigs.

Brunner *et al*. (1976) collected germinable blackberry seeds from the droppings of emus and foxes, concluding that both foxes and birds are probably responsible for dispersing blackberry over large areas of Victorian bushland.

In another study, field collection of dung verified that both cassowaries and feral pigs consume pond apple and pass viable seed (Setter *et al.* 2002). Although pigs ate less fruit than cassowaries and passed less intact seeds, pigs are more numerous and frequent a wider range of ecosystem types, and may therefore be more important than cassowaries in spreading pond apple.

A number of Australian studies have explored the interactions between frugivorous birds and weeds. The abundance and feeding patterns of pied currawongs was investigated in Armidale, New South Wales, to assess their role in seed dispersal of ornamental weeds (Bass 1996). The seeds of 22 different ornamental species were recovered from regurgitate sampling sites, and the author concluded that pied currawong mediated seed dispersal appears to be driving the current pattern of ornamental weed invasion in the study area. In Queensland, as many as 38

bird species were observed feeding on 28 weed species (Stansbury and Vivian-Smith 2003). Another study from Queensland found a total of 340 seeds from 15 plant species, using scat analysis of birds visiting fruit-bearing plants (Florentine *et al.* 2003).

While the threat of weeds to biodiversity cannot be ignored, in some cases, such as in heavily modified landscapes, fleshy-fruited exotic plants play an important ecological role in sustaining native frugivores. To manage this conservation conflict, Gosper and Vivian-Smith (2008) advocate a replacement approach in which native fleshy-fruited plants are planted to support native frugivore populations in the event of extensive invasive plant control.

Wind

Wind dispersal, termed anemochory, can transport seeds over long distances. Plant species dispersed by wind, also called anemochores, have seeds with several distinct forms; dusts (e.g. orchid seeds and fungal spores), winged seeds and plumed seeds. Winged seeds are adapted for gliding, or rotating. Plumed seeds have a specialized featherlike structure, the pappus, attached to the seed coat (Radosevich and Holt 1984). For an example of seeds with a pappus, see Figure 7.

Figure 7. *Taraxacum officinale* (dandelion weed) (photo courtesy of B. Sindel, UNE).

The seed of *Salix nigra*, one of the willows, is excellently equipped for dispersal by wind. This seed has a halo of delicate hairs, and can float on the slightest breeze for hundreds of metres, sometimes travelling up to 50 or even 100 km (Cremer 2003). In another group of

plants, the 'tumble-weeds', the part of the plant carrying the seed breaks off and drifts along with the wind, releasing and distributing the seed as it goes (Ridley 1930). Kochia (*Bassia scoparia*) is an example of a tumble-weed. In Western Australia Dodd and Randall (2002) found seedlings and mature plants up to 5 km from the introduction sites, with lines of plants marking the paths of tumbling parent plants (Dodd and Randall 2002). In this way, the estimated area infested at two sites increased from less than 10 ha each in spring 1992, to 750 ha in January 1993.

Wind dispersal occurs less in vegetated areas than in the open (Wilson and Crome 1989). Human structures, such as roads or tracks, may therefore greatly aid the role of wind in dispersing exotic species by removing obstacles to seed transport by wind. Parendes and Jones (2000) observed that roads may act as corridors for the dispersal of weed seeds. In this study, the species that occurred more frequently along roads had seed morphological characteristics (special appendages or light seeds) that suggest a high potential for dispersal by wind. Wangen and Webster (2006) studied the invasion of *Acer platanoides* on Mackinac Island, Michigan, USA. It is commonly planted as a street tree and rains a tremendous amount of seed onto the road surface and passing vehicles. Consequently, the seeds are dispersed by floating down road corridors that act as wind tunnels, by simply blowing along the road surface, or by 'catching a ride' on passing vehicles.

