Fireweed in Australia

Directions for Future Research

Professor Brian Sindel
School of Environmental and Rural Science
University of New England
Armidale, New South Wales 2351

Phone 02 6773 3747
Fax 02 6773 3238
Email bsindel@une.edu.au

January 2009

Report for the Bega Valley Fireweed Association
PO Box 79
Bega NSW 2550
http://thebegavalley.org.au/fireweed.html

Contents

Executive Summary

- *Senecio madagascariensis* (fireweed) is one of the worst weeds of coastal pastures of southeastern Australia. It contains toxic pyrrolizidine alkaloids that cause liver damage in livestock, reducing their growth and leading, in some cases, to death.

- Originating in south eastern Africa, fireweed was introduced to the Hunter Valley in Australia around 1918 (probably through shipping) and has since spread north and south in coastal New South Wales and southern Queensland, and is now invading pastures on the Monaro and Northern Tablelands of New South Wales and Atherton Tablelands of far north Queensland.

- The weed is causing considerable concern to farmers in certain areas, and in 2005, over 350 people attended a public meeting in Bega to discuss the problem of fireweed in the Bega Valley. Subsequently, the Bega Valley Fireweed Association (BVFA) was formed to fight for effective controls of fireweed at a national level.

- In 2006, the BVFA received funding under the National Landcare Program (NLP) to undertake a regionally based socio-economic analysis of the impact of fireweed; and support research on the possible hybridisation of fireweed with related native species, to map the spread of fireweed nationally, to assess the toxic effect of pyrrolizidine alkaloids from fireweed on animals, and to review the feasibility of biological control.

- This report incorporates the findings of those studies with results of previous studies to identify gaps in our understanding of fireweed, and recommend directions for future research to inform the new National Weeds Research Centre's (NWRC) fireweed program, to which $300,000 has been initially allocated.

- The key deficiency in research remains a comprehensive search for potential biological control agents in the area of origin of the weed. Now that this area has been pinpointed around the KwaZulu-Natal province of South Africa, $200,000 should be immediately spent to initiate this process. If promising agents are found, then additional funds will be required to bring such agents into the country for further testing and possible release.

- Although competitive pastures suppress fireweed growth to some extent, fireweed is not simply a management problem for individual landholders. In continuing drought times, which are likely to increase with climate change, it is difficult to maintain high pasture cover and there are few other economic options available for fireweed control. It is also probable that fireweed management will become more difficult in the future because of greater restrictions being placed on fireweed-effective herbicides.

- Additional gaps in our understanding of the ecology, impact and management of fireweed, as highlighted in this report, should also be investigated through the allocation of a $100,000 3-year PhD project.

- Specific priorities for future research, including the above projects, are as follows.

1. Investigate all possible biological control agents in South Africa from the KwaZulu-Natal Province, from where the weed is now known to originate.

2. Investigate the ecology of fireweed in South Africa and the factors limiting its weediness there to better inform management strategies in Australia.

3. Investigate gaps in our understanding of the ecology of fireweed in Australia including longevity of seed in the soil, and seedling emergence times with and without control measures.

4. Investigate the impact of fireweed on pasture production and pasture availability under varying seasonal conditions and in different pasture types and at varying densities to better quantify the cost of fireweed and provide greater incentives for adoption of fireweed management.

5. Investigate consumption rates of fireweed by different livestock types at a range of infestation levels in pastures and under different grazing management scenarios.

6. Investigate the presence of pyrrolizidine alkaloids in animal products derived from livestock grazing in fireweed infested pastures.

7. Investigate the management of fireweed with sheep or goats, which tend to graze fireweed more readily than cattle and are less susceptible to fireweed poisoning.

8. Investigate the presence of herbicide resistance in populations of fireweed that have a long history of herbicide use, particularly to the herbicide bromoxynil.

Why this Report?

Fireweed (*Senecio madagascariensis* Poir.) is an invasive weed with wind-blown seed that commonly occurs in temperate and subtropical pastures along the south east coast of Australia. Containing pyrrolizidine alkaloids, it is poisonous to livestock, particularly cattle. However, once cattle are familiar with the weed, they tend to avoid it, which, while reducing livestock intake and incidences of poisoning, allows the weed to compete more vigorously with pastures reducing their productivity. Poisoning is more likely to occur where other feed is limited, when plants are young and not easily differentiated from the rest of the pasture, when contaminated hay is consumed or when stock are newly introduced to the weed (Sindel *et al.* 1998). While herbicides are available that effectively kill fireweed, year-long management is made difficult because of the ability of the weed in these coastal environments to germinate and flower throughout much of the year (Sindel and Michael 1996).

In Australia fireweed was introduced to the Hunter Valley around 1918 (Sindel 1986), probably through shipping. By the 1980s the weed had spread north and south in coastal New South Wales and southern Queensland in similar climatic regions to where it originated in southern Africa and also where it is found in Argentina (Sindel and Michael 1992a). Since the 1980s, the weed has invaded grazing areas along the south coast of New South Wales around Bega and on both the Southern and Northern Tablelands of New South Wales and in northern Queensland on the Atherton Tablelands (Sindel *et al.* 2008a).

In November 2005, over 350 people attended a public meeting at the Bega RSL Club, under the auspices of the NSW Farmers Federation to discuss the problem of fireweed in the Bega Valley. The size of this meeting is testimony to the concern that this invasive weed is causing in the area (Figure 1).

Figure 1 *Fireweed was first noticed in the Bega Valley in 1968 and appears to have been introduced with free fodder from the north coast of New South Wales. During drought conditions over recent years it has greatly expanded its presence in the landscape as seen by its yellow tinge.*

From that meeting, a committee was formed, with Mr Noel Watson as Convenor, with the purpose of fighting for effective controls of fireweed and to lobby Government at all levels to support and provide funding to expedite the release of a biological control for fireweed (Figure 2). This committee was incorporated as the Bega Valley Fireweed Association Inc. (BVFA) to be able to receive Federal Government funding and has taken on a national focus (BVFA 2008).

In 2006, the BVFA received $100,000 under the National Landcare Program (NLP) to undertake a regionally based socio-economic analysis of the impact of fireweed; and support research on the possible hybridisation of fireweed with related native species, to map the spread of fireweed nationally, to assess the toxic effect of pyrrolizidine alkaloids from fireweed on animals, and to review the feasibility of biological control. The Southern Councils Group (SCG), a voluntary association of seven Local Government Authorities located in the Illawarra and South East Regions of New South Wales including Bega, Eurobodalla, Kiama, Shellharbour, Shoalhaven, Wingecarribee and Wollongong, provided $35,000 in additional support.

Figure 2 *Members of the Bega Valley Fireweed Association and representatives from the Weeds CRC, University of New England, CSIRO and MLA inspect pastures invaded by fireweed near Bega on the South Coast of New South Wales.*

This combined funding culminated in a national workshop in May 2008 (BVFA 2008) in Bega at which the results of the various studies funded under the grant from the NLP were presented. The speakers and co-authors at the conference included Mr John Madden (Hassall & Associates Pty Ltd), Mr Reg Kidd (Chairman NSW Noxious Weeds Advisory Committee), Dr Brian Sindel (Associate Professor of Weed Science, University of New England and Cooperative Research Centre for Australian Weed Management), Dr John Edgar (CSIRO Honorary Fellow and World Health Organisation), Professor Andy Lowe (Professor of Conservation Biology at the University of Adelaide and Head of Science at Adelaide Botanic Gardens and State Herbarium), Dr Andy Sheppard (CSIRO

Entomology), and Dr Rachel McFadyen (CEO of the Cooperative Research Centre for Australian Weed Management. While copies of these presentations are available in full at http://thebegavalley.org.au/fireweed.html, along with other valuable information on fireweed, the findings of these projects have been summarized and incorporated in this report.

Copies of the full presentations from the National Fireweed Conference on projects funded under the NLP are available at http://thebegavalley.org.au/fireweed.html

Prior to this workshop in the lead-up to the Federal election in late 2007, the Labor Party, in Opposition, committed funding when in Government of $300,000 to "*conduct a risk analysis and further testing of biological control agents for management of fireweed*", "*raise awareness about best practice management of fireweed*", and "*undertake further assessment of fireweed for consideration for inclusion on the Weeds of National Significance list*". This announcement of the priority for biological control was based on the fact that "*A previous cross-jurisdictional government process determined there is a need for more testing of potential biological control agents of fireweed*" (O'Brien and Kelly, Media Release, 6 November 2007). The newly elected Federal Member for Eden Monaro, the Honourable Mike Kelly, who co-issued the statement, made a brief appearance at the National Workshop on fireweed and promised that the $300,000 was only an initial investment in fireweed research and that further funding would be forthcoming as needed.

As a long-term researcher of fireweed (Appendix 1), and at the request of the BVFA and the Department of Agriculture, Forestry and Fisheries (DAFF), my brief in this report is to summarise what we already know about fireweed, including from the presentations made at the National Conference from projects funded under the NLP, identify gaps in our knowledge, describe current research activities on fireweed, and provide direction for future research priorities for fireweed for expenditure of the $300,000 and subsequent funding. This initial research will be allocated through the new National Weeds Research Centre (NWRC), established by the Federal Government to take over from the Cooperative Research Centre (CRC) for Australian Weed Management which ceased operation in mid 2008. In doing so, I examine reports of the further recent spread of fireweed in Australia and factors such as climate change that may affect its potential distribution. The weed is causing considerable concern to farmers in certain areas of Australia and debate as to how easy or difficult it is to control. The question of whether the weed warrants investment in a biological program or whether it is simply a 'management issue' for individual landholders is specifically addressed.

What do we Know?

Identity

Botanical name

Senecio madagascariensis Poir., in the tribe Senecioneae and family Asteraceae (Compositae), was first described by Poiret in 1817, the type specimen having been collected by Commerson in Madagascar (Poiret 1817). In southern Africa it has also been classified under the names *S. ruderalis* Harv. and *S. junodianus* O. Hoffm. and in some instances mistakenly been given the names of the allied but distinct species *S. burchellii* DC. (Hilliard 1977) and *S. pellucidus* DC. (Radford *et al.* 1995b). Likewise, when it first appeared in Argentina in the early 1940s it was given the name *S. incognitus* Cabrera (Cabrera 1941). Subsequently, Cabrera (1963) and Cabrera and Ré (1965) concluded that they were dealing with the southern African plant *S. burchellii*, and it was by this name that it then became known (Garese 1963, 1965, Chutrau 1973). Cabrera and Ré (1965) also identified the species as occurring in Australia, having examined a specimen collected at Wallsend in the Hunter Valley, New South Wales, which had previously been identified as a form of the native Australian species *S. lautus* Soland.

In compiling a list of potentially troublesome weeds in North America, Reed (1977) included *S. madagascariensis* under the name *S. burchellii* and, like Cabrera and Ré (1965), recorded its occurrence in Australia. *S. lautus* Forst. f. ex Willd. was also described but remained confused with *S. madagascariensis* in terms of identity and distribution.

It was only following the most recent treatment of the Compositae in Natal (Hilliard 1977) that the name *S. madagascariensis* Poir. was applied in Argentina to the introduced southern African species (Cabrera and Zardini 1978, 1980, Guillén *et al.* 1984, Volkart 1984), and later adopted in Australia (Michael 1981). Although questions have been raised over taxonomic status in Australia (Marohasy 1993), cytological studies (Radford *et al.* 1995b) provide further evidence that Australian fireweed is *S. madagascariensis*. However, until recently, a question remained concerning the exact provenance of fireweed within the variable *S. madagascariensis* complex in Madagascar and southern Africa (Marohasy 1993, Radford *et al.* 1995b). This question has now been answered through additional genetic studies, and, as discussed later in this report, provides support and a focus for renewed investigation of biological control agents in southern Africa.

Senecio is from the Latin *senex*, meaning 'old man', and refers to the white, beard-like pappus of the plant; *madagascariensis* literally means 'of Madagascar' and refers to its earliest collection from that island (Parsons and Cuthbertson 1992).

A full description of *S. madagascariensis* is given in Appendix 2.

Common name

The most frequently given reason for the common name 'fireweed' in Australia is the ability of the plant 'to spread like wild fire'. Other possible explanations include its bright yellow colour, its apparent potential to cause spontaneous combustion in lucerne hay, and its appearance soon after grass fires. It should not be confused with other species of *Senecio* sometimes also referred to as fireweed, for example, cotton fireweed (*S. quadridentatus* Labill.), fireweed groundsel (*S. linearifolius* A.Rich.) (Hartley 1979), and hill fireweed (*S. hispidulus* A.Rich.) (Cunningham *et al.* 1981). Nor should it be confused with *Epilobium angustifolium* L. (syn. *Chamaenerion angustifolium* (L.) Scop.), an abundant plant in Europe and

North America, often known as fireweed due to its appearance after fires and its ability to spread rapidly (Salisbury 1961, Dana 1963).

In Argentina, two of the common names given to *S. madagascariensis* are 'golden button' (boton de oro) and 'the yellow flower of Mar del Plata' (flor amarilla de Mar del Plata) (Laguinge 1959, cited by Verona *et al.* 1982). Because of possible confusion with other species given the same names, Fernández and Montes (1984) considered it preferable to simply use the generic name 'senecio'.

In Hawaii, the weed is known as 'fireweed', 'Madagascar fireweed', and 'variable groundsel', though the common name preferred by the Weed Science Society of America, to promote consistency in naming, is 'Madagascar ragwort' (Motooka *et al.* 2003).

Recent taxonomical revisions

As stated earlier, until the 1980s in Australia, *S. madagascariensis* (the introduced fireweed) was confused with a similar native *Senecio* species (then called *S. lautus*) and first correctly named in 1981 as *S. madagascariensis* and recognized as a southern African plant (Michael 1981). Subsequent investigations have shown that our *S. madagascariensis* is most similar to plants from the KwaZulu-Natal province in South Africa, and that it is from this region that our fireweed most likely originated (Radford *et al.* 2000).

Following concerns by Michael (1992) and Belcher (1993; 1994) and subsequent detailed taxonomic work on the lautusoid *Senecio* complex, many of our native plants previously confused with *S. madagascariensis* (e.g. *S. lautus* var *dissectifolius*), particularly in south eastern coastal areas, are now no longer considered to be *S. lautus* but are referred to as *S. pinnatifolius* (Radford *et al.* 2004; Thompson 2005). A range of other natives in the lautusoid complex that can be differentiated from *S. madagascariensis* have also been described (Thompson 2005).

Differentiation between *S. madagascariensis* and these native *Senecio* species (and particularly *S. pinnatifolius* which commonly co-occurs with the introduced fireweed) has been important because many of these natives have been regarded as essentially non-weedy (Sindel 1986), they occur in different areas (all but northern tropical Australia) (Figure 3), and the toxic alkaloids vary. The fact that the invasive *S. madagascariensis* is introduced (non-native) also opens up the possibility of biological control of the weed in Australia.

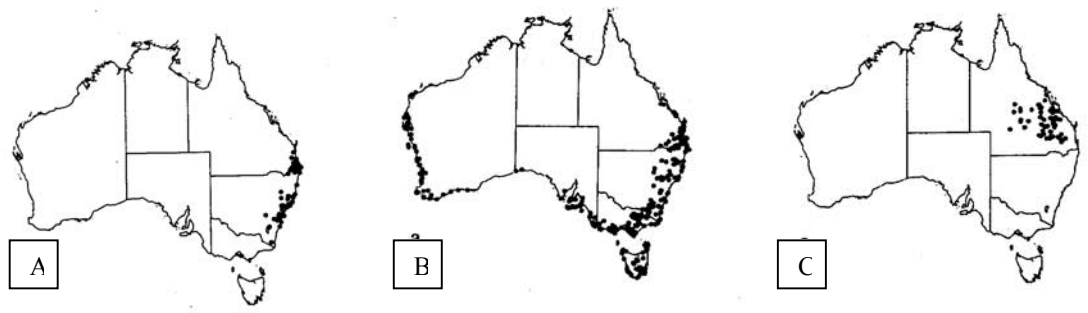

Figure 3 *Distribution in Australia of A.* Senecio madagascariensis, and two native species sometimes confused with fireweed*, B.* S. pinnatifolius*, and C.* S. brigalowensis*, based on specimens from Australian herbaria (Thompson 2005).*

One example of the confusion between the introduced fireweed and the native species occurred in 2007 when it was reported in the media and apparently advised by state primary industry department employees that the introduced fireweed had invaded and was widespread around the Rockhampton area in central Queensland. This, however, was not the introduced *S. madagascariensis* but rather the native *S. brigalowensis* (see distribution in Figure 3). The species are very similar but can be distinguished on floral and leaf characteristics. Also, anecdotal information from the field indicates that the native *S. brigalowensis* is difficult to pull out by hand due to its tap root system, whereas fireweed pulls out much more readily because of its relatively shallow fibrous root system (McFadyen, personal communication) (Figure 4).