Water

Water dispersal, or hydrochory, can occur in floodwaters, stormwater and by natural waterways and oceans. In many aquatic and semi-aquatic plants, vegetative diaspores can float for a long time and may be more important than seeds for long-distance dispersal (Johansson and Nilsson 1993). Many kinds of weed seeds, even those without special modifications, are readily dispersed by water. Weed seeds differ in their ability to float on water, and there are also various adaptations of fruit and seed that aid water dissemination (Radosevich and Holt 1984). Water lettuce (*Pistia stratiotes*) is an excellent example of a weed species equipped for water dispersal. The seed is buoyant, being flattened at the apex and containing an air chamber. The seedling is also buoyant, as the leaves of *P. stratiotes* are densely covered with short white hairs, which trap air and shed water (Parsons and Cuthbertson 2001).

Auld *et al.* (1982) observed that river systems in eastern New South Wales have provided a transport mechanism for tiger pear (*Opuntia aurantiaca*). From figure 8, it is apparent that river systems provide a mechanism for long distance dispersal of tiger pear, with some infestations occurring at considerable distances from previous infestations.

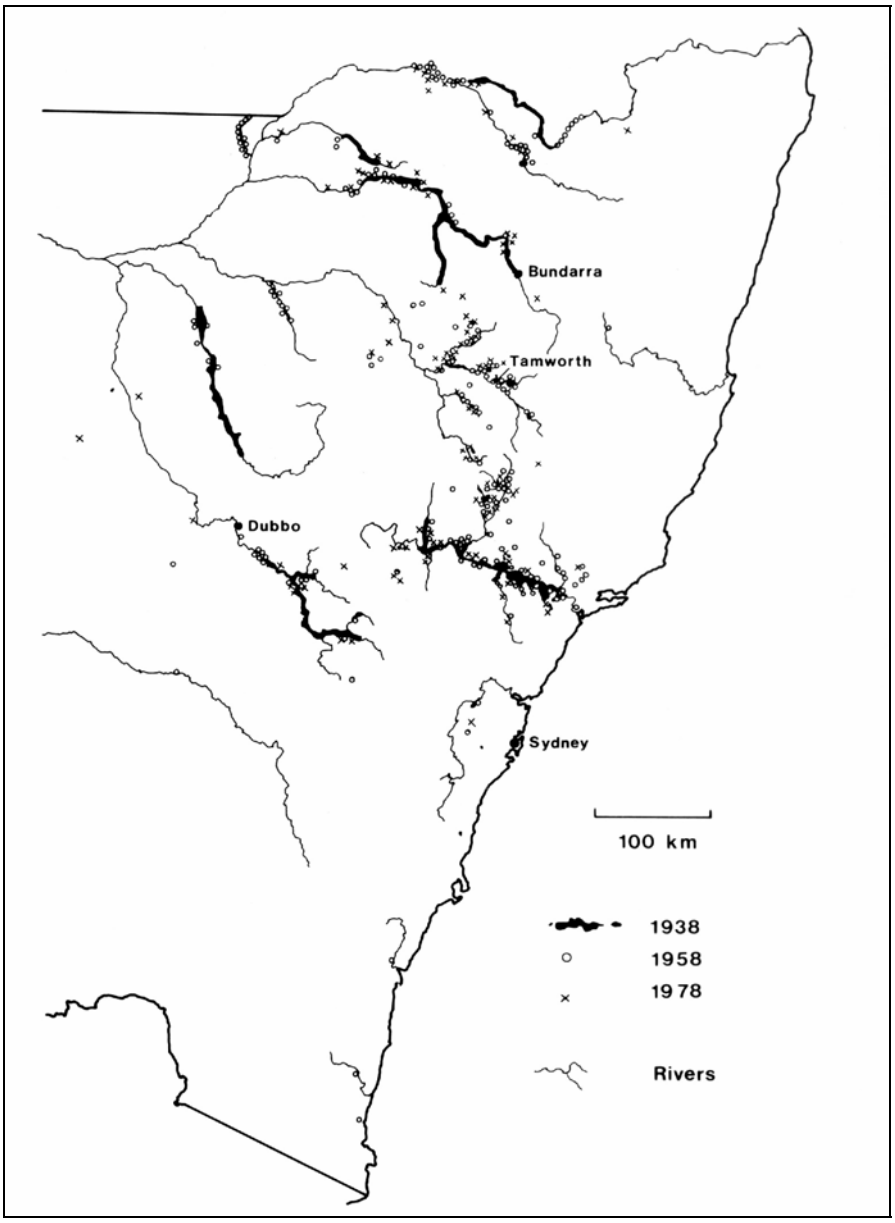

Figure 8. Spread of tiger pear in eastern New South Wales for the years 1938, 1958 and 1978 (Auld *et al.* 1982).

In a study by Hill *et al*. (2005) areas within two metres of a creek edge were found to have higher exotic species richness and cover than areas further from the creek edge. Also, creeks draining a developed catchment were consistently associated with increased invasion by

exotic species, but this effect was largely confined to in the narrow strip of land along the creek edge. Further evidence of the importance of river flow in dispersing weeds is from a study by Lawes and McAllister (2006). These authors used a network approach to determine sources and sinks in the Burdekin catchment, Northern Australia. Sources of weeds were located in the upper catchment, and sinks were located in the medium to lower reaches of the catchment. The implication of this study is that, by controlling weed populations in the source parts of the catchment, spread to medium and lower areas could be reduced.

Floodwater can also play an important role in plant invasions. The spread of athel pine (*Tamarix aphylla*) along the Finke River in Central Australia is an excellent example of the role of floodwater dispersal in facilitating the range expansion of an invasive species. Major flows in the Finke River in 1974 dispersed seed of athel pine along its entire length. Further floods in 1983 and 1984 enabled more plants to establish from seed and vegetable matter, probably from those trees established in the 1974 floods (Fuller 1993). The sources of infestation were plantings at homesteads near the River (Griffin *et al.* 1989).

Irrigation water can also play an important role in dispersing weed seeds (Radosevich and Holt 1984; Zimdahl 1999). Hawkey (1995) found evidence that weed seeds are being introduced, often in large numbers, into cotton fields in the Macquarie Valley via irrigation water. Another important attribute of irrigation water as an agent of dispersal is that it appears capable of transporting weeds over long distances, and thus it may be important in introducing new weeds to a region (Dastgheib 1989).

Chapter 5: Pathway case studies

These three case studies are presented in order to show the large number of pathways that have been identified to spread weeds. They also demonstrate the use of different approaches in the identification of weed pathways. Some of the differences, and their implications, will be briefly discussed at the end of this chapter.

Case study 1: Queensland

The Queensland Weed Spread Prevention Strategy (Department of Natural Resources and Mines 2008) has been designed to meet Objective 2.6.3 of the Queensland Weeds Strategy 2002–2006 "To minimise the spread of weeds to new areas in the state" (Department of Natural Resources and Mines undated). The prevention strategy was developed by the Working Group for the Prevention of Weed Spread, comprising representatives of state government agencies, industry, and natural resource management groups. It builds on outcomes from the national Strategic Analysis and Scoping Study on Human Spread of Weeds (Barker 2005) and will contribute to a national strategy for weed spread prevention. In the strategy, seven broad goals are identified, and an action plan is presented. The action plan comprises outcomes, management initiatives, responsibilities, priority ranking and performance targets. It is intended to provide clear direction to all parties involved in addressing the problem of weed spread and enable them to make the best use of available resources.

The Queensland Weed Spread Prevention Strategy identifies ten pathways for potential weed spread involving human activity (Table 4). The management activities that are proposed to minimise spread via these pathways include: codes of practice; environmental management systems; communication; weed risk assessments; education and awareness; research and development; provision of resources; and construction of clean-down facilities. To ensure compliance with regulation and best management practices, the strategy has listed options such as auditing and surveillance, compliance evaluation, third party inspections, and incentives and levies.

Table 4. Ten pathways for potential weed spread involving human activity (source: Department of Natural Resources and Water 2008).