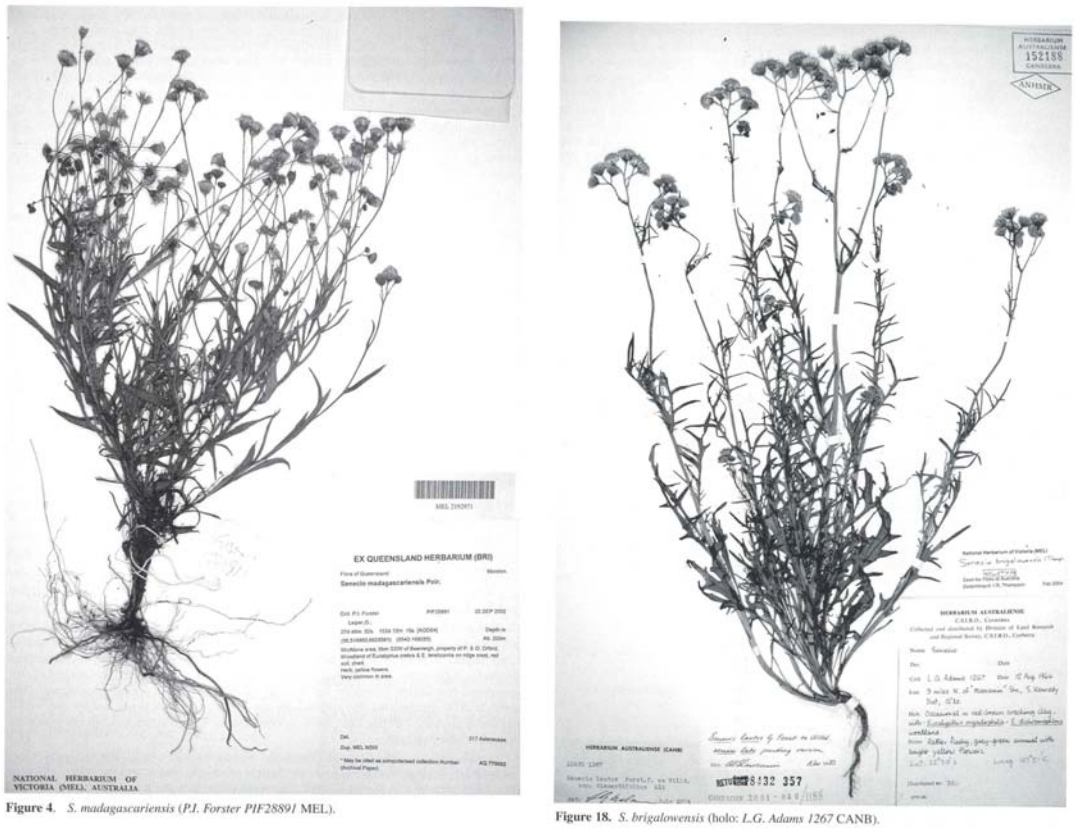

Figure 4 *Herbarium specimens of* Senecio madagascariensis *(left) and* S. brigalowensis *(right) showing overall similarities, but also differences in leaf shape and root structure (Thompson 2005).*

Worldwide distribution

Africa

In southern Africa, *S. madagascariensis* is known to occur up to 1500 m above sea level and is widely distributed from southern Madagascar and the Mascarene islands through coastal southern Moçambique to Natal, the Transkei and eastern and southern Cape as far west as the Uniondale district. Though not common, it is also found in the Transvaal (Hilliard 1977) and has been recorded at Chipinga in eastern Zimbabwe (C. Jeffrey, personal communication).

In Natal, *S. madagascariensis* is usually found only on disturbed land fallows, contour banks and road verges and the like. But in the spring of 1983, following 3 years of drought, it appeared widely in undisturbed natural vegetation and sown pastures. This widespread appearance did not recur in the next spring owing to a year of much more normal rainfall (N.M. Tainton, personal communication). *S. madagascariensis* is not thought to be a serious problem in Natal (O.M. Hilliard, personal communication).

S. madagascariensis has also recently been introduced and reported naturalized much further north near Gilgil in the highlands of Kenya at an altitude of 2600 m (C. Jeffrey, personal communication). It is not eaten by cattle and is causing a considerable weed problem.

South America

In Argentina, *S. madagascariensis* was first recorded (then under the name *S. incognitus*) surrounding the port of Bahia Blanca in the early 1940s (Cabrera 1941). Since then it has spread greatly and is now a significant weed of agricultural crops and grasslands in the south-eastern part of Buenos Aires province (Verona *et al.* 1982). It is also found in large areas of the provinces of Santa Fe, Rios, Corrientes and Mendoza (Volkart 1984) and has been reported growing in Uruguay (Sindel *et al.* 2008a).

As in Kenya, *S. madagascariensis* has also been recorded from the cool moist equatorial environment of the Colombian highlands near Bogota at 2800 m (J.T. Swarbrick, personal communication). Little is known about its prevalence there other than that it is typically a roadside weed.

Japan

In Japan, *S. madagascariensis* has been reported as being distributed in the warm temperate south western areas of Japan, including the Tokyo area, where precipitation ranges from about 1000 to 1700 mm (Michael and Fujihara, personal communications).

Hawaii

The ecotype of *S. madagascariensis* that occurs in Hawaii appears to be closely related both genetically (Le Roux *et al.* 2006) and toxicologically (Gardner *et al.* 2006) to that which occurs in Australia, supporting the contention that the weed may well have been introduced to Hawaii from Australia (Lowe *et al.* 2008). While there appears to be no direct evidence to suggest how the weed may have been introduced to Hawaii, fireweed was first observed on the island of Hawaii in the early 1980s and is suspected to have been introduced by contaminated groundcover seed imported from Australia (Starr *et al.* 1999; Motooka *et al.* 2004). It is now widespread on Hawaii and on the adjacent island of Maui. The first signs of the weed on Maui were along roadways. A single infestation on Kauai at the northwestern end of the archipelago, known to have occurred with the application of groundcover seed along a highway, has apparently been eradicated. The weed can be observed in flower and seed stages in cattle grazing areas on the island of Hawaii at all times of the year. The potential for livestock poisoning in this area is therefore considered to be extremely high (Gardner *et al.* 2006).

Spread and distribution in Australia

It is thought that fireweed may have been introduced to Australia in the ballast of ships trading between Europe and Australia via the Cape of southern Africa (Sindel 1996). The

earliest record of fireweed in New South Wales, and probably in Australia, is a specimen collected at Raymond Terrace in 1918 (Nelson 1980). It first became prominent in pastures in the Hunter Valley and from there spread throughout many parts of coastal New South Wales, being introduced to the north coast in about 1940 in crop seed (Green 1953). By the mid 1960s fireweed was identified as one of the main weeds of that region (Auld 1971).

In the late 1980s fireweed was restricted principally to coastal pastures from north of Brisbane to Nowra with small infestations near Bega on the south coast of NSW (Sindel and Michael 1988) and isolated plants further inland, particularly at Dubbo on the Central Western Plains of New South Wales (Sindel and Michael 1992a). There the weed has been introduced in livestock feed from the coast and is thriving in a micro environmental niche around water holes and irrigated areas in the confines of the Western Plains Zoo. This occurrence (Figure 5) indicates that other inland irrigated areas could also be at risk of invasion (Sindel 1996).

Figure 5 *The yellow tinge of fireweed growing in the giraffe enclosure of the Western Plains Zoo, Dubbo.*

Recent spread

Based on the then distributions in Australia and overseas, Sindel and Michael (1992a) predicted that fireweed could well spread further north in eastern Queensland, further south through coastal Victoria, and into higher altitude areas in tropical Queensland, though areas with heavy frosts may have reduced the 'weediness' of the species, since young seedlings were shown to be somewhat sensitive to frost (Sindel and Michael 1989).

Fireweed is now widespread in the Bega area where once it occurred only in isolated patches, and its movement in the Dorrigo and Nowendoc areas on the Northern Tablelands and in the Monaro region on the Southern Tablelands of New South Wales suggests that this invasive pasture weed has not yet reached its potential distribution in Australia. In 2007 the weed was also found growing on the Atherton Tablelands in far north Queensland, in line with predictions by Sindel and Michael (1992a).

Future spread

Currently, fireweed is especially abundant in New South Wales in the Richmond, Manning and Hunter Valleys, in the County of Cumberland around Sydney, between Wollongong and Berry and around Bega, but distribution also extends along the whole New South Wales coastline and into the northern and southern Tablelands (Nelson and Michael 1982, Watson *et al.* 1984, 1994, Sindel and Michael 1988, 1992a, Radford *et al.* 1995a, Radford 1997a). Occasional plants are found as roadside weeds on the North-West Slopes of New South Wales where they have probably been spread by passing traffic. Another isolated occurrence was a single specimen which was collected near Melbourne (Batnarring 38º 23' 30" S, 145º 08' E) in Victoria (National Herbarium of Victoria).

In Queensland the weed is most prevalent in coastal pastures south of Brisbane, but infestations have also been found north of Brisbane near Caboolture, Gympie and now the Atherton Tablelands (Figure 6).

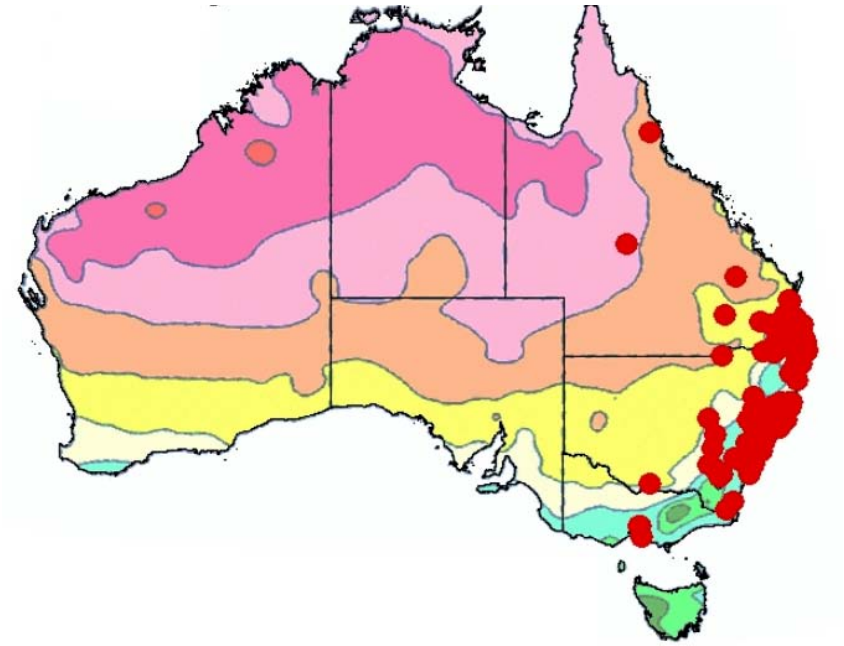

Figure 6 *Distribution of fireweed in Australia based on herbarium records (red dots) overlaid on temperature contours (Lowe* et al. *2008).*

In some areas with a long history of infestation, the spread of fireweed from one farm to another has ceased, whereas over its range as a whole, it is still spreading rapidly (Sindel and Michael 1988, Radford *et al.* 1995a, Lowe *et al.* 2008, Sindel *et al.* 2008b) (Figure 7). Bioclimatic analysis of the current distribution of fireweed in Australia and latitudinal limits in Africa and South America in 1992 suggested that the weed would largely remain restricted to south-eastern Australia (Sindel and Michael 1992a) (Figure 8).

When distribution data from southern Madagascar were used to predict potential distribution, they indicated that fireweed may be climatically suited to vast areas across northern Australia receiving at least 400 mm of rainfall annually (Sparks unpublished data, cited by Cruttwell McFadyen 1991). However, DNA sequencing (Scott *et al.* 1998) and isozyme analysis (Radford 1997b) show that Australian populations are genetically closer to plants from South Africa (Natal) than from Madagascar.

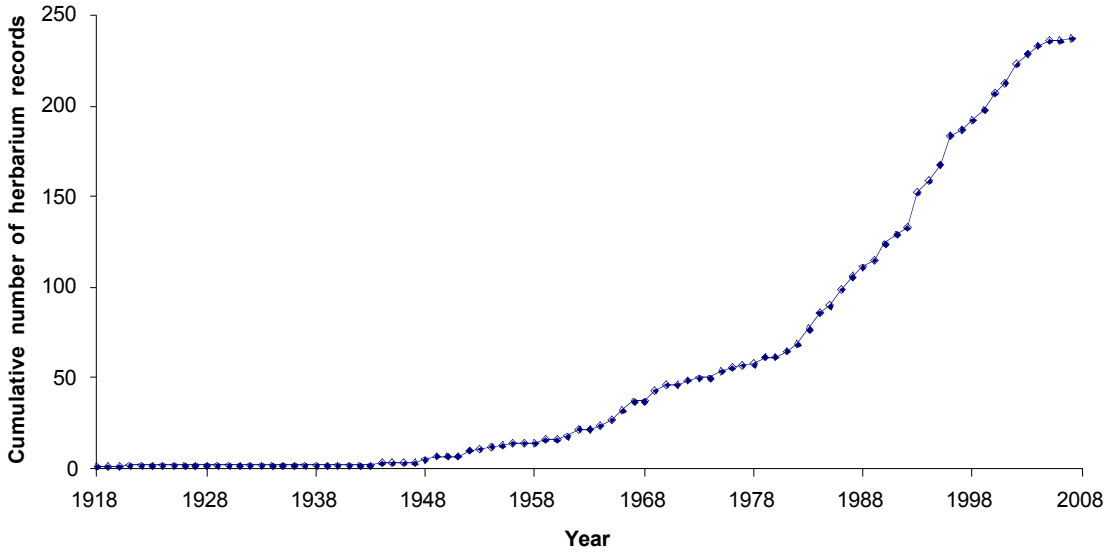

Figure 7 *Spread of fireweed in Australia based on number of herbarium specimens collected, showing that fireweed continues to spread rapidly (Lowe* et al. *2008).*

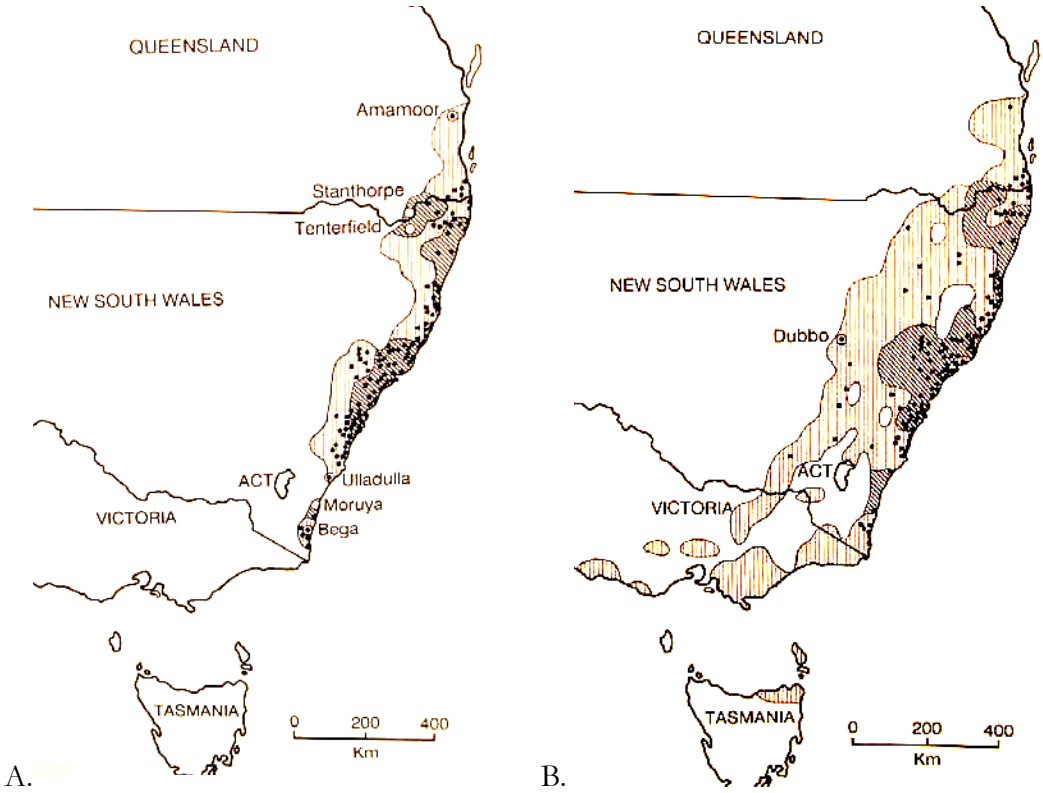

Figure 8 *Predicted potential distribution of fireweed in Australia by Sindel and Michael (1992a) using BIOCLIM based on A. established localities and B. established localities and outliers, where cross hatching represented suitable climates and vertical hatching represented more marginal climates.*

S. madagascariensis is also non-weedy in the semi-arid environment of south-western Madagascar (Marohasy 1989) and differs in form to the predominant invasive ecotype in Australia (Radford *et al.* 1995b). For these reasons, Sindel (1996) suggests that the use of data from Madagascar for predicting the potential distribution of fireweed in Australia is unlikely to be as reliable as the conservative use of current Australian distribution data.