Pathway	Examples
Transportation over land	Agricultural machinery, stock carriers, cars, trucks, buses, all-terrain vehicles, construction equipment and fire fighting equipment, trains, hikers, horses, and pets, and also via tankers and pipelines when transferring water (containing aquatic weeds) from one storage to another.
Transportation over water	All types of ships (including cruise ships), recreational boats and other large or small craft including industrial, tourist, recreational and law enforcement vessels, military crafts, barges, semi-submersible dry docks, oil derricks (freshwater, marine or both), and stowaways in holds.
Tourism	For recreation, business or relocation purposes. A particular risk in national parks and protected areas.
Movement of plants and plant parts	Fruit, vegetables, nuts, roots, seeds and edible flowers; plants 'in trade' (intentionally released - authorised or unauthorized - or escaped); 'hitchhiker seed' such as weed seeds that have contaminated other seed for sowing or eating, or transported in water, food, growing media, nesting or bedding; and particularly, the dumping of garden waste in parks, reserves and council dumps.
Transportation of live food animals and animal parts	Movement of stock and/or their contaminated waste (containing viable weed seed from a food source such as prickly acacia) and 'hitchhikers' on or in live animals and in their water, food, growing medium, nesting or bedding.
Plant and aquarium trade	Importation and supply of plants, plant parts, seeds and aquatics, and sites of deliberate introduction such as botanical gardens, nurseries, landscaping and garden suppliers, research facilities, public and private plantings, and aquariums/water gardening facilities.
Movement of construction and landscaping material	Extraction and storage of soil, gravel, sand, mulch and rocks.
Gas, power and mineral resources	Mining of resources and development and maintenance of movement corridors.
Waste disposal	Illegal dumping, unsafe disposal and movement of weed waste.
Ecosystem disturbance	Habitat creation, restoration or enhancement; forestry use; road construction; provision of utilities; land clearing; development; stream channels; construction of highways, railroads and utility rights of way; bushfires and fire management; grazing; agriculture; and extreme weather events such as cyclones and drought.

Case study 2: Victoria

Victoria is a national leader in encouraging industry and government responsibility and action to combat the spread of weeds. Tackling Weeds on Private Land (TWoPL) is a $9 million, three-year initiative by the State Government to tackle Victoria's weed problem. The initiative has involved working together with the Garden Industry (GI), the Fodder Industry (FI), Catchment Management Authorities (CMAs), Linear Reserves Managers (LRMs) and Municipal Councils (MCs). From 2005 to 2007, a number of reports have been written about these sectors, and are available from the DPI website (http://www.dpi.vic.gov.au). These documents include annual reports and project evaluation, extension and communication recommendations, and analyses of stakeholder attitudes and actions towards preventing weed spread.

Early in the TWoPL project, significant gaps were identified in the level of knowledge about the relative risks for weed spread through the activities of different industries and organisations. The need for an objective, quantifiable risk assessment of all possible industries, organisations and weed spread pathways was recognised. The process is reported in Weiss *et al.* (2006) and in Thomas *et al.* (2007), and will only be basically outlined in this review. A reference group of Department of Primary Industries staff identified all known introduction pathways, organisations and industries whose activities might introduce and or spread weeds. The identified pathways are shown in Table 5. Using the identified pathways, a matrix of industries, organisations and pathways was developed. Part of this matrix is shown in Table 6, to demonstrate the use of this approach for industries involved in gardening and landscaping. In this table, the symbol “Y” indicates the pathways are used by each industry and organisation.

Table 5. Definitions, description and examples of pathway categories (adapted from Thomas *et al.* 2007).

Pathway	Examples
Deliberate introduction via community	Internet plants, garden clubs, cuttings, seeds, plants by mail
Deliberate introduction via business (seeds, plants, plant parts)	Garden / aquarium plant sales, cut flowers, research for improved industry species (pastures, crops, turf etc), crops (grass, shrub, trees etc)
Human movement (business or recreation)	Contaminated clothing, boots or personal equipment (eg camping)
Controlled stock movement (external or internal contamination of livestock)	Internally (ingestion of contaminated feed), externally (wool or coats)
Contaminated vehicles (used for business or recreation)	4WD, trucks, cars, motorbikes
Contaminated equipment (used for business operations)	Slashing, grading, harvesters, earth moving, farm machinery, bee hives, shipping containers, defence force
Contaminated aquatic equipment (used on water for recreation or business)	Jet ski, boats, boat trailers, house-boats, yachts
Contaminated goods or produce	Fodder, grains, straw, agricultural products, potting mix, mulch, soil, gravel, landscape and construction materials
Waste disposal (inappropriate disposal of plants or plant parts)	Mulches from tips, garden waste - "over the back fence", dumping of garden waste in reserves, viable seed and plant waste products
Animal movement (other than stock Seeds externally on coats or ingested)	Birds, native animals, dogs, cats, foxes
Wind (distribution of wind-blown seeds)	Not assessed
Water (distribution of seeds or parts via waterways)	Not assessed