Factors affecting further spread

Frost Carthew (2006) recently investigated the effect of frost on the growth of fireweed and whether fireweed could be cold acclimated (hardened off) at low temperatures, and therefore be protected from the deleterious effects of frost. Visual damage, colour assessment, dry weights and plant survival all indicated that plants grown under warmer conditions prior to frosting were more susceptible to frost than plants exposed to cooler temperatures. These results suggest that fireweed does become cold acclimated and that frost may not be as important a factor in limiting the spread of fireweed as first thought (Carthew 2006). Future studies will be needed to investigate the relative invasiveness of fireweed in colder Tableland areas compared with warmer coastal regions. Anecdotal evidence indicates that plants can grow vigorously in these areas when temperatures are warming in spring, but invasive capacity will be dependent on a range of plant attributes.

Climate change If as predicted, climate is changing and becoming warmer and drier in many parts of Australia, this will affect the continued spread of fireweed and its potential distribution. The movement of the weed into cooler highland areas, as seems to be occurring now in New South Wales and Queensland, may increase in the future. Likewise, cooler southern Australian areas in New South Wales (e.g. on the Monaro Tablelands) and Victoria may become more susceptible to invasion. The increase in extreme climatic events such as floods and droughts associated with climate change will definitely open up new opportunities for fireweed invasion. Droughts in particular cause an increase in bare ground, which when rains fall, is colonised by weeds such as fireweed, which, at the same time, may be being dispersed through drought-relief fodder. Intense rainfall events are also likely to see fireweed spread as its seeds are dispersed by large floods.

Other factors The realized distribution of a weed is often tempered by factors in addition to climatic suitability such as soil type, land use systems, competition, opportunity and vectors for spread (see later discussion), and pests and pathogens, or by factors that interact with climate. For example, the rust fungus *Puccinia lagenophorae* Cooke that commonly infects fireweed in Australia in wet weather may become less of a constraint on growth and reproduction of the weed if there are drier times ahead, though increasing temperatures may be of benefit. The extent to which this pathogen constrains fireweed in Australia is largely unknown. Because of all these factors, predicting the potential distribution of a weed is often fraught with difficulty and uncertainty.

Habitat

Fireweed is an opportunistic weed with the ability to invade and colonize a great variety of habitats in a short period of time. Its rapid spread in the last 60 years in Argentina (Fernández and Montes 1984) and along the east coast of Australia (Watson *et al.* 1984, Sindel and Michael 1992a, Radford *et al.* 1995a, Lowe *et al.* 2008) is a clear indication of its invasive potential.

Climatic requirements
In general, apart from at high altitudes in equatorial climates, fireweed is currently restricted in distribution to humid maritime and sub-tropical regions of the world and occurs in similar latitudes on the eastern seaboard of the three continents of the Southern Hemisphere where annual precipitation ranges from approximately 500 to 1000 mm and occasionally reaches 1500 mm (Sindel 1989). The annual mean temperature of established fireweed sites in Australia ranges from 12.3 to 20.1°C (Sindel and Michael 1992a). Young seedlings are more sensitive to frost than older plants and this may contribute to its restriction to areas with low frost incidence (Sindel and Michael 1989), though as noted earlier, fireweed plants are able to be hardened to the effects of frost over their growth cycle.

Soils
On a local scale the pattern of distribution may vary considerably due to differences in soil and previous cultural systems. Fireweed is able to grow on a wide range of soils of varying fertility (Verona *et al.* 1982). Although it prefers soils which are well drained, not compacted, and of high fertility, it can also grow in sand and heavily limed soil. Watson *et al.* (1984) suggest that low fertility soils are less likely to support vigorous pastures and, lacking competition, fireweed grows freely.

Plant associations
In Australia fireweed is more abundant in poorly grassed, neglected or heavily grazed pastures, and on cultivated land during the autumn to spring period (Figure 9). In most of the colonized coastal areas, it has the competitive advantage of active winter growth when pasture production is low. Its impact has been minimal in areas of relatively undisturbed native vegetation (Sindel 1996, Radford 1997a). On the other hand, *S. pinnatifolius* is often found in undisturbed native habitats (Figure 9). Dominant pasture species most commonly associated with fireweed in coastal New South Wales include kikuyu (*Pennisetum clandestinum* Hochst. ex Chiov), white clover (*Trifolim repens* L.), couch grass (*Cynodon dactylon* (L.) Pers.) and paspalum (*Paspalum dilatatum* Poir.) (Radford *et al.* 1995a).

Growth and development

Perennation
Fireweed is a short lived perennial plant (Green 1953, Cabrera and Ré 1965, Martin and Colman 1977, Verona *et al.* 1982) but it behaves most commonly as an annual (Hilliard 1977, Walker and Kirkland 1981, Radford 1997a), growing strongly from autumn to spring. The majority of plants die off at the end of their first year of growth, especially in agricultural soils, but it is common to find plants which continue to grow and reproduce actively during their second year (Nelson and Michael 1982, Verona *et al.* 1982). This occurs even without some external stimulus, such as mechanical damage, which can promote the regeneration of the stem. However, fireweed cannot be considered a strict perennial, because with rare exceptions the few plants that survive the second year are decrepit and ready to senesce (Verona *et al.* 1982). It is likely that for this reason, Humbert (1963) records *S. madagascariensis* as a biennial.

A.

B.

C.

Figure 9 *Fireweed growing densely in A. heavily grazed pastures and B. where cultivation has stimulated germination and emergence of fireweed seed, compared with C. a typical native habitat for* S. pinnatifolius.

In this context, *S. madagascariensis* represents a species with high plasticity or capacity to vary its life cycle which may be associated with the stability of the habitat which supports it. In a study in the County of Cumberland, New South Wales, all fireweed plants behaved as annuals at a site where the pasture was grazed and relatively vigorous, while up to 40% of plants survived into a second year of growth at two less-productive, ungrazed sites (Sindel and Michael 1996). Another study on the lower north coast of New South Wales found longevity to be approximately double for plants at a more coastal site than for inland populations (Radford 1997a). It is possible that extremes of temperature caused higher mortality at the inland site as rainfall was similar.

Physiology

Growth rates of fireweed (dry matter and leaf area) are positively correlated with mean air temperature (Nelson 1980, Fernández and Verona 1983). Dry matter allocation to leaves prevails during the early developmental stages while an increasing proportion of assimilates go into the stems over the life of the plant. Allocation to roots decreases rapidly with plant age (Fernández and Verona 1983). Seedlings demonstrate some tolerance to shade and an ability to recover quickly if shade is removed. In the early stages of development, seedlings grow taller under heavy shade and a reduction in net assimilation rate is partially compensated for by an increase in leaf area ratio. Nevertheless, increasing shade reduces the growth of roots and shoots, particularly at levels of irradiance less than 20%. Capitula (flowering head) production is particularly sensitive even to low levels of shade (Sindel 1989).

Phenology

Fireweed is capable of germinating, growing and reproducing during a large part of the year, although most seed germinates in flushes during autumn and late winter/spring, with most plants dying off in late spring and summer (Sindel and Michael 1996, Radford 1997a) (Figure 10). Fireweed seedlings develop rapidly (Fernández and Verona 1985) so that plants may produce flowers 6 - 10 weeks after emergence (Sindel and Michael 1996). Time to flowering decreases with increasing temperature (Nelson 1980). Flushes of flowering occur in spring and autumn, though some plants can be found flowering at most times of the year (Verona *et al.* 1982, Sindel and Michael 1996, Radford 1997a), which is just one of the reasons why it is difficult to stop fresh seed entering the soil seed bank on an annual basis.

Reproduction

Floral biology and breeding system

Fireweed in Australia is an obligate out-breeder, not producing seed when capitula were bagged (to prevent insect pollination) or when self pollination was performed (Radford 1997a). This means that a lone plant will not produce viable seed. Disc florets are hermaphrodite, although ray florets do not produce anthers and are therefore male infertile. As with other species in the family Asteraceae (Clarke and Lee 1993), floral maturity is achieved when pollen is shed into the anther tube and is pushed out of the corolla by the upward growth of the style (I.J. Radford, personal observation). After the pollen is shed or removed by insects the style arms separate and become receptive. Ray

florets mature first with the remaining flowers maturing in series towards the centre of each capitulum (flower head).

Insects, including European honey bees and hover flies, were observed to collect pollen from fireweed capitula (I.J. Radford, personal observation). Insect pollinators apparently did not distinguish between exotic fireweed and native *S. pinnatifolius* capitula, freely visiting both species when grown together. Successful pollination was evident from the number of viable achenes produced.

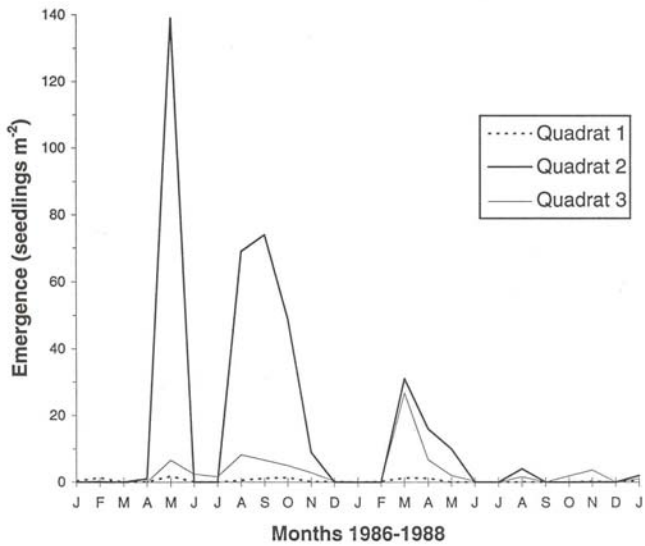

Figure 10 *Emergence of fireweed in 3 quadrats in pasture south west of Sydney, New South Wales, from January 1986 to January 1988 (from Sindel and Michael 1996).*

Although there was an average of 110 florets produced per capitulum on fireweed plants grown under laboratory conditions, only 55 mature achenes were recorded per capitulum in plants from field sites in 1993 and 1994 (Radford 1997a). Seed set per capitulum has elsewhere been reported to be as high as 120 (Watson *et al.* 1984).

Genetic variation

Studies have not yet shown any variation in DNA sequences in Australian populations of fireweed (Scott 1994). However, variation has been recorded in isozyme analyses (Radford 1997a), though the total (H_T = 0.251) and within population variations (H_S = 0.195) were lower than average for short lived perennial or annual plants, species with regional or widespread distributions, species with wind dispersed propagules or weedy species generally (Hamrick and Godt 1990). This is not surprising given the weed's relatively recent introduction to Australia from southern Africa (Michael 1981). Nevertheless, greater genetic variation was found in Australian fireweed than for many inbreeding weedy species which have been introduced to exotic locations (Brown and Marshall 1981, Warwick 1991, Chaboudez and Burdon 1995). Fireweed in Australia partitions its variation predominantly within populations (c. 80%), as is typical of an outbreeding species. Australian populations of *S. madagascariensis* were found to have lower genetic variation than

that found in South Africa and Madagascar (Radford 1997b) and than the closely related native species, *S. pinnatifolius*, using isozyme, morphometric (Radford 1997a) and DNA markers (Scott 1994, Scott *et al.* 1998).

While there is relatively high morphological diversity in the African region (Hilliard 1977, Marohasy1993, Radford 1997b) compared with Australian fireweed populations (Radford 1997a), ITS-1 DNA sequences show very little variation in southern Africa (Scott *et al.* 1998), with only one out of 235 base pair substitutions differing.

Cytological studies from Australia, New Zealand, Argentina and Africa (Ornduff 1960, 1964, Turner 1970, Lawrence 1980, Verona *et al.* 1982, Radford *et al.* 1995b) show a clear distinction in chromosome number between *S. lautus* and *S. pinnatifolius* ($2n$=40) and fireweed ($2n$=20).

Seed production and dispersal

Fireweed reproduces prolifically. An individual plant may produce up to 230 capitula with 80 seeds per capitulum (total of 18 000 seeds) during the period of its lifecycle (N.R. Nelson, personal communication), though in field populations, mean seed production was estimated as only 225 per plant in 1993 and 1994 (Radford 1997a). Seed production per unit area varied from 4644 m^{-2} in 1993 at two sites on the New South Wales coast down to 760 m^{-2} in 1994, probably due to drought. Comparatively high plant density and biomass at other sites on the New South Wales coast (Sindel and Michael 1996, Radford 1997a) indicate that average seed production may be much greater than 5000 m^{-2} in many areas. Reproductive peaks were recorded in May and September 1993, and March, June and October in 1994. The quantity of seed set is also dependent on the time of seedling establishment and the consequent size of the plant at the peak flowering periods (Fernández and Montes 1984). Seed viability has not been found to be related to the time of seed set (Alonso *et al.* 1982).

The seeds of fireweed are small and light (135 μ g) and each is attached to a relatively persistent pappus of white hairs which aids dispersal by wind, especially in convection currents (Figure 11). Preliminary studies indicate that fireweed may be caught up by winds more easily than many other wind-dispersed *Senecio* species (Sindel 1989). While only a very small fraction of propagules is usually dispersed to a great distance from the parent plant (more than 5 m) by this means, such wind-borne achenes nevertheless contribute largely to the success of fireweed as a weed and invader of pasture land (Sheldon and Burrows 1973, Sindel 1989).

The seeds can also be dispersed in hay and grain products, on clothing and vehicles, and by livestock, birds and other animals. There have also been suggestions that seed has blown into piles of superphosphate and then been spread to new areas when the fertiliser was applied aerially. Whether fireweed seeds are able to pass unharmed through the digestive tracts of cattle, sheep, goats or birds is not known.

Since heavy infestations of fireweed occur along runway verges at the Sydney international airport, it is also possible that large jumps in dispersal (overseas and locally) could be initiated through international and domestic flights (Figure 12).

Physiology of seeds and germination

Fireweed produces three types of achenes (seeds) in the following percentages: dark brown (9%), light brown (80%) and green (11%) (Figure 13). Dark brown and green seeds are situated on the periphery of the receptacle of the capitulum and appear to be associated with the male sterile ray florets. The three seed morphs do not differ in mean weight or

length (Alonso *et al.* 1982) but do have different rates of germination and levels of dormancy. Light brown seeds germinate quickly while dark brown seeds have a comparatively high level of innate dormancy. Light brown seeds appear adapted to take advantage en masse of disturbed or otherwise favourable conditions, while dark brown seeds may be more important for the persistence of the weed under conditions unfavourable for establishment (Fernández unpublished data). Green seeds show intermediate responses.

Figure 11 *Mature capitula of fireweed showing wind dispersal of the pappused fruits (seeds).*

Figure 12 *Fireweed growing between runways at Sydney's Kingsford Smith International Airport.*

Figure 13 *Different coloured seeds of fireweed show variation in dormancy and germination characteristics, aiding in its adaptation and survival.*

At the moment of dispersal, a high proportion of seed is viable and ready to germinate (Alonso *et al.* 1982). Nelson and Michael (1982) recorded 90% germination at 20°C 3 days after collection. For this reason more than one generation may occur throughout the winter period (Nelson 1980). While extreme temperatures induce dormancy of the seeds, innate dormancy is negligible under normal conditions (Alonso *et al.* 1982, Nelson and Michael 1982, Radford 1997a). This strategy would be disadvantageous for the persistence of annual arable weeds (Chancellor 1984), but because fireweed grows predominantly in pasture areas, the conditions for germination may not always be present.

Fireweed germinates well between 15 and 27°C but above and below this range the percentage germination falls sharply. While this wide temperature range is consistent with germination of fireweed over much of the year, high summer and cool winter temperatures may help to explain the lack of new seedlings appearing in those periods (Figure 10). The rate of germination is most rapid between 20 and 25°C (Nelson and Michael 1982). Seed will not germinate at 35°C, but seeds exposed to this temperature are viable when germinated at 20°C (B.M. Sindel, personal observation). The optimum temperatures observed for germination and the ability of the seeds to withstand high summer temperatures are to be expected of a winter-growing species in coastal south eastern Australia (Nelson 1980).

Although light (Nelson and Michael 1982) and nitrates (Alonso *et al.* 1982) are not essential, they generally stimulate germination. Guillén *et al.* (1984) concluded that *S. madagascariensis* seed is positively photoblastic - requiring intermittent radiation for germination. The promotion of germination by irradiation with red light and its reversion by far-red light led these authors to believe that the mechanism of fireweed dormancy is operated by the phytochrome system. This responsiveness of fireweed seed to light may also affect seedling establishment and survival of seed by determining the maximum depth of soil from which germination can take place, i.e. 2 cm (Alonso *et al.* 1982).

Percentage germination is not affected by osmotic potentials over the range 0 to -300 kPa but decreases at potentials below -300 kPa (Alonso *et al.* 1982). A small percentage of seeds is still able to germinate at -1000 kPa.

Under laboratory storage, all seeds are estimated to lose their viability after 4 to 5 years (Alonso *et al.* 1982). On the other hand, seeds buried 3 cm deep in soil 1 month after collection lost 9% viability over 15 months (germination decreased from 63 to 54%)

(Radford 1997a). Although regression equations for these data had low precision (R^2<0.25), estimates based on these figures suggest that some seeds may remain viable in the soil for up to 10 years. Longer term field investigations of seed longevity are required.

Vegetative reproduction
Rooting along the woody stems of decumbent fireweed plants has been observed (Nelson 1980). Hence, it is possible that shoots associated with these adventitious roots remain alive while those of the parent roots die off over summer. In some plants, regrowth from roots can also occur following the death of the top growth over summer (Watson *et al.* 1984).

Hybridization

Hybridization between native and exotic species can have several outcomes including enhanced weediness in hybrid offspring, evolution of new hybrid lineages, and decline or even extinction of hybridising species (Prentis *et al.* 2007, Lowe *et al.* 2008). In Australia, there has been concern over the possible hybridisation of the introduced and invasive fireweed (*S. madagascariensis*) and co-occurring native *Senecio* species. Plants of intermediate morphology have been observed in a mixed population of *S. madagascariensis* and the native *S. pinnatifolius* together with plants containing common DNA sequences at one site in Queensland (Scott 1994, McFadyen and Sparks 1996). Species-specific isozyme markers have also been used to identify plants from three field sites with seeds of hybrid origin. However, no further morphological intermediates have been observed in the field (Radford 1997a, Prentis *et al.* 2007).

Molecular and morphological studies have demonstrated the potential for hybridisation (Radford 1997a, Prentis *et al.* 2007). However, hybrids produced by artificial crosses between *S. madagascariensis* and *S. pinnatifolius* in the laboratory were sterile (Radford 1997a). Pollen from adult hybrids was non-viable, small and irregular in shape compared with parent pollen. No mature fruits were produced from hybrid plants under open pollination tests (Radford 1997a). While low hybrid viability maintains a strong barrier to introgression between this native and exotic species pair, a hybridization advantage was observed for fireweed. As a result of asymmetric hybridization, *S. pinnatifolius* would appear to be under threat if fireweed increases numerically in areas of contact (Prentis *et al.* 2007). Further work on possible hybridisation and its influence on the invasion success of fireweed in Australia is currently being undertaken by Dormontt (2008).

Population dynamics

Above-ground populations of fireweed vary dramatically between sites and years, with peaks being reached in autumn and spring, coinciding with flushes of germination. For instance, large population fluctuations were recorded at two sites on the north coast of New South Wales between 1993 (plant density 10.3 and 12.5 m^{-2}) and 1994 (2.8 and 1.7 m^{-2}) which was a drought year (Radford 1997a). Survival curves of cohorts typically show rapid mortality following germination and again nearing senescence in late spring and summer. Mean life expectancy (calculated from the mean time from emergence to 50% survival of each accession) ranged in one study from 1.5 months to 3.7 months depending on the site (Sindel and Michael 1996). In another study, plants remained alive for between 3.7 and 4.7 months after producing their first flower buds (Radford 1997a).

Several factors have been observed to contribute to the premature death of fireweed including moisture and temperature stress, frost, infection by the rust fungus *Puccinia lagenophorae*, damage by pasture slugs or native insects such as the stem borer *Patagoniodes farinaria* (Turner), and trampling and grazing by cattle. Seedlings which emerge in either early autumn or early spring under good conditions for growth, and which survive initial competition from pastures, are able to grow rapidly, flower and set seed before growth is retarded either by low winter temperatures or hot, dry summer conditions respectively. Individual plants may die young and leave some progeny, but other individuals are able to exploit a long growing season (Fernández and Verona 1984). Early autumn accessions and large over-summering plants therefore have the greatest potential to increase the seed population of fireweed (Sindel and Michael 1996). The conditions leading to 'fireweed years' need to be more clearly elucidated.

Soil seed banks in field populations have been estimated to average over 12 000 seeds m^{-2}. However, only 3.6% (about 450) were found to germinate using gibberellic acid to stimulate germination (Radford 1997a), suggesting that this was an aging seed population. Low viability may also be explained by high mortality at the soil surface due to dessication and predation. More seeds were at or just below the soil surface (<10 mm) than deeper in the soil profile (10-30 mm), making it likely that the majority of viable seeds would have the potential to emerge from the soil if given the right conditions to germinate. The dynamics of such soil seed banks, as with their longevity, needs further research.

Impact

In Australia, fireweed has had a significant impact on agriculture due to its invasiveness and competitiveness with useful pasture species, and its toxicity to livestock. Farmers are also conscious that the weed looks bad on their properties and regard it as the worst weed of pastures in most coastal areas of New South Wales (Sindel and Michael 1988).

Invasiveness and competition

Since introduction, the number of farms in coastal New South Wales infested with fireweed has increased exponentially so that in 1985 fireweed occurred on 90% of farms surveyed from eight regions by Sindel and Michael (1988). In the Gloucester area, the rate of spread had levelled off, while in the Taree area, fireweed colonized all farms in a period of just 20 years.

Fireweed has been considered important because of its ability to invade a range of pasture types including those growing on highly fertile soil (Verona *et al.* 1982). The weed has the potential to compete strongly with existing pasture plants for light, moisture and soil nutrients (notably phosphorus and nitrogen), and it is thought that this competition can lead to the deterioration of pastures (Watson *et al.* 1984, 1994). Dense infestations of over 5 000 plants m^{-2} have been observed (Sindel and Michael 1996).

The avoidance of fireweed and the pasture growing beneath it by cattle favours its growth and competitiveness, and because of its branched habit, can also lead to sizeable reductions in the effective grazing area. Hence in a crop of grazing oats, fireweed at a density of 40 plants m^{-2} may reduce pasture yield by over 70% and reduce the grazing area by as much as 60% (Sindel 1987). The relative competitiveness of fireweed with oats increases as soil nitrogen and phosphorus levels increase. A greater percentage of dry matter is also partitioned into stems and flowering capitula than at low nutrient levels,

thereby raising its relative reproductive effort, and hence its invasive potential (Sindel and Michael 1992b).

Experiments designed to quantify pasture production loss due to fireweed have proved inconclusive. A significant increase (c. 60%) in pasture growth was recorded at one site west of Sydney where fireweed had been removed using weed specific herbicides (Radford *et al.* 1997). However, drought during the experimental period (1993/1994) meant that positive pasture growth was recorded for only three of the nine harvest intervals (Figure 14). Although pasture production was approximately double in non-fireweed than fireweed pasture for the other two positive growth periods, high variability between samples meant that treatment differences were not statistically significant. Further information on the impact of fireweed on pasture production under a range of pasture and environmental conditions is required. However, research on fireweed control should not be delayed whilst this information is obtained given the already clear detrimental impacts of the weed on Australian agriculture.

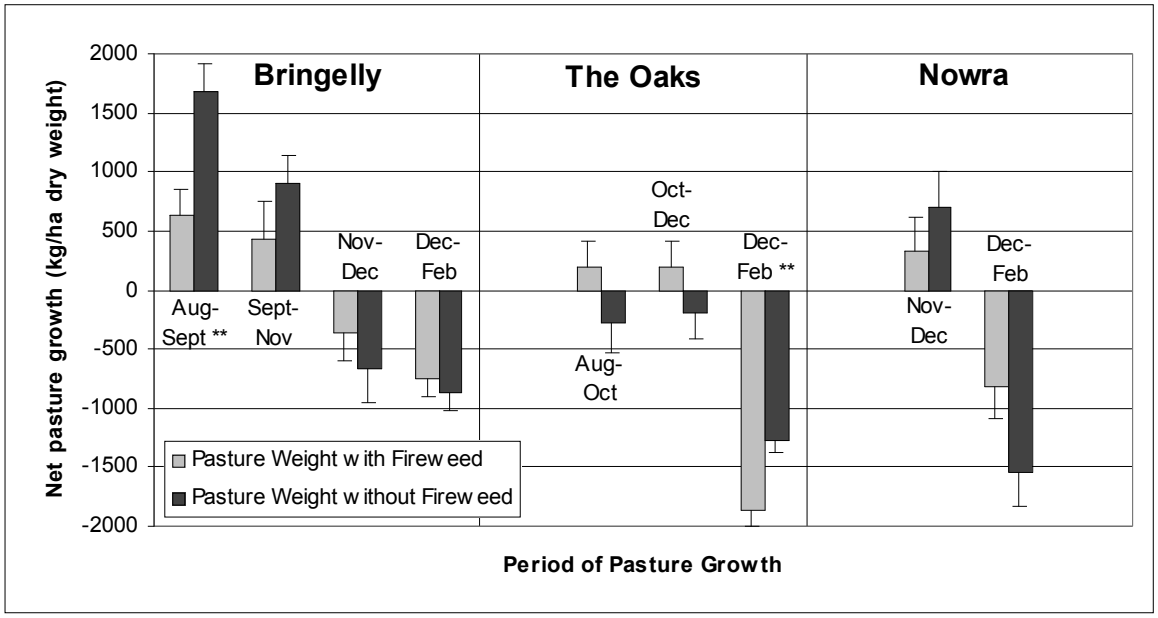

Figure 14 *Pasture growth recorded in the presence and absence of* Senecio madagascariensis *(fireweed) (Radford* et al. *1997). Vertical bars represent the standard error of the mean biomass change over the interval between harvests. ** signifies that differences between pasture with and without fireweed were significant (P<0.01).*

While fireweed grows in all types of pasture (Green 1953), its density is influenced by the quantity of ground cover (Martin and Colman 1977). Lynch and Strang (1973) observed that fireweed occurred more frequently on sites where pastures had failed and where cattle had formed permanent camps. These areas were dominated by the unproductive couch grass and carpet grass (*Axonopus affinis* Chase). A dry summer can lead to a decline in pasture density and vigour, and indirectly result in a large germination of fireweed when autumn rains come (Sindel and Michael 1988, 1996). Fireweed was also observed to be abundant after the breaking of the 1983 drought (Sindel 1986). Likewise, soil disturbance often leads to an increase in the emergence of fireweed seedlings. The weed is not generally a problem in irrigated pastures or crops, possibly due to the better overall growth

of desirable plants and the more intensive management of these situations (Fernández and Montes 1984, Watson *et al.* 1984).

Fernández (personal communication) has identified four principal reasons why *S. madagascariensis* invades pastures in Argentina. They are the abundance of 'inoculum' (seeds) produced by the weed in the stubble of many cereal crops during autumn; insufficient sowing of adapted and improved pasture species, and their early grazing; overgrazing, particularly during periods of low pasture regrowth; and the avoidance of the weed by cattle, favouring its growth and spread.

Due to high seed production and ease of distribution, the potential of fireweed for further colonization, once established, appears to be one of its most important invasive characteristics. Others which may be added are its annual/perennial habit; its adaptability and variability in the field; germination, growth and flowering during much of the year; and the possibility of a long flowering period.

Economic and social impact

At a farm scale, research conducted by Hassall & Associates (Madden 2008) indicated that impacts on carrying capacity of pastures on the South Coast of New South Wales have, in most cases, slowly increased over a number of years and become particularly significant when there has been a year with poor ground cover. Case studies with individual landholders reported a reduced livestock carrying capacity of between 15% and 50%, depending on the length and extent of infestation and also the management regime implemented.

Fireweed was conservatively estimated to be able to reduce the output of broadacre, low input grazing systems in the South Coast region of New South Wales by 20%. Based on the value of production of these systems (Australian Bureau of Statistics Farm Survey 2001), this represents over $8 million in agricultural production annually (Madden 2008). In addition, there was a broad range of social impacts resulting from fireweed infestation including conflict between landholders; emotional problems experienced by those managing fireweed; viability and succession issues for farm families; long term impacts on land values and perceptions; concern for human and livestock health; and issues associated with the State and Local government (Madden 2008).

The following is a quote from a Bega Valley beef farmer. *"Fireweed is worse than any drought. Fireweed cannot be effectively or economically controlled using the current available methods. Without biological control to help in the battle against this aggressive intruder, how can a dedicated farmer sit back and watch the property he has devoted his entire working life to become totally destroyed, with no hope of recovery, without experiencing major depression and associated problems. You cannot imagine the heart break of walking through paddocks yellow with the toxic weed knowing that if your livestock eat it, they will be poisoned; knowing that your ability to earn a living for your family has been taken away; knowing that the land you love (in good times and bad) has been contaminated with this cancer that is outside your ability to control. The asset that you have built up over a lifetime's work has become worthless. Try selling land infested with fireweed. Not a day goes by in our household that fireweed is not mentioned repeatedly. There is no future for a 5th generation of our family on the land unless major inroads are made quickly into viable control and possible eradication of fireweed"* (BVFA 2008). Such comments convey the depth of mental health implications of the continuing spread of fireweed.

Toxicity

To livestock While both native *Senecio* (Bennetts 1935, Noble *et al.* 1994) and *S. madagascariensis* (then known as *S. lautus*) (Green 1953, Whittet 1958) had been incriminated

in the poisoning of grazing animals in Australia for many years, mortalities and poor growth of cattle in the Hunter Valley of New South Wales in 1981 confirmed the toxicity of fireweed (Walker and Kirkland 1981). Likewise, fireweed fed to three calves in a controlled experiment, caused the death of two within 77 days and depressed growth rate in the third. These findings were augmented with a study of a substantial field mortality of cattle in the Bulahdelah district on the Central Coast of New South Wales (Kirkland *et al.* 1982) which, on the basis of the autopsy results, histopathology and consumption of fireweed, was found to be caused by fireweed toxicity. Autopsy and subsequent laboratory tests on the south coast of New South Wales have also confirmed deaths of beef cattle consistent with fireweed poisoning (BVFA 2008).

Like many *Senecio* species, fireweed contains pyrrolizidine alkaloids (PAs), in the case of fireweed up to at least 12 (Gardner *et al.* 2006), including senecionine (Culvenor unpublished data, cited by Bull *et al.* 1968, McBarron 1976) which, when ingested by livestock, accumulate and damage the liver so as to reduce growth and, in severe cases, cause death, despite being at apparently relatively moderate concentrations in Australia (0.02 to 0.03% w/w total alkaloids) (Walker and Kirkland 1981, Colegate 2008). In Hawaii, the average total PA content varied from a low of 0.02% to nearly 0.2% (217 μg/g to a high of 1990 μg/g) on a dry weight basis among the locations sampled. Variation in alkaloid content also varied greatly between individual plants, ranging from virtually no PA content to 0.7% (Gardner *et al.* 2006). The disease is progressive; symptoms and deaths of animals commonly occur weeks or months after consumption of the plant has ceased (Bull 1955, Molyneux *et al.* 1988). There is evidence to indicate that fireweed contains higher levels of alkaloids when young (Colegate 2008), which is when cattle are more likely to consume the weed, not being able to differentiate the weed from other pasture or selectively avoid its intake.

The clinical signs of fireweed poisoning are diverse. Weakness, marked loss of condition, and emaciation with recumbency and death were observed by Walker and Kirkland (1981) to be most prominent. However, the most common effect attributed to fireweed in cattle is ill-thrift and poor growth in young stock. Varying degrees of chronic, but not fatal, damage are seen in animals from the central coast of New South Wales (Watson *et al.* 1984) and it is the low-level, sub-clinical exposures that can lead to the major losses in productivity including poor feed utilisation, reduced weight gains, reduced milk yields and adverse effects on reproduction and breeding (Colegate 2008).

Movement of stock to areas free of fireweed may prevent further development of the disease, but because this form of liver damage is irreversible (Bull *et al.* 1968), the syndrome of ill-thrift and poor growth may continue. Sheep and goats are generally less susceptible to fireweed poisoning than cattle and horses (Bull 1955, Dollahite 1972), though PAs may exacerbate copper poisoning to which sheep in particular are highly susceptible (Colegate 2008). Fireweed may therefore cause more poisoning problems on soils where copper levels are relatively high.