Table 6. Part of the industry and weed spread pathway matrix developed for initial weed spread pathway risk assessment (adapted from Thomas *et al*. 2007).

Potential weed spread industry/organisation/individual	Human movement	Deliberate intro. by community	Vehicles (NOT machinery)	Equipment	Goods/produce	Deliberate intro. by business	Waste disposal
Nursery and garden industry (incl. nurseries, growers, cut flowers, weekend markets, internet trade)		Y				Y	Y
Landscaping industry (designers, constructors)	Y	Y	Y	Y	Y	Y	Y
Bulk suppliers of landscaping and road building materials.	Y		Y	Y	Y	Y	Y
Community groups (garden clubs, specialist plant collectors, "friends of…")	Y	Y	Y			Y	
Botanical gardens and other plant collections and zoos. Historic houses/gardens		Y					?

Case study 3: Australia

In this case study, pathways were identified based on reported means of introduction and spread for 61 national priority weeds[2]. This set includes the 20 Weeds of National Significance (WONS), 28 weeds on the Environmental Alert List, and 17 agricultural sleeper weeds. See Appendix 1 for the complete list of national priority species. Pathways identified for the 61 weeds are presented in Table 6, together with descriptions and examples of each pathway.

The WONS species are nationally agreed priority plant species for control and management that have been selected based on their high rankings for invasiveness, potential to spread, and impact on socioeconomic and environmental assets (Australian Weeds Committee 2006). The weeds on the Environmental Alert List are in the early stages of establishment and have the potential to become a significant threat to biodiversity if they are not managed (B. Goody 2007, pers. comm.). Pathways for spreading the WONS and Alert weeds were identified using the management guides produced by the CRC for Australian Weed Management (2003).

The 17 agricultural sleeper weeds have been identified by the Bureau of Rural Sciences and are endorsed by the Australian Weeds Committee. Species on this list have potential to cause significant national effects on agriculture if they are allowed to spread. Nine of these weeds have been targeted for attempted early eradication, and the feasibility of eradication is being explored for the remaining eight (Bureau of Rural Sciences 2007). Pathways of spread for the sleeper species have been identified from Cunningham and Brown (2006) and Cunningham *et al*. (2003). The second edition of Noxious Weeds of Australia (Parsons and Cuthbertson 2001) also provided information on pathways for most[3] of the national priority weeds.

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[2] Four weeds were on both the alert list and the list of sleeper weeds (*Asystasia gangetica* ssp. *micrantha*, *Hieracium aurantiacu*, *Nassella charruana* and *Piptochaetium montevidense*.

[3] Some case study species were not listed in this source, particularly the sleeper weeds.

Table 6. Pathways, descriptions and examples for weeds of national importance.