Pyrrolizidine alkaloids are in a group of chemicals known as genotoxic carcinogens. In addition to causing liver damage, they may cause cancer, mutations, fetal abnormalities, and lung changes, leading to right heart congestive failure (Edgar 2008).

Conflicting opinions as to the risk to livestock grazing infested pastures arise from the fact that fireweed is generally unpalatable to cattle and horses, possibly due to the bitter flavour of its alkaloids (Arnold 1966). Where its ingestion cannot be avoided, such as in pastures heavily infested with young plants, poor quality pastures and in contaminated hay and silage, poisoning is more likely to occur. Poisoning from prepared feeds is of

particular concern given that the alkaloids may remain present when the plant is dried (Colegate 2008) and 24% of all graziers in a 1985 survey found fireweed in pasture or crops used for hay or silage (Sindel and Michael 1988). Because cultivation more often than not stimulates germination of fireweed (Sindel 1986), land used for fodder crops can easily become infested. Nevertheless, despite its toxic potential, the level of *acute* stock poisoning from fireweed is apparently low (Sindel and Michael 1988). However, few autopsies are carried out on individual stock deaths, and so it is difficult to obtain accurate numbers of livestock poisonings. This is an area that also requires further investigation, but again should not delay research on potential biological control solutions.

To humans Pyrrolizidine alkaloids can pose a health risk for humans when included in dietary products (Edgar 2008), and in Australia, the Food Standards Australia New Zealand (2001) has set a recommended limit of exposure of 1 microgram per kilogram bodyweight per day based on the prevention of hepatic veno-occlusive disease (Colegate 2008). While humans have been exposed to direct consumption of PAs through grains, cooking spices and medicinal herbs prepared or contaminated with PA-producing plants, the potential for exposure to PAs (and their *N*-oxides) also exists *via* honey and bee products (Edgar *et al.* 2001; Beales *et al.* 2004; Betteridge *et al.* 2005; Boppré *et al.* 2005), milk (James *et al.* 1994), eggs (Edgar and Smith 2000), and meat (Seawright 1994).

According to Colegate (2008), who recently assessed fireweed toxicity issues, and analysed and detected PAs in fireweed plants and honey from the Bega Valley of southern New South Wales, "*animal-derived food for humans, especially bee-products and honey produced by bees foraging on fireweed, require monitoring for the presence of fireweed pyrrolizidine alkaloids*". Locally-produced and consumed honey and pollen products should be specifically monitored because of the potential for higher exposures to PAs (Edgar 2008). On the other hand, the New South Wales Noxious Weeds Advisory Committee indicated in a review of fireweed that the New South Wales Food Authority is of the opinion that the amounts of PAs present in milk are too low to present a risk to public health and that the practice of bulking milk lessens any potential impact (Kidd 2008).

Legislation

Some serious weeds are required by law to be controlled by all landholders in an area. These are known as noxious or declared weeds.

In New South Wales, the law that controls these noxious weeds is the Noxious Weeds Act 1993. Although fireweed was declared a noxious weed in certain shires of New South Wales from 1946 to 1971 (Martin and Colman 1977), it is now generally considered that eradication and prevention of spread within an area once it is established are not feasible. Nevertheless, it remains a Class 4 declared noxious weed in 18 local control authority (LCA) areas, whereby the growth and spread of the plant must be controlled according to the measures specified in a management plan published by the LCA (NSW DPI 2005). Fireweed is declared only in three LCAs north of Sydney. In each of these areas where fireweed is declared, plans focus on requiring landholders to take steps to limit the spread of fireweed and to reduce its incidence. In practice it appears that, their Class 4 management plans are not enforced in those parts of the LCAs where fireweed is well established. On the south coast, fireweed is declared in the Shoalhaven City Council, Eurobodalla Shire and Bega Valley Shire Council areas. All three south coast LCAs where fireweed is declared have adopted a zonal approach (Kidd 2008).

In Queensland, fireweed is a declared Class 2 plant under the *Land Protection (Pest and Stock Route Management) Act 2002*. A Class 2 pest is one that has already spread over substantial areas of Queensland, but its impact is so serious that control should be attempted to avoid further spread onto properties that are still free of the pest. By law, all landholders must try to keep their land free of Class 2 pests and it is an offence to keep or sell these pests without a permit (Anon 2008).

In Victoria, fireweed is listed as an 'Alert Weed', a potential weed of the future. Victorian Alert Weeds are considered to "*pose a serious threat to Victoria's agricultural and natural assets*" or "*affect human health*" (Plant and Roberton 2008).

Fireweed management

Despite the importance of fireweed, very little work has been done on its management, and that has been mostly confined to work with herbicides, the elucidation of the principles of control, and preliminary studies on biological control. After undertaking a socio-economic study of the impact of fireweed on the south coast of New South Wales (Madden 2008), Hassall & Associates concluded that in developing a strategy for better control of fireweed, the following principles should be applied:

- the range of control options should be suitable for all landholders and industries;
- consideration should be given to landholders who do not rely on agriculture for income;
- it is important to examine possibilities for integrated control;
- consideration of the social circumstances facing the farming population need to be incorporated into the strategy; and
- the strategy should explore options on a regional or national scale for control.

Herbicides

The optimum time for herbicide application is during the small seedling to early flowering stages (normally autumn to winter) (Tracanna *et al.* 1983, Watson *et al.* 1984). Herbicides, such as glyphosate and bromoxynil, although not applied very extensively, can be very effective (Table 1).

Table 1 Use and success of control methods for fireweed. Results are a percentage of survey respondents; data amended from Sindel and Michael (1988).

Method	Use (%)[A]	Success (%)[B]		
		Low	Moderate	High
Hand weeding	74	37	29	34
Mowing	68	41	46	13
Cultivation	19	33	54	13
Herbicides	12	22	37	41
Sheep or goats	5	11	22	67
Competitive pastures	35	21	37	42

[A] As a proportion of respondents who attempted control.
[B] As a proportion of respondents who attempted control by that method.

Bromoxynil is very effective on young plants at a rate of 280 g a.i. (active ingredient) ha^{-1}, but when applied to advanced plants, the percentage kill dropped to less than 55% (T.E. Launders, personal communication). It was concluded that after bud formation, between 500 and 560 g a.i. ha^{-1} were needed. In trials with ropewick applicators on fireweed, both bromoxynil at 200 g a.i. L^{-1}, and glyphosate at 100 g a.i. L^{-1} proved effective against young plants. Glyphosate was needed to ensure a good kill after flowering (Launders 1984a). Two passes of the applicator using glyphosate gave a 94% kill of flowering plants compared with 69% with only one pass (Launders 1984b). Preliminary tests indicate that both herbicides reduce the germination of fireweed seed when sprayed on plants at the late flowering stage, with glyphosate being the more effective of the two. Bromoxynil has the advantage of being a selective herbicide, whereby most desirable pasture species are not damaged. However, legumes can be damaged when bromoxynil is applied at above 20°C (Kidd 2008). Glyphosate, on the other hand, is a non-selective herbicide, and will kill most other desirable pasture species with which it comes in contact. Bromoxynil is therefore the herbicide of choice.

Because of the periodic flushes of fireweed germination during autumn and spring, and the emergence of small numbers of plants throughout most of the year, spraying only once during the season is unlikely to be effective. This problem lead Johnston (2007) to suggest that research was needed to better determine optimal spraying times. But because pastures that initially proved suitable for invasion by fireweed are likely to suffer the same fate again, herbicide control should be carried out in conjunction with more sustainable longer term control measures such as pasture management and biological control.

Also, in the near future it is possible that the Australian Pesticides and Veterinary Medicines Authority (APVMA) will impose greater restrictions on the use of bromoxynil in pastures to reduce the likelihood of residue contamination of food products for export and domestic human consumption (APVMA 2008). Longer harvest intervals after spraying and the imposition of buffer zones to reduce contamination due to spray drift could severely impair the ability of farmers in coastal areas with relatively small property sizes to control fireweed with this herbicide. With few other herbicide options currently available, it will be even more imperative that biological control options be fully explored.

Pasture management

The essential principle of any fireweed control program must be maintenance of a vigorous, competitive pasture (Launders 1986). Any factors which open up pastures, such as overgrazing, drought, uncompetitive pasture species, and areas bared by trampling e.g. around watering or feeding places, appear to favour the development of fireweed. On the other hand, farmers have found that the maintenance of competitive perennial pastures offers some level of success (Table 1).

Vigorous pasture growth may prevent substantial emergence of fireweed despite favourable climatic conditions for germination (Sindel and Michael 1996). Given that its seeds are positively photoblastic (Guillén *et al.* 1984), it is not surprising that fireweed appears to exploit open spaces in pastures. A dense pasture during early autumn to winter and spring is likely to provide the best form of control. This may be achieved by growing early winter pasture species, by allowing standover of summer pasture feed, or by using winter-summer pasture combinations (Watson *et al.* 1984). These options are particularly relevant since fireweed is of greatest abundance in naturalized summer-growing pastures such as paspalum/carpet grass dominant pastures on the central and north coasts of New

South Wales (Martin and Colman 1977, Launders 1979). Drought, low productivity and high relative stocking rates in the winter months can predispose them to invasion.

Due to the need for continuity of feed, particularly on dairy farms, new pasture species may need to be drilled directly into the existing pasture rather than using conventional cultivation before sowing. Possible winter species include phalaris (*Phalaris aqatica* L.), ryegrass (*Lolium* spp.), fescue (*Festuca arundinacea* Schreber), white clover, subterranean clover (*Trifolium subterraneum* L.) and oats (*Avena* spp.), while summer species such as kikuyu, paspalum, setaria (*Setaria sphacelata* (Schum.) Stapf & C.E. Hubb.) and Rhodes grass (*Chloris gayana* Kunth) have potential. Even under heavy grazing, kikuyu dominance can markedly reduce fireweed density (Martin and Colman 1977). Kikuyu has a longer period of active growth in autumn than either carpet grass or paspalum and can produce more dry matter (Colman 1970). It therefore competes more strongly with regenerating seedlings of fireweed and is considered by graziers to be the best competitor (Sindel and Michael 1988). However, because fireweed germinates in both autumn and spring (Figure 10), it cannot be readily avoided in the establishment of new competitive pasture species and so it is likely that a selective herbicide such as bromoxynil will need to be applied soon after pasture establishment in order to kill the large number of fireweed seedlings emerging with the pasture (Sindel 1989).

Careful fertilizer management is also likely to be a critical tool in fireweed control (Nelson 1980). The application of fertilizer during the active growth period of the grasses could increase their yield, and therefore decrease the density of fireweed. Italian ryegrass (*Lolium multiflorum* Lam.) cv. Concord showed good potential to suppress the growth of fireweed under these conditions (Sindel and Michael 1990). However, if application occurs when a pasture is unable to respond, for example in autumn when the summer-growing species have ceased active growth, then fireweed growth may be favoured, particularly in view of the stimulatory effect of nitrates on fireweed germination (Alonso *et al.* 1982) and on development and flowering of established plants (Sindel and Michael 1992b, 1996).

Planting of improved pasture species without appropriate long term management may be of little use in suppression of fireweed. Although pasture species such as kikuyu, white clover and paspalum are thought to be good competitors (Sindel and Michael 1988) these species were also more commonly associated with high rather than low fireweed abundance (Radford *et al.* 1995a). In contrast, ryegrass, speargrass, phalaris and native pastures were more often associated with low or zero fireweed abundance. These results indicate that improved pasture species require optimal conditions for them to be effective competitors of fireweed and that without appropriate management they may encourage increased fireweed infestation (Radford *et al.* 1995a). Maintenance of optimal conditions for competitive pastures is made difficult by drought, and may become more of a problem in future under various climate change scenarios.

Grazing

Heavy grazing with cattle is not an effective control method because most fireweed seedlings utilize the improved light environment to quickly grow above the pasture canopy. Once plants are distinguishable from the pasture they are usually avoided by cattle. In contrast, low stocking rates or no grazing at peak emergence times (especially during autumn and spring) can allow pasture to compete more vigorously with fireweed and effect some control (Fernández and Montes 1984, Launders 1985).

Experience shows that grazing with sheep or goats may be of some use in fireweed control (Watson *et al.* 1984) since they readily eat fireweed and are some 10-20 times less susceptible to poisoning than cattle and horses (Bull 1955, Dollahite 1972). Grazing with sheep or goats, however, is not without difficulties, including an increased incidence of parasites and diseases, and the need for improved fencing (Campbell *et al.* 1979). Also, although relatively resistant, they are not totally resistant to the effects of pyrrolizidine alkaloids. Only a very small proportion of farmers utilize their potential despite a high success rate (Table 1), presumably due to the difficulties of running sheep and goats in coastal pastures. Nevertheless, in a recent industry report on fireweed management to Meat and Livestock Australia, Johnston (2007) considered that research into using goats or sheep for fireweed control was worth pursuing.

Hand weeding

Fireweed is rare amongst weeds in Australia in that hand weeding is widely practised (Table 1), due to its occurrence on relatively small coastal farms and in densely populated areas (Sindel 1996). Hand weeding has not met with overwhelming success.

Mowing

The success achieved with mowing throughout the autumn to spring period has also been somewhat variable (Table 1). In trials near Taree, close mowing did not kill fireweed plants but only slowed their growth and delayed flowering. Because mowing may promote regrowth (Verona *et al.* 1982), some fireweed plants survive through summer and continue to grow and flower in the second year.

Nevertheless, regular mowing can assist in control over small areas. Fernández (unpublished data) obtained a 20% reduction in plant survival with one cut at either 5 or 10 cm and 70% reduction with two successive cuts at 10 cm 2 months apart. The plants surviving after one cut at these heights, however, increased their specific growth rate by 40-50%. Mowing when conditions are unfavourable for pasture growth, or in young and unthrifty pastures, should be avoided since the weed may recover more quickly than the pasture and therefore become dominant.

Cultivation

Because fireweed does not germinate well in the dark (Nelson 1980), burial of the seed might reduce plant populations and aid control. To test this hypothesis, Daniel (1984) used a mouldboard plough to invert the soil. Rather than decreasing fireweed density, it increased. Cultivation of pastures in order to establish improved species has also been observed to increase the density of fireweed (Launders 1979, Sindel 1989). Perhaps because of its stimulatory effect, graziers do not use cultivation widely as a means of control (Table 1). In cropping situations, similar to that which occur in Argentina (Fernández and Montes 1984), control of fireweed by cultivation is likely to be much more beneficial.

Natural enemies

In excess of 100 species of insects have been found on fireweed in Australia (Holtkamp and Hosking 1996). The most common of these are a leaf feeding beetle, *Chalcolampra* sp. (Coleoptera: Chrysomelidae); two seed head feeding bugs, *Nysius clevelandensis* Evans and *Nysius vinitor* Bergroth (Hemiptera: Lygaeidae) and three moths, two being leaf feeders, the magpie moth, *Nyctemera amica* (White) (Lepidoptera: Arctiidae) and light brown apple moth,

Epiphyas postvittana (Walker) (Lepidoptera: Tortricidae) and one, the blue stem borer, *Patagoniodes farinaria* (Turner) (Lepidoptera: Pyralidae) which ringbarks stems. The larvae of *Chalcolampra* sp. and *N. amica* can cause significant defoliation of fireweed plants in some districts in some years. This defoliation may weaken and kill some plants but does not exert any significant control. Larvae of *P. farinaria* kill many plants every year, especially on the north coast of New South Wales, but do not significantly reduce fireweed numbers in these areas. Interestingly, *P. farinaria* has also been recorded causing significant damage to the introduced species *Senecio jacobaea* L. (ragwort) in Tasmania (Ireson and McQuillan 1984) and New Zealand (Common 1990).

A stem mining fly, *Melanagromyza seneciophila* Spencer (Diptera: Agromyzidae); a leaf mining fly, *Chromatomyia syngenesiae* Hardy (Diptera: Agromyzidae) and two species of gall forming flies, *Sphenella ruficeps* (Macquart) (Diptera: Tephritidae) which forms galls in flower heads and *Trupanea prolata* Hardy and Drew (Diptera: Tephritidae) which forms galls in stems and flower heads, are also commonly found on fireweed. Most of the above insects are specific to *Senecio* spp. although some, such as *E. postvittana* and the two *Nysius* spp., feed on a wide range of species in a number of families, while *C. syngenesiae* feeds on a number of species within the family Asteraceae (Spencer 1977). More than 40 species of Hymenoptera have also been found. Their role is unclear but many are probably parasitoids of other insects found, although some may form galls. Various pasture slugs are also known to feed on the plant (Watson *et al.* 1984).

Three rusts occur on fireweed in the field, the most common of which is the autoecious rust fungus *Puccinia lagenophorae.* It can cause considerable growth retardation on heavily infected plants, but like other plant diseases, the severity and spread of this rust on fireweed is dependent on prevailing weather conditions. The rust, thought to be native to Australia and New Zealand, was discovered here as early as 1884 (Wilson *et al.* 1965). It has both telia and aecia but no pycnia. The telia and aecia, when found on the leaves and stems of plants, are dark brown to black and pale yellow to orange respectively. The rust attacks a range of plants in the family Asteraceae including many garden plants, for example calendula or English marigold (*Calendula officinalis* L.), English daisy (*Bellis perennis* L.) and garden cineraria (*Senecio cruentus* DC.) (Wilson *et al.* 1965). Although inoculation with *P. lagenophorae* is likely to reduce the competitive ability of fireweed and its impact on the yield of pastures, the practical problems of large scale culture of rusts for the present, limit their potential value in inundative biological control. A grey mould fungus (Watson *et al.* 1984) and the white rust *Albugo tragopogonis* (DC.) S.F. Gray (Holtkamp and Hosking 1993) also infect fireweed.

In Argentina, during its vegetative stages of growth, *S. madagascariensis* is frequently attacked by ants, principally *Acromyrmex lundi* Guer. (Verona *et al.* 1982). These eat the leaves and vegetative shoots and in the more advanced plants feed on the beginnings of the inflorescences. Another insect, still unidentified, feeds on the ovaries, reducing their growth and the reproductive capacity of the weed. In young branches, fly larvae (*Lamproxynella* sp.) cause the formation of galls. A pseudococcid has also been observed in the roots. In greenhouse-grown plants the aphid *Myzus persicae* (Sulz.) has been found to feed on the leaves. In gardens, young plants are eaten by the snail *Helix aspera* (Mull.).

Biological control

Whilst the relative impact of natural enemies of fireweed in Australia is unknown, the confirmation of taxonomic differentiation between *S. madagascariensis* and *S. pinnatifolius* (then known as *S. lautus,* Michael 1981) opened up the possibility of classical biological

control. However, the fact that the native insects do not appear to discriminate between these two species suggests that imported biological control agents may show a similar lack of discrimination (Holtkamp and Hosking 1993) but this has not been tested.

Only three agents have been host-tested against fireweed – two moths from Madagascar and one rust fungus from South Africa. Surveys conducted in Madagascar by the Queensland Department of Lands (Marohasy 1989) found 14 potential biological control agents. Two of the most damaging of these - a flower-head feeding pyralid moth (*Phycitoides* sp.) and a tip- and stem-boring tortricid moth (*Lobesia* sp.) - were imported by researchers at the Alan Fletcher Research Station and tested for host specificity. Both insects were found to have unacceptably wide host ranges in large-cage choice experiments. The agents caused severe damage to *S. pinnatifolius*, other *Senecio* spp., and, in the case of *Lobesia* sp., to plants from other genera, i.e. *Crassocephalum crepidioides* (Benth.) S. Moore and *Erechthites* sp. (McFadyen and Sparks 1996).

This lack of discrimination between *S. madagascariensis* and *S. pinnatifolius* by both native and introduced predators, plus temporal and spatial coincidence of the host plants in eastern Australia (Radford 1997a), means that there may be several hurdles to be overcome before such insect biological control agents for fireweed could be released. The arguments for further research on this type of biological control are discussed later in this report. It has now been discovered that the fireweed in Australia is unlikely to have originated from Madagascar but rather southern Africa It is important, therefore, that future collections of potential agents be concentrated in the KwaZulu-Natal province of South Africa, where plants most closely related to Australian fireweed are found (Radford 1997b, Scott *et al.* 1998) to improve the likelihood of collecting host-specific control agents (Marohasy 1993, Radford *et al.* 1995b, McFadyen and Sparks 1996).

The third agent to be tested for host specificity by CSIRO with funding assistance from the Shoalhaven City Council was a *Puccinia* rust fungus from South Africa. While the rust could not be fully identified within the constraints of the project, it is possible that it was a strain of the *Puccinia lagenophorae* rust already commonly found on fireweed in Australia. This rust did not attack the native *S. pinnatifolius* (named as *S. lautus*) tested. "*The accession of* S. lautus *used in these tests was found to be immune to all South African and Australian rust isolates investigated. Whilst this is encouraging news with regards to the specificity of the South African rust isolates, these results highlight that the South African and Australian rust fungi probably consist of a numbers of races or forms that are specialised on different hosts.*" (Morin 2003). However, the rust appeared no more virulent than the strains of the same rust already common in Australia, therefore no further work on that strain was done. This work by CSIRO only looked at one species of rust and no other potential biocontrol agents were considered from this region. No detailed study has therefore been undertaken of all potential biocontrol agents (insects, mites and fungi) found attacking *S. madagascariensis* in the KwaZulu-Natal and adjacent areas of southern Africa (McFadyen, personal communication).

What Research is Underway?

At the time of writing of this report, the author is only aware of one research project currently being undertaken on fireweed in Australia, that being a PhD and Australian Research Council project by Dormontt and Lowe at the University of Adelaide on the evolutionary invasion consequences of hybridisation between *S. madagascariensis* and *S. pinnatifolius* (Dormontt 2008). This work will help more accurately identify the possible source origin in Southern Africa of Australian fireweed, assess the rate and role of hybridisation of the invasive weed with the closely related native species and whether admixture has occurred whereby hybridisation has occurred between disparate source populations of *S. madagascariensis* introduced at different times into Australia. While of considerable scientific interest in understanding the processes and consequences of invasion, this project has no direct benefits to landholders in their attempts to control fireweed.

It has been suggested that Dormontt may also consider assessing possible herbicide resistance in fireweed in Australia given her extensive collections of fireweed seed from along the east coast of Australia.

Various State departments have extension programs aimed at fireweed, most notably the appointment of a fireweed project officer in the Bega region of New South Wales (Blackmore, personal communication), but these do not apparently involve major research components. The CRC for Australian Weed Management was considering a biological control program for fireweed but because of the CRC's demise in mid 2008, this program did not go ahead.

What Research is Needed?

Biological control

Is fireweed just a management issue?

The fact that a dense pasture sward helps to reduce the establishment of fireweed seedlings, increase their rate of mortality, and reduce the vigour and seeding capacity of surviving plants, has led to the view in some quarters (particularly amongst government departmental staff) that fireweed is simply a 'management problem' with which individual farmers need to deal by growing better pastures.

However, this competitive effect of pastures is common to most weeds of pastures in Australia, many of which have been the subject of successful biological control programs, such as Paterson's curse (*Echium plantagineum*) and ragwort (*Senecio jacobaea*). The fact that vigorous perennial pastures provide long-term benefit in fireweed control does not negate the need for additional control methods such as biological control that form part of an integrated weed management program.

Also, many of the farmers who are trying to control fireweed do have good pastures in good seasons where there is ample and timely rainfall, but in times of drought, it is very difficult to maintain high pasture cover, and if neighbours have fireweed, then wind-borne seeds are likely to be blown in and reinfest the pastures. This causes much social conflict between neighbours and personal stress over the intractability of fireweed (Kidd 2008).

The herbicide bromoxynil is effective against fireweed, but because the weed can germinate at several times throughout the year, particularly in coastal environments, one spray application is usually insufficient to provide year-long control and sufficient plants progress through to maturity and set seed to continue the weed's invasive potential. Multiple applications of herbicide are costly, and also increase the likelihood of the development of herbicide resistance in fireweed. An application before the APVMA (APVMA 2008) may also lead to greater restrictions on the use of bromoxynil for fireweed control in pastures in the future.

Given the weed's continuing spread despite current control efforts by farmers and land managers and the continued drought conditions in many regions leading to low pasture cover (and the likelihood that this situation will increase with climate change) with few economical options available to many farmers, there is a case for again pursuing biological control. Biological control, if successful, is an environmentally friendly form of weed management and can penetrate all areas occupied by the weed, including sensitive areas of native vegetation that may otherwise be damaged by other forms of weed control.

Cost effectiveness of biocontrol

The cost effectiveness of biological control is undeniable. Page and Lacey (2006) from the AEC group on behalf of the CRC for Australian Weed Management examined the economic impact of Australian weed biological control. Overall, the benefit cost ratio (BCR) of past biological weed control programs in Australia has been 23.1. This implies that for every dollar invested in the weed biocontrol effort, a benefit of $23.10 is generated, comprising $17.40 for agriculture (control cost savings and increased production), $3.80 to society (health benefits), and $1.90 for Government (control cost savings).

In 1985, Sindel and Michael (1988) conducted a survey of 800 dairy farmers and graziers and were able to estimate that the costs to the dairy industry alone in NSW from

fireweed were 100,000 man hours plus $250,000 per annum. Based on these figures, Page and Lacey (2006) estimated the total costs of fireweed to farmers in Australia to be $5.4 million annually. However, to be conservative, Page and Lacey reduced this estimate by 50% to $2.7 million to take into account that the intensity of the fireweed problem varies from year to year depending on seasonal rainfall conditions.

Given the cost of fireweed to the Australian economy, a biological control program was initiated in 1989 and ran for 5 years up to 1994 at an estimated cost of $377,000 (Page and Lacey 2006). The fireweed biological control program focussed on Madagascar but did not result in the release of any biocontrol agents because preliminary investigations with promising *Phycitodes* sp. and *Lobesia* sp. moths from Madagascar showed that their host ranges were too wide and that native *Senecio* species may sustain damage if such insects were introduced (McFadyen and Sparks 1996). The fireweed biocontrol program therefore, did not result in any financial benefits. However, a cost benefit analysis (CBA) was conducted to demonstrate the level of benefits that needed to be achieved had biocontrol agents been released for the program to provide a positive return on investment. This CBA showed that the distribution of biocontrol would have only needed to be 2.1% to break even. This highlights the low level of benefits generally required by biocontrol programs generally and fireweed specifically in order to provide a positive return on investment. This is due to the low costs of these programs relative to the costs of the weed (Page and Lacey 2006). The Australian biological control program for the close relative of fireweed, ragwort (*S. jacobaea*), also a poisonous weed of pastures, resulted in a BCR of 32.4. The financial gains of a successful fireweed biological control program are therefore likely to be considerable.

Pinpointing the area of origin of fireweed

Since these early investigations into biological control of fireweed, it has been discovered that the ecotype of fireweed that occurs in Australia is not closely related to that which occurs in Madagascar, but is most similar to *S. madagascariensis* from the KwaZulu-Natal province in South Africa, an area in which there has been no comprehensive investigation of potential biological control agents for fireweed. All indications are that the species does not generally behave as a weed in this area (Figure 15), suggesting that ecological or biological factors such as pests or predators are acting to constrain populations of the species. This is the basis on which biological control agents may be introduced from the area of origin of a weed to the new invaded range.

Until potential biological control agents from this region have been adequately assessed there will always be a question as to whether biological control of fireweed is feasible in Australia and farmers will demand government action. The Australian Government has a unique opportunity now, with money allocated, to initiate this process.

Host specificity

One potential impediment to the introduction of biological control agents to Australia could be a lack of host specificity amongst agents given the number of closely related native *Senecio* species in Australia. However, Radford and colleagues at the University of Sydney, after researching the relationships between fireweed and several Australian native *Senecio* species, concluded that the release of biocontrol agents for fireweed would cause little damage to the apparently most similar native *S. pinnatifolius* complex in most areas.

A.

B.

C.

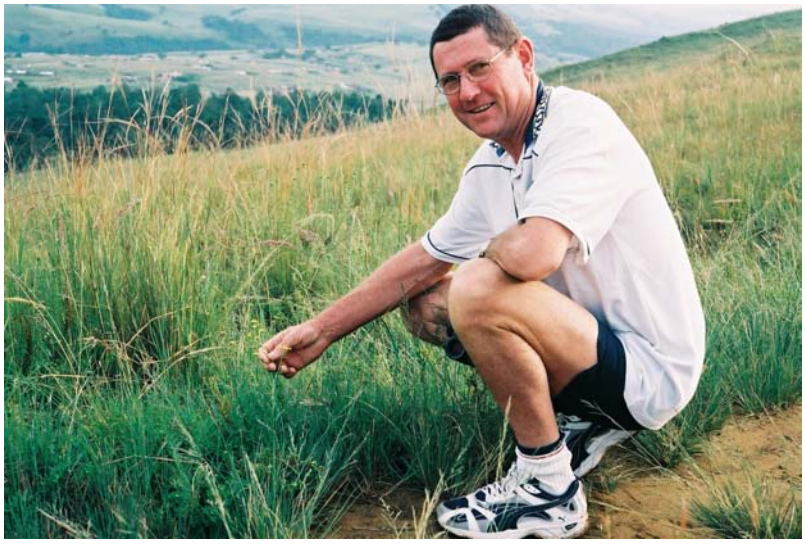

Figure 15 Senecio madagascariensis *in its native range near an African farm house A. circled, B. in the KwaZulu-Natal province of South Africa, and C. next to a track in open grazed grassland.*

According to the Dairy Research and Development Corporation, who funded Radford's work, Radford and colleagues argue that "S. pinnatifolius *[then described as S. lautus] occurs predominantly in small, scattered populations throughout Australia, slowing the spread of [biological] control agents, and reducing the numbers of predators that can be supported."* Some damage could occur to coastal populations in headland, dune and range environments. *However,* 'S. pinnatifolius *populations are active for shorter periods each year and less regularly between seasons than fireweed, again reducing the number of insects that could be supported by* S. pinnatifolius. *The large number of seeds in the soil, combined with their longevity and dormancy, mean that* S. pinnatifolius *could survive short-term or localised high-intensity insect attack. Sexual reproduction and high genetic diversity in* S. pinnatifolius *would also reduce the likelihood of severe damage. Diverse habitats and microclimates would also make S. pinnatifolius more difficult for introduced insects to find, and for them to persist. The very low number of hybrids at field sites means that hybrids are not likely to have an important role in the spread of biocontrol agents from fireweed to* S. pinnatifolius.*"* Radford and colleagues also note that even for target species, biological control does not lead to extinction, only reduction in populations (Anon. 1996).

The fact that the native and toxic *S. brigalowensis* (Thompson 2005) exploded throughout central Queensland pastures in 2007 (McFadyen, personal observations), indicates that it too can behave in a weedy fashion in favourable seasons (Figure 16) and may not be unreasonably disadvantaged by the release of any biological control agent for fireweed. Equally, there is some evidence to suggest that fireweed invasion progressively displaces the native *S. pinnatifolius* (McFadyen and Lowe, personal communications), and that left uncontrolled, fireweed will do more harm to the native *Senecio* species than what a biological control agent would do that was not absolutely specific to *S. madagascariensis*.

Alternatively, rust fungi are likely to be more specific to *S. madagascariensis* than insects and therefore be more acceptable for biocontrol (Morin 2003). For biological control agents that are not absolutely specific to *S. madagascariensis*, a CBA is required to weigh up the advantages and disadvantages of the release of such organisms. Other biocontrol programs have succeeded despite the presence of Australian native species in the same genus, e.g. *Rumex* species, *Acacia nilotica*, and the related *S. jacobaeae* (ragwort).

Figure 16 *Native* Senecio brigalowensis *behaving as a weed in central Queensland in 2007 (courtesy of* R. McFadyen*).*

Potential collaboration

Fireweed is also now known to occur in Japan, Hawaii and Uruguay, as well as Argentina, and this co-occurrence, with similarities in region of origin for Australian and Hawaii at least (Le Roux *et al.* 2006), may well provide opportunities for collaboration in any biological control program. The arctiid moth (*Secusio extensa*) collected from "fireweed" in Madagascar has been tested in Hawaii on five species, including a *Senecio*. However, the moth was not specific enough – and would not be suitable for release in Australia where there are a number of native *Senecio* species. Hawaiian researchers are planning further agent selection activities (Sheppard and McFadyen 2008), and like Australian researchers have now discovered that their fireweed is unlikely to have originated in Madagascar.

The identification of the probable region of origin of Australian and Hawaiian fireweed in the KwaZulu-Natal province of South Africa and its general lack of weediness there, gives both direction for where to search for prospective biological control agents and some hope for finding agents that could suppress fireweed's growth in Australia.

First stage

The first stage of a biocontrol program would therefore be a detailed study, through at least 1 year, of all potential biocontrol agents (insects, mites and fungi) found attacking *S. madagascariensis* in the KwaZulu-Natal and adjacent areas of southern Africa. McFadyen (personal communication) has suggested that such a study would result in a list of potential agents, from which between five and ten (depending on resources) could be selected for detailed testing to establish 1) virulence on the Australian fireweed *S. madagascariensis*; and 2) levels of attack if any on native Australian *Senecio* species. If there was no damage to native species, then introduction and release of agents would be straightforward. If damage to one or more native species was likely, then a CBA would be required, assessing levels of damage (both environmental and economic) caused by the introduced fireweed versus the likely environmental damage that would be caused by the introduced agent. If well resourced, such a biocontrol program against fireweed could have a reasonable chance of success.