Pathway	Description	Example
Ornamental horticulture	Intentional	Any plant grown for aesthetic purpose (including aquatic plants), often involving commercial propagation (i.e. by nurseries), but also involving the actions of community members.
Revegetation	Intentional	Shade, shelter, soil stabilisation.
Stock Fodder	Intentional	Trees, shrubs, grasses.
Functional horticulture	Intentional	For rubber, rootstock, therapeutic and culinary uses.
Timber and firewood	Intentional	Forestry plantations of *Pinus sp.*
Machinery, vehicles and equipment	Accidental	Harvesters, earth moving equipment (e.g. graders), passenger vehicles, boats, boat trailers etc.
Sediment and stones	Accidental	Sand, soil, gravel.
Human apparel	Accidental	Cloths, footwear.
Waste disposal	Accidental	Unsafe dumping of garden refuse and aquarium plants.
Livestock (internal and external transport)	Accidental	Cattle, sheep, goats, horses.
Agricultural produce	Accidental	Hay, grain.
Seed	Accidental	Crop and pasture seed.
Landscaping materials	Accidental	Mulch, turf.
Military activity	Accidental	Troop movement into and within Australia in military campaigns, peacekeeping and training activities.
Ballast	Accidental	Ship ballast.
Firewood	Accidental	Weed seeds in the firewood or attached to vehicles and equipment used in wood collection.
Flower bulbs	Accidental	Bulbs contaminated with weed rhizomes.
Research	Accidental	Escape from pasture research facility.
Packing material	Accidental	Crates, boxes.
Birds (internal and external transport)	Natural	Emus, blackbirds.
Animals (internal and external transport)	Natural	Foxes, feral pigs, ants.
Wind	Natural	Wind-borne seeds, such as *Salix nigra*
Water	Natural	Seeds carried in floodwater.

Comparing case studies

By examining these case studies, one may observe that the effectiveness of strategies to manage weed spread will be influenced by the processes used in pathway identification and risk assessment. In the second case study (Victoria), the focus is on the industries, individuals and organisations that are involved in spreading weeds. The risk of each pathway is viewed through the matrix of industry/organisation and the vector of spread. Thus, it is possible to determine the parties responsible for the majority of weed spread, and hence to determine the areas to which resources should be devoted. By comparison, the pathways identified in the

Queensland Weed Spread Prevention Strategy, and in the case study using national priority weeds, are more general. The pathways identified in these two case studies do not readily lend themselves to determining the specific persons or groups that can be targeted in weed prevention activities.

Another difference between the case studies is in the recognition of non-human dispersal pathways. In the study using national priority species, birds, animals, wind and water are indicated as pathways of weed spread. The TWoPL project (Victoria) has identified animal movement, wind and water as pathways of weed spread, but did not assess the latter two in the risk assessment matrix. The Queensland Weed Spread Prevention Strategy has chosen to focus on human pathways of weed spread, and thus, there is the possibility that forthcoming management actions may largely overlook non-human agents of weed spread.

Chapter 6: Management directions

Human induced spread

A wide range of tools have been developed and are being implemented to manage weed spread by humans, including policies, legislation, standards, guidelines, codes of practice, vendor declarations, research (e.g. into vehicle modifications), and education and awareness material. A national list of tools to reduce human-induced weed spread is available from the Weeds Australia website (see http://www.weeds.org.au/weedspread.htm). The effectiveness of tools (e.g. policy, legislation, vendor declarations, industry codes of practice and certification schemes) to reduce human-induced weed spread has been assessed by a national scoping study (Barker 2005). The major findings of the study were:

- government, industry and other organisations are committed to preventing weed spread;
- no one tool was seen as effective across Australia and only a few tools were identified at the State/Territory level;
- there is a lack of objective measures to evaluate the effectiveness of weed prevention tools; and
- participants found it difficult to determine whether ineffective tools were themselves flawed, or rendered ineffective because of insufficient resources for implementation.
- it was strongly recommended that weed spread management needs to be consistent across all States and Territories and at all levels of government.

The Australian Weeds Strategy provides a national framework to guide and complement state, territory, regional and local government strategies and industry initiatives (Australian Weeds Committee 2007). The implementation of the Strategy will begin with the development of an operational plan. A National Weed Spread Prevention Action Plan (currently being developed) will establish a framework to prevent weed spread. A draft version of this document was released in July 2006 (National Weed Spread Prevention Committee 2006). The focus is on the management of the human-induced spread of weeds within Australia, because, as stated within the draft action plan, human-induced spread is amenable to preventative actions and is the dominant method of long distance and local dispersal for most

weed species. While it is too early yet to comment on the ability of the plan to unify and improve the effectiveness of national weed prevention activities, it is a laudable first step in managing human-induced weed spread.

Weed spread by non-human agents

This review has demonstrated that natural agents play an important role in weed spread, especially at the local scale. While it is accepted that there are limitations to human ability to control weed spread by natural agents, there are actions that can be undertaken to curb this type of spread and to minimise non-target effects of weed control on native Australian animals. Some examples from the literature are discussed below.