Having recently assessed the pros and cons of further biological control work on fireweed in Australia, Sheppard and McFadyen (2008) concluded that biological control is potentially a long-term option for control of fireweed as part of an integrated management approach.

Recommendation 1 - Investigate biocontrol agents in Southern Africa.

It is a misconception to think that all biological control avenues have been explored for fireweed. It is recommended that the NWRC immediately invest $200,000 to investigate the potential of biological control agents from the KwaZulu-Natal province and surrounding areas in South Africa for control of fireweed in Australia. If there are agents that show potential for biocontrol, then the Federal Government will only then be required to allocate additional funds for further agent evaluation, importation and release.

Recommendation 2 - Investigate ecology of fireweed in Southern Africa.

It is recommended that the NWRC co-invest with South African agencies in the ecology of fireweed in Southern Africa to determine the factors limiting the weediness of the species in its native range. This will help guide with the selection of biological control agents for Australia and provide information by which management in Australia can be used to suppress the weed here.

Ecology

There have been no definitive studies in Australia on the longevity of fireweed seed in the soil. This is critical information for farmers to know how long they must prevent seeding of fireweed on their properties in order to be able to exhaust the weed seed bank. Likewise, seedling emergence dynamics with and without control measures need to be ascertained more fully to be able to better time pasture and grazing activities and herbicide applications aimed at managing fireweed.

In regard to the future spread of fireweed, work is also required on the relative lifecycles and invasiveness of fireweed on tableland areas of eastern Australia compared with that in coastal pastures.

Recommendation 3 - Investigate aspects of the ecology of fireweed in Australia.

It is recommended that the NWRC invest $100,000 for a 3 year PhD study to investigate several aspects of the ecology of fireweed in Australia necessary for better management of the weed i.e. the longevity and emergence of fireweed seeds in the soil with and without control measures and across varying environmental conditions. Invasive characteristics should also be compared along transects from coastal to tableland areas. Similarly, the conditions leading to 'fireweed years' need to be more clearly elucidated.

Impact

The resources devoted to control of any weed should be commensurate with the current and potential future impact of that weed. While at a national level we know that fireweed currently has a direct impact on the farming community of several million dollars annually (Page and Lacey 2006), which warrants continued work on control, many impacts have not been fully quantified, such as those on livestock health and future costs due to increasing spread. Quantifying the impacts of fireweed on pasture production and pasture availability to livestock at an individual farm level would not only assist farmers in making decisions about fireweed control at different weed densities, but serve as a powerful extension tool.

Recommendation 4 - Investigate impact of fireweed on pasture production and pasture availability.

Within the above PhD project, the student could also assess the impact of fireweed on pasture production and availability, which has been attempted previously but due to drought conditions proven inconclusive.

While fireweed is known to contain toxic pyrrolizidine alkaloids (PAs), which may be more highly concentrated in young plants (Colegate 2008) when stock are more likely to consume the weed, and that the weed has been the cause of deaths in livestock, and that PAs can get into the human food chain, for example, through honey production from plants containing PAs, we do not yet have reliable data on how regularly livestock are consuming fireweed and under what conditions, and on whether PAs are getting into dairy and beef products from livestock consumption of fireweed or into bee products in Australia.

Recommendation 5 - Investigate consumption rates of fireweed.

Within the same PhD, the student could assess consumption rates of fireweed by different livestock types at a range of infestation levels in pastures and under different grazing management scenarios.

Recommendation 6 - Investigate presence of PAs in animal products.

Work to investigate the PAs in animal products, particularly bee products and honey produced by bees foraging on fireweed is needed, but would need to be the subject of additional funding to the $300,000 allocated for fireweed research to the NWRC initially.

Better management

While pasture competition must remain the centrepiece of a long-term integrated fireweed control program, particularly at times of the year when fireweed is germinating (hence the need for Recommendation 3), farmer surveys show that incorporation of sheep or goats into a grazing herd can dramatically reduce the presence of fireweed within pastures. Such an arrangement may be difficult to achieve in some situations in coastal pastures where there are considerable structural and infrastructure barriers to adoption (Johnston 2007), but if fireweed continues to spread to Tableland areas then sheep and goats may have a greater part to play in fireweed management.

Edgar (2008) provided a though-provoking preliminary assessment of a way to change the rumen microflora in cattle to enhance the ability of ruminants, such as sheep and goats, to destroy PAs and ideally to make some ruminants completely resistant to PAs. While the primary motivation for research to change rumen bacteria is likely to be the reduction of methane production by cattle (with climate change benefits), and therefore considered outside the scope and recommendations of this report, the benefits derived in fireweed control and reduction in poisoning could be significant. The relevant exerpt from Edgar's presentation is therefore reproduced in Appendix 3.

Recommendation 7 - Investigate management of fireweed with sheep or goats.

Research funded by industry should be undertaken looking at the potential for sheep and goats to control fireweed within mixed grazing herds. Important aspects to measure will be the resultant health of the pasture, weed densities and sheep and goat health from both short and long term exposure to fireweed. Whether seeds are able to pass through the guts of sheep and goats in a viable condition will also need to be ascertained.

Farmers currently attempt to manage fireweed through combinations of hand-pulling, slashing, pasture management and herbicide use. Most of the research on management has been on the use of herbicides, though if bromoxynil becomes more restricted in its use, alternative chemistries may again need to be looked at. Given the repeated use of herbicides on many properties for fireweed control over many years, it is conceivable that herbicide resistance may develop in populations of fireweed that have a long history of herbicide use, particularly to the chemical bromoxynil, the most reliable and widely used herbicide for fireweed control. The first record of herbicide resistance in the world was of a species closely related to fireweed, common groundsel (*Senecio vulgaris*) in the USA after 7 years intensive use of simazine (Ryan 1970), and while weeds in annual cropping systems have developed herbicide resistance much more quickly, herbicide resistance has now been found in several weeds of pastures subjected to regular herbicide application, including nodding thistle (*Carduus nutans*) in New Zealand (Harrington 1990), and giant Parramatta grass (*Sporobolus fertilis*) (Ramasamy *et al.* 2008) and serrated tussock (*Nassella trichotoma*) (McLaren *et al.* 2008) in Australia.

Recommendation 8 - Investigate presence of herbicide resistance in fireweed.

It has been suggested that Dormontt, as part of her PhD undertake preliminary studies to screen fireweed populations for herbicide resistance to the herbicide bromoxynil, but it is not clear yet whether her work program will allow sufficient time for this activity.

On the second day of the National Conference on fireweed at Bega in May 2008, stakeholders came together in a workshop to explore potential options for management while further work is being undertaken on biological control. For a number of management options (e.g. pasture, chemical, mechanical) a number of groups raised the importance of improving our understanding of existing control methods, developing agreed "best practices" and encouraging the adoption of these practices by land managers. Though group discussions were focused on one control technique all groups stressed the importance of an integrated approach to managing fireweed. All groups identified the need for a range of organisations to continue to work together to improve our approaches to managing fireweed.

While refinement of management practices (such as timing and selection of herbicides), development of extension materials, and encouragement of adoption of best management practices are vital, it can be argued that these activities are best done at a state, regional and local level, as for example, has occurred with the recent appointment by New South Wales Department of Primary Industries of a fireweed project officer in the Bega region (Blackmore, personal communication). On the other hand, the limited initial funds for fireweed work of the NWRC ($300,000) should be channeled as seed money into the highest *research* priorities as per the above recommendations.

Conclusion

Weeds such as fireweed can create considerable consternation within communities, often because of their invasiveness and impact on the social and financial wellbeing of the landholders concerned, and the failure of management strategies to halt the invasion of the weed. Fireweed in Australia is one hot topic in this regard. An integrated approach to weed management requires utilization of a range of techniques. Given the continued spread of fireweed both in Australia and overseas, the prospect of climate change leading to further spread, its origin having been identified, possible future restrictions on the use of the herbicide bromoxynil on fireweed in Australia, the lack of a detailed study of potential biological control agents in southern Africa, and the allocation of funds by the Federal Government for this purpose, a search for possible biological control agents in the KwaZulu-Natal province and surrounding areas of South Africa should be the first priority for fireweed funding of the NWRC and initiated as a matter of urgency. Additional gaps in our understanding of the ecology, impact and management of fireweed, as highlighted in this report, should also be investigated.

Acknowledgments

This report was funded by the BVFA and relies heavily on two earlier papers by the author and his colleagues, Sindel *et al.* (1998) and Sindel *et al.* (2008a). My coauthors on these papers are gratefully acknowledged for their views and the information they provided – Dr Ian Radford (CSIRO), Dr Peter Michael (Sydney University), Royce Holtkamp (NSW Department of Primary Industries), Dr Rachel McFadyen (CRC for Australian Weed Management) and Janah Carthew (University of New England). I thank Dr Andy Sheppard (CSIRO) for his helpful input. Unless indicated otherwise, all photographs are those of the author.

Acronyms

ACIAR	Australian Centre for International Agricultural Research
APVMA	Australian Pesticides and Veterinary Medicines Authority
BCR	Benefit Cost Ratio
BVFA	Bega Valley Fireweed Association
CBA	Cost Benefit Analysis
CEO	Chief Executive Officer
CRC	Cooperative Research Centre
CRDC	Cotton Research and Development Corporation
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFF	Department of Agriculture, Forestry and Fisheries
DNA	Deoxyribonucleic acid
DPI	Department of Primary Industries
FSANZ	Food Standards Australia New Zealand
GMO	Genetically Modified Organism
GRDC	Grains Research and Development Corporation
LCA	Local Control Authority
LWA	Land and Water Australia
MLA	Meat and Livestock Australia
NHT	National Heritage Trust
NLP	National Landcare Program
NWRC	National Weeds Research Centre
PA	Pyrrolizidine Alkaloid
RIRDC	Rural Industries Research and Development Corporation
RSL	Returned Serviceman's League
SCG	Southern Councils Group
UNE	University of New England
USDA	United States Department of Agriculture

References

Ali, S.I. (1964a). *Senecio lautus* complex in Australia. I. Taxonomic considerations and discussion of some of the related taxa from New Zealand. *Australian Journal of Botany* 12, 282-91.

Ali, S.I. (1964b). *Senecio lautus* complex in Australia. II. Cultural studies of populations. *Australian Journal of Botany* 12, 292-316.

Ali, S.I. (1966). *Senecio lautus* complex in Australia. III. The genetic system. *Australian Journal of Botany* 14, 317-27.

Ali, S.I. (1968). *Senecio lautus* complex in Australia. IV. The biology of the complex. *Phyton (Horn, Austria)* 13, 53-62.

Ali, S.I. (1969). *Senecio lautus* complex in Australia. V. Taxonomic interpretations. *Australian Journal of Botany* 17, 161-76.

Alonso, S.I., Fernández, O.N., Langero, S.I., and Verona, C.A. (1982). Characteristics of seed germination of *Senecio madagascariensis* Poiret (Compositae) (In Spanish). *Ecología Argentina* 7, 95-116.

Anon. (1996). Little Damage Likely from Fireweed Control. Research Note 45. December 1996. Dairy Research and Development Corporation.

Anon. (2008). Declared Plants of Queensland. Fact Sheet. Queensland Department of Primary Industries and Fisheries, Land Protection (Invasive Plants and Animals).

APVMA (2008). Australian Pesticides and Veterinary Medicines Authority, Trade Advice Note on Bromoxynil in the product Nufarm Bromicide 200 Selective Herbicide (APVMA Product Number 31614) http://www.apvma.gov.au/registration/TAN.shtml (accessed 12/1/09).

Arnold, G.W. (1966). The special senses in grazing animals. II. Smell, taste and touch and dietary habits in sheep. *Australian Journal of Agricultural Research* 17, 531-42.

Auld, B.A. (1971). Survey of weed problems of the North Coast of New South Wales. *Tropical Grasslands* 5, 27-30.

Beales, K.A., Betteridge, K., Colegate, S.M., and Edgar, J.A. (2004). Solid phase extraction and LCMS analysis of pyrrolizidine alkaloids in honeys. *Journal of Agricultural and Food Chemistry* 52, 6664-72.

Belcher, R.O. (1993). The '*Senecio* aff. *lautus*' complex (Asteraceae) in Australia. I. Criteria for exclusion of lautusoid *Senecio* of Australia from *S. lautus* sensu stricto of New Zealand. *Australian Systematic Botany* 6, 359-63.

Belcher, R.O. (1994). The '*Senecio* aff. *lautus*' complex (Asteraceae) in Australia. II. Clarification of names given to pseudolautusoid Australian specimens of *Senecio* by Richard and by Candolle. *Australian Systematic Botany* 7, 71-85.

Bennetts, H.W. (1935). An investigation of plants poisonous to stock in Western Australia. *Journal of the Department of Agriculture, Western Australia* 12, 431-41.

Betteridge, K., Cao, Y. and Colegate, S.M. (2005). Improved method of extraction and LC-MS analysis of pyrrolizidine alkaloids and their *N*-oxides in honey: Application to *Echium vulgare* honeys. *Journal of Agriculture and Food Chemistry* 53, 1894-902.

Boppré, M., Colegate, S.M., and Edgar, J.A. (2005). Pyrrolizidine alkaloids of *Echium vulgare* honey found in pure pollen. *Journal of Agriculture and Food Chemistry* 53, 594-600.

Brown, A.H.D. and Marshall, D.R. (1981). Evolutionary changes accompanying colonization in plants. Evolution Today, Proceedings of the Second International Congress of Systematic and Evolutionary Biology, eds. G.G.E. Scudder and J.L.

Reveal, pp. 351-63. The Hunt Institute for Botanical Documentation, Carnegie-Mellon University, Pittsburgh.

Bull, L.B. (1955). The histological evidence of liver damage from pyrrolizidine alkaloids: megalocytosis of the liver cells and inclusion globules. *Australian Veterinary Journal* 31, 33-40.

Bull, L.B., Culvenor, C.C.J. and Dick, A.T. (1968). 'The Pyrrolizidine Alkaloids - Their Chemistry, Pathogenicity and other Biological Properties.' (North Holland Pub. Co., Amsterdam).

BVFA (2008). Bega Valley Fireweed Association Inc. http://thebegavalley.org.au/fireweed.html (accessed 9/1/09).

Cabrera, A.L. (1941). Compuestas bonaerenses. *Revista del Museo de La Plata* 4, 1-450.

Cabrera, A.L. (1963). Compositae. In 'Flora de la Provincia de Buenos Aires', Tomo IV, 6. (Colección cientifica del INTA. Buenos Aires).

Cabrera, A.L., and Ré, R.R. (1965). Sobre un *Senecio adventicio* en la provincia de Buenos Aires. *Revista de la Facultad de Agronomía, Universidad Nacional de La Plata* 41, 43-50.

Cabrera, A.L., and Zardini, E.M. (1978). 'Manual de la Flora de Los Alrededores de Buenos Aires.' (Editorial Acmé, Buenos Aires).

Cabrera, A.L., and Zardini, E.M. (1980). Sinopsis preliminar de las especies Argentinas del género *Senecio* (Compositae). *Darwiniana* 22, 428-92.

Campbell, M.H., Holst, P.J., Auld, B.A., and Medd, R.W. (1979). Control of three pasture weeds using goats. Proceedings of the 7th Asian-Pacific Weed Science Society Conference, eds R.W. Medd and B.A. Auld, 1, 201-5. Council of Australian Weed Science Societies, Sydney.

Carthew, J. (2006). The effects of frost on fireweed (*Senecio madagascariensis*). Honours thesis, School of Environmental and Rural Science, University of New England.

Chaboudez, P. and Burdon, J.J. (1995). Frequency-dependent selection in a wild plant-pathogen system. *Oecologia* 102, 490-3.

Chancellor, R.J. (1984). The role of dormancy in weed control. *Schweizerische Landwirtschaftliche Forschung* 23, 69-74.

Chutrau, N. (1973). Control of weeds resistant to 2,4-D in pastures (In Spanish). Paper given at Primera Reunión Argentina sobre la Maleza y su Control, Tucumán, 1972. *Malezas y su Control* 2, 79.

Clarke, I. and Lee, H. (1993). 'Name that Flower; the Identification of Flowering Plants'. (Melbourne University Press, Melbourne).

Colegate, S.M. (2008). Fireweed Toxicity. Facts and Perspectives. Unpublished Report for the Bega Valley Fireweed Association.

Colman, R.L. (1970). Future use of nitrogen fertilizers on pastures and crops in sub-tropical New South Wales. *Journal of the Australian Institute of Agricultural Science* 36, 224-32.

Common, I.F.B. (1990). 'Moths of Australia'. (Melbourne University Press, Melbourne).