Birds and animals

Research in South Australia has identified that the frequency of bird dispersal of olives could be reduced by:

- planting large fruited varieties, because birds prefer small and medium sized fruit;
- providing suitable places for starlings and other birds to perch near or within olive groves and away from natural areas; and
- removing fallen fruit from the ground and/or maintaining tall grass under trees to prevent birds accessing fruit.

The Animal and Plant Control Commission convened an Olives Advisory Group to discuss various options arising from this study. A discussion paper was produced, outlining a code of practice, the formation of an olive group register, a risk assessment system for local government planners, and guidelines for how to deal with the level of risk. The code of conduct includes best practice strategies for the management of birds, foxes, and emus (Hanson 2002).

The CRC for Weed Management has produced high quality research to reduce the impact of weed removal on dependent frugivorous animals. As a result of this work, two fact-sheets have been produced (available at http://www.weedscrc.org.au). These documents provide gardeners and land managers with information about using native plant species with similar fruits to invasive species, including WONS. The idea is to replace weeds with native plants to provide the fruit resources required by native animals.

Setter (2002) has recommended that control plans for pond apple in districts where cassowary are present should make provision for revegetation with appropriate cassowary food plants, and should perhaps be staggered over time. Associated efforts should include raising community awareness of the threat of pond apple, to discourage retention of the plant as a food source for cassowaries, and to publicise efforts to minimise negative impacts of pond apple removal on cassowaries.

Water movement

Vines are well represented among the most highly ranked invasive plants in South East Queensland, where they make up a quarter of the 50 most invasive species (Batianoff and Butler 2003). Vivian-Smith and Panetta (2002) reported evidence that four weedy vines Madeira vine (*Anredera cordifolia*), cats claw creeper (*Macfadyena unguis-cati*), balloon vine (*Cardiospermum grandifolium*), and white moth vine *(Araujia sericifera)* have the capacity to spread via water movement. This study revealed a need for further work to determine actual dispersal patterns and to assess recolonisation potential of species via dormant propagule banks and dispersal from upstream environments. Such information can provide critical input to catchment-wide weed management strategies and riparian weed management programs. These strategies would benefit coastal ecosystems, such as wetlands and floodplains, which are frequently under invasion pressure from upstream weed populations.

Chapter 7: Conclusions

Weeds are dispersed within Australia by innumerable mechanisms. A wide variety of pathways have been identified and discussed in this review. Human induced weed spread is an important causal factor, and various tools have been developed to reduce weed spread via accidental and deliberate means. However, there is scepticism over the capacity of these tools to limit weed spread, especially as there are no objective measures to evaluate their effectiveness. It is important that these tools are objectively assessed, enabling their further refinement and enhanced potential to control weed spread. Because even well designed tools cannot work without adequate resources, it is important that funding is directed towards high priority activities, and that such activities are coordinated and consistent at a national level. The National Weed Spread Prevention Action Plan is expected to provide critical direction for weed spread prevention activities at a national level, but at this stage the document has not

been finalised and so it is difficult to comment on its effectiveness. However, it is considered an important step for the future management of human-induced weed spread.

Natural agents should not be overlooked in national efforts to curb-weed spread. There is considerable evidence to confirm the role of wind, water, and animals in weed spread. People have an important role in reducing weed spread by natural agents, and the literature abounds with tactics that can be utilised for this purpose, and to prevent negative consequences of weed removal for native animals.

While a range of human and non-human pathways has been identified as important in weed dispersal, not all of them will have equal importance as means of weed spread within Australia, and some will be more amenable to management than others. Expert opinion, as sought in the next stage of this project, will provide important information to determine the relative risk of different weed pathways, and to develop strategies for their management.

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Appendix 1: National priority weeds

Common name	Scientific name
Weeds of National Significance	Source: CRC for Australian Weed Management 2003
Alligator Weed	*Alternanthera philoxeroides*
Athel Pine	*Tamarix aphylla*
Bitou bush / Boneseed	*Chrysanthemoides monilifera*
Blackberry	*Rubus fruticosus agg.*
Bridal Creeper	*Asparagus asparagoides*
Cabomba	*Cabomba caroliniana*
Chilean Needle Grass	*Nassella neesiana*
Gorse	*Ulex europaeus*
Hymenachne	*Hymenachne amplexicaulis*
Lantana	*Lantana camara*
Mesquite	*Prosopis* spp.
Mimosa	*Mimosa pigra*
Parkinsonia	*Parkinsonia aculeata*
Parthenium weed	*Parthenium hysterophorus*
Pond Apple	*Annona glabra*
Prickly Acacia	*Acacia nilotica* ssp. *indica*
Rubber Vine	*Cryptostegia grandiflora*
Salvinia	*Salvinia molesta*
Serrated Tussock	*Nassella trichotoma*
Willows except Weeping Willows, Pussy Willow and Sterile Pussy Willow	*Salix* spp. except *S. babylonica, S.* x *calodendron* and *S.* x *reichardtiji*
Weeds on the Environmental Alert List	Source: CRC for Australian Weed Management 2003
Barleria or porcupine flower	*Barleria prionitis*
Blue hound's tongue	*Cynoglossum creticum*
Cane needle grass	*Nassella hyalina*
Chinese rain tree	*Koelreuteria elegans* ssp. *formosana*
Chinese violet	*Asystasia gangetica* ssp. *micrantha*
Cutch tree	*Acacia catechu*
Cyperus	*Cyperus teneristolon*
False yellowhead	*Dittrichia viscosa*
Garden geranium	*Pelargonium alchemilloides*
Heather	*Calluna vulgaris*
Holly leaved senecio	*Senecio glastifolius*
Horsetails	*Equisetum* spp.
Karoo thorn	*Acacia karroo*
Kochia	*Bassia scoparia*
Lagarosiphon	*Lagarosiphon major*
Laurel clock vine	*Thunbergia laurifolia*
Leaf cactus	*Pereskia aculeata*
Lobed needle grass	*Nassella charruana*
Orange hawkweed	*Hieracium aurantiacum*
Praxelis	*Praxelis clematidea*
Rosewood or tipuana tree	*Tipuana tipu*
Senegal tea plant	*Gymnocoronis spilanthoides*
Siam weed or chromolaena	*Chromolaena odorata*
Subterranean Cape sedge	*Trianoptiles solitaria*
Uruguayan rice grass	*Piptochaetium montevidense*
White Spanish broom	*Cytisus multiflorus*
White weeping broom	*Retama raetam*
Yellow soldier	*Lachenalia reflexa*

Priority Agricultural Sleeper Weeds for Eradication	**Sources: Cunningham and Brown (2006) Cunningham *et al.* (2003.)**
Pannicle Joint Vetch	*Aeschynomene paniculata*
Chinese violet	*Asystasia gangetica* ssp. *micrantha*
Chilquilla	*Baccharis pingraea*
Brillantaisia	*Brillantaisia lamium*
Mallee cockspur	*Centaurea eriophora*
Common crupina	*Crupina vulgaris*
Chilean dodder	*Cuscuta suaveolens*
Parodi spike rush	*Eleocharis parodii*
Snake cotton	*Froelichia floridana*
Badhara bush	*Gmelina elliptica*
Orange hawkweed	*Hieracium aurantiacum*
Square-stalked St John's wort	*Hypericum tetrapterum*
Lobed needle grass, Uruguay needle grass	*Nassella charruana*
Meadow parsley, Water dropwort	*Oenanthe pimpinelloides*
Tuarian thistle	*Onopordum tauricum*
Uruguayan rice grass	*Piptochaetium montevidense*
Creeping yellowcress	*Rorippa sylvestris*
Duplicates (alert weeds that are also sleeper weeds)	
Chinese violet	*Asystasia gangetica* ssp. *micrantha*
Orange hawkweed	*Hieracium aurantiacum*
Lobed needle grass, Uruguay needle grass	*Nassella charruana*
Uruguayan rice grass	*Piptochaetium montevidense*
Total (minus duplicates)	61