Cruttwell McFadyen, R.E. (1991). Climate modelling and the biological control of weeds: one view. *Plant Protection Quarterly* 6, 14-5.

Cunningham, G.M., Mulham, W.E., Milthorpe, P.L. and Leigh, J.H. (1981). 'Plants of Western New South Wales.' (Government Printing Office, Sydney).

Dana, W.S. Mrs. (1963). 'How to Know the Wild Flowers.' (Dover Publications Inc., New York).

Daniel, R.P. (1984). The biology and control of fireweed (*Senecio madagascariensis*). B.Sc.Agr. Thesis, University of Sydney.

Dollahite, J.W. (1972). The use of sheep and goats to control senecio poisoning in cattle. *South Western Veterinarian* 25, 223-6.

Dormontt, E.E. (2008). The evolutionary consequences of hybridisation between a native and invasive *Senecio*. Proceedings of the 16th Australian Weeds Conference, Cairns, 2008, eds R.D. van Klinken, V.A. Osten, F.D. Panetta and J.C. Scanlan, p. 146, The Weed Society of Queensland Inc., Brisbane.

Edgar, J.A. (2008). The Poisonous Substances (Pyrrolizidine Alkaloids, PAs) found in Fireweed. Food Safety Implications. Presentation to the National Fireweed Conference, Bega RSL, 28 May 2008 (Bega Valley Fireweed Association, Bega) http://thebegavalley.org.au/fireweed.html (accessed 9/1/09).

Edgar, J.A., Roeder, E. and Molyneux, R.J. (2001). Honey from plants containing pyrrolizidine alkaloids: A potential threat to health. *Journal of Agriculture and Food Chemistry* 50, 2719-30.

Edgar, J.A. and Smith, L.W. (2000). Transfer of pyrrolizidine alkaloids into eggs: Food safety implications. *In* 'Natural and Selected Synthetic Toxins: Biological Implications', eds A.T. Tu and W. Gaffield, pp. 118-28 (American Chemical Society, Washington, DC).

Fernández, O.N. and Montes, L. (1984). Senecio. Serie: Materiales de Divulgación. No. 18. Secretaria de Agricultura y Ganaderia Instituto Nacional De Tecnologio Agropecuaria Estación Experimental Regional Agropecuaria, Balcarce, Buenos Aires, Rep. Argentina.

Fernández, O.N. and Verona, C.A. (1983). Growth and dry matter partition in *Senecio madagascariensis* Poiret (Compositae) (In Spanish). *Revista de la Facultad de Agronomía, Universidad de Buenos Aires* 4, 213-25.

Fernández, O.N. and Verona, C.A. (1984). Reproductive characteristics of *Senecio madagascariensis* Poiret (Compositae) (In Spanish). *Revista de la Facultad de Agronomía, Universidad de Buenos Aires* 5, 125-37.

Fernández, O.N. and Verona, C.A. (1985). Comparative analysis of growth and assimilate partition of seedlings of *Senecio madagascariensis*, *Crepis capillaris*, *Trifolium repens* and *Lolium perenne* (In Spanish). *Revista de la Facultad de Agronomía, Universidad de Buenos Aires* 6, 1-9.

Gardner, D.R., Thorne, M.S., Molyneux, R.J., Pfister, J.A. and Seawright, A.A. (2006). Pyrrolizidine alkaloids in *Senecio madagascariensis* from Australia and Hawaii and assessment of possible livestock poisoning. *Biochemical Systematics and Ecology* 34, 736-44.

Garese, P. (1963). *Senecio burchellii* DC., a species which is invading the S.E. region of Buenos Aires province (In Spanish). 3rd Reunión Nacional sobre Malezas y su Control, Buenos Aires.

Garese, P. (1965). The present situation in regard to weed problems in the country (In Spanish). Reunión de Programación de Malezas.

Green, K.R. (1953). Fireweed. *The Agricultural Gazette of New South Wales* 64, 527.

Guillén, D., Romero, C. and Montaldi, E.R. (1984). Germination of *Senecio madagascariensis* Poir. (In Spanish). *Revista de la Facultad de Agronomía, Universidad Nacional de La Plata* 60, 5-9.

Hamrick, J.L. and Godt, M.J.W. (1990). Allozyme diversity in plant species. *In* 'Plant Population Genetics, Breeding and Genetic Resources', eds. A.H.D. Brown, M.T. Clegg, A.L. Kahler and B.S. Wier., pp. 43-63. (Sinauer Associates, Sunderland).

Harrington, K.C. (1990). Spraying history and fitness of nodding thistle, *Carduus nutans*, populations resistant to MCPA and 2,4-D. Proceedings of the 9th Australian Weeds Conference, ed. J.W. Heap. pp. 201-4. Crop Science Society of South Australia, Adelaide.

Hartley, W. (1979). 'A Checklist of Economic Plants in Australia.' (Commonwealth Scientific and Industrial Research Organisation, Melbourne).

Hilliard, O.M. (1977). 'Compositae in Natal', pp.404-6. (University of Natal Press, Pietermaritzburg).

Holtkamp, R.H. and Hosking, J.R. (1993). Insects and diseases of fireweed, *Senecio madagascariensis*, and the closely related *Senecio lautus* complex. Proceedings of the 10th Australian and 14th Asian Pacific Weed Conference pp. 104-6. The Weed Society of Queensland, Brisbane.

Holtkamp, R.H. and Hosking, J.R. (1996). Insects and Diseases of Fireweed, *Senecio madagascariensis*. NSW Agriculture. Agnote 2/091. 3rd Edition.

Humbert, H. (1963). 'Flore de Madagascar', pp.734-8. (Muséum National d'Histoire Naturelle, Paris).

Ireson, J.E. and McQuillan, P.B. (1984). Observations on the biology and behaviour of *Homoeosoma farinaria* Turner (Lepidoptera: Pyralidae) on *Senecio jacobaea* L., in Tasmania. *Journal of the Australian Entomological Society* 23, 285-92.

James, L.F., Panter, K.E., Molyneux, R.J., Stegelmeier, B.L. and Wagstaff, D.J. (1994). Plant toxicants in milk. *In* 'Plant-associated Toxins: Agricultural, Phytochemical and Ecological Aspects'. Eds S.M. Colegate and P.R. Dorling, pp. 83-8 (CAB International).

Johnston, W.H. (2007). Scoping a Management Program for Fireweed on the South Coast of NSW. Final Report. Meat and Livestock Australia Ltd., North Sydney.

Kidd, R. (2008). Noxious Weeds Advisory Committee Fireweed Review 2008. Presentation to the National Fireweed Conference, Bega RSL, 28 May 2008 (Bega Valley Fireweed Association, Bega) http://thebegavalley.org.au/fireweed.html (accessed 9/1/09).

Kirkland, P.D., Moore, R.E., Walker, K.H., Seaman, J.T. and Dunn, S.E. (1982). Deaths in cattle associated with *Senecio lautus* consumption. *Australian Veterinary Journal* 59, 64.

Laguinge, E.G. (1959). Nombres vulgares de malezas Argentinas. Memoria de la reunión de lucha contra la maleza. Revista Argentina de Agronomía Suplemento No.3. Buenos Aires.

Launders, T.E. (1979). Can fireweed (*Senecio lautus*) be extinguished? *Australian Weeds Research Newsletter* 27, 26-7.

Launders, T.E. (1984a). Use of ropewick applicators on fireweed (*Senecio madagascariensis*). *Australian Weeds Research Newsletter* 32, 21.

Launders, T.E. (1984b). Use of ropewick applicators on fireweed (*Senecio madagascariensis*), 1983 trial. *Australian Weeds Research Newsletter* 32, 22.

Launders, T.E. (1985). What's new with fireweed? Third Biennial Noxious Plants Conference, Canberra, Australia, pp. 85-7.

Launders, T.E. (1986). Competitive pastures and control of fireweed. *Australian Weeds Research Newsletter* 35, 42-3.

Lawrence, M.E. (1980). *Senecio* L. (Asteraceae) in Australia: chromosome numbers and the occurrence of polyploidy. *Australian Journal of Botany* 28, 151-65.

Le Roux, J.J., Wieczorek, A.M., Ramadan, M.M. and Tran, C.T. (2006). Resolving the native provenance of invasive fireweed (*Senecio madagascariensis* Poir.) in the

Hawaiian Islands as inferred from phylogenetic analysis. *Diversity and Distributions* 12, 694-702.

Lowe, A., Dormontt, E. and Prentis, P. (2008). Testing for Rapid Adaptation in Fireweed. Presentation to the National Fireweed Conference, Bega RSL, 28 May 2008 (Bega Valley Fireweed Association, Bega) http://thebegavalley.org.au/fireweed.html (accessed 9/1/09).

Lynch, P.W. and Strang, J. (1973). Fireweed on the Central Coast. *The Agricultural Gazette of New South Wales* 84, 374.

McBarron, E.J. (1976). 'Medical and Veterinary Aspects of Plant Poisons in New South Wales', pp. 83-6. (Studio Press, Sydney).

McFadyen, R. and Sparks, D. (1996). Biological control of fireweed. Proceedings of the Eleventh Australian Weeds Conference, ed R.C.H. Shepherd, pp. 305-8. Weed Science Society of Victoria Inc., Melbourne.

McLaren, D.A., Merton, E., Pritchard, G., Ramasamy, S., Grech, C. and Bonilla, J. (2008). Evaluating the extent of serrated tussock (*Nassella trichotoma*) resistance to the herbicide, flupropanate in Australia. Proceedings of the 16th Australian Weeds Conference, Cairns, 2008, eds R.D. van Klinken, V.A. Osten, F.D. Panetta and J.C. Scanlan, pp. 94-6, The Weed Society of Queensland Inc., Brisbane.

Madden, J. (2008). Socio Economics of Fireweed. Presentation to the National Fireweed Conference, Bega RSL, 28 May 2008 (Bega Valley Fireweed Association, Bega) http://thebegavalley.org.au/fireweed.html (accessed 9/1/09).

Marohasy, J.J. (1989). A survey of fireweed (*Senecio madagascariensis* Poir.) and its natural enemies in Madagascar with a view to biological control in Australia. *Plant Protectection Quarterly* 4, 139-40.

Marohasy, J.J. (1993). Are we justified in considering fireweed (*Senecio madagascariensis*) an exotic? Proceedings of the 10th Australian and 14th Asian Pacific Weed Conference pp. 122-7. The Weed Society of Queensland, Brisbane.

Martin, R.J. and Colman, R.L. (1977). The effects of fertilizers, herbicides and grazing intensity on the incidence of fireweed (*Senecio lautus*) in sub-tropical pastures. *Australian Journal of Experimental Agriculture and Animal Husbandry* 17, 296-300.

Michael, P.W. (1981). Alien plants. *In* 'Australian Vegetation', ed. R.H. Groves, pp. 44-64. (Cambridge University Press, Cambridge).

Michael, P.W. (1992). *Senecio lautus* sensu lato - an unresolved complex. *Australian Systematic Botany Newsletter* 72, 10-1.

Molyneux R.J., Johnson A.E. and Stuart L.D. (1988). Delayed manifestation of Senecio-induced pyrrolizidine alkaloidosis in cattle: case reports. *Veterinary and Human Toxicology* 30, 201-5.

Morin, L. (2003). Potential for Fireweed Biocontrol. A Report for the Shoalhaven City Council, May 2003, 20 pp. (CSIRO, Canberra).

Motooka, P., Castro, L., Nelson, D., Nagai, G. and Ching, L. (2003). 'Weeds of Hawai'i's Pastures and Natural Areas; an Identification and Management Guide'. (College of Tropical Agriculture and Human Resources, University of Hawai'i, Manoa) http://www.ctahr.hawaii.edu/forestry/Data/Weeds_Hawaii.asp (accessed 9/1/09).

Motooka, P., Nagai, G., Onuma, K., DuPonte, M., Kawabata, A., Fukumoto, G., Powley, J., 2004. Control of Madagascar Ragwort (aka Madagascar Fireweed, *Senecio madagascariensis*). University of Hawai'i at Manoa. College of Tropical Agriculture and Human Resources. Publication WC-2 (revised). http://www2.ctahr.hawaii.edu/oc/freepubs/pdf/WC-2.pdf (accessed 9/1/09).

Nelson, N.R. (1980). The germination and growth characteristics of fireweed (*Senecio madagascariensis*). B.Sc.Agr. Thesis, University of Sydney.

Nelson, N.R. and Michael, P.W. (1982). Germination and growth of *Senecio madagascariensis* Poir. (fireweed), a toxic plant of pastures in coastal New South Wales. Proceedings of the 2nd Australian Agronomy Conference, p.173. (Griffin Press, Netley, South Australia).

Noble, J.W., Crossley, J de B., Hill, B.D., Pierce, R.J., McKenzie, R.A., Debritz, M. and Morely, A.A. (1994). Pyrrolizidine alkaloidosis of cattle associated with *Senecio lautus*. *Australian Veterinary Journal* 71, 196-200.

NSW DPI (2005). New South Wales Department of Primary Industries Noxious Weed Declarations. http://www.dpi.nsw.gov.au/agriculture/pests-weeds/weeds/noxweed (accessed 9/1/09).

Ornduff, R. (1960). An interpretation of the *Senecio lautus* complex in New Zealand. *Transactions of The Royal Society of New Zealand* 88, 63-77.

Ornduff, R. (1964). Evolutionary pathways of the *Senecio lautus* alliance in New Zealand and Australia. *Evolution* 18, 349-60.

Page, A.R. and Lacey, K.L. (2006). 'Economic Impact Assessment of Australian Weed Biological Control'. 151 pp. Technical Series #10. (CRC for Australian Weed Management, Adelaide).

Parsons, W.T. and Cuthbertson, E.G. (1992). 'Noxious Weeds of Australia'. 692 pp. (Inkata Press, Melbourne).

Plant, R. and Roberton, S. (2008). Fireweed, *Senecio madagascariensis*. Victorian Alert Fact Sheet. Victorian Government Department of Primary Industries, Melbourne.

Poiret, J.L.M. (1817). *In* 'Encyclopédie Méthodique Botanique Supplement', ed. M. Lamarck, Tome V. p.130.

Prentis, P.J., White, E.M., Radford, I.J., Lowe, A.J. and Clarke, A.R. (2007). Can hybridisation cause local extinction: a case for demographic swamping of the Australian native *Senecio pinnatifolius* by the invasive *Senecio madagascariensis*? *New Phytologist*, 176, 902-12.

Radford, I.J. (1997a). Impact Assessment for the Biological Control of *Senecio madagascariensis* Poir. (Fireweed). Ph.D. Thesis, University of Sydney.

Radford, I.J. (1997b). Unpublished Report. Genetic Relationships Between Australian Fireweed and South African and Madagascan Populations of *Senecio madagascariensis* Poir. Final Report, Meat Research Corporation.

Radford, I.J., Cousens, R.D. and Michael, P.W. (2004). Morphological and genetic variation in the *Senecio pinnatifolius* complex: are variants worthy of taxonomic recognition? *Australian Systematic Botany* 17, 29-48.

Radford, I.J., King, D. and Cousens, R.D. (1995a). A survey of *Senecio madagascariensis* Poir. (fireweed) density in pastures of coastal New South Wales. *Plant Protection Quarterly* 10**,** 107-11.

Radford, I.J., King, D. and Cousens, R.D. (1997). Unpublished Report. Pasture Production Impact of *Senecio madagascariensis* (Fireweed). Dairy Research and Development Corporation Final Report.

Radford, I.J., Liu, Q. and Michael, P.W. (1995b). Chromosome counts for the Australian weed known as *Senecio madagascariensis* (Asteraceae). *Australian Systematic Botany* 8, 1029-33.

Radford, I.J., Muller, P., Fiffer, S. and Michael, P.W. (2000). Genetic relationships between Australian fireweed and South African and Madagascan populations of *Senecio madagascariensis* Poir. and closely related *Senecio* species. *Australian Systematic Botany* 13, 409-23.

Ramasamy, S., McLaren, D.A., Pritchard, G., Officer, D., Bonilla, J., Preston, C. and Lawrie, A.C. (2008). 2,2-DPA resistance in giant Parramatta grass (*Sporobolus fertilis*). Proceedings of the 16th Australian Weeds Conference, Cairns, 2008, eds R.D. van Klinken, V.A. Osten, F.D. Panetta and J.C. Scanlan, pp. 71-3, The Weed Society of Queensland Inc., Brisbane.

Reed, C.F. (1977). 'Economically Important Foreign Weeds. Potential Problems in the United States.' United States Department of Agriculture. (U.S. Government Printing Office, Washington).

Ryan, G.F. (1970). Resistance of common groundsel to simazine and atrazine. *Weed Science* 18, 614-6.

Salisbury, E.J. (1961). 'Weeds and Aliens.' (Collins Press, London).

Scott, L.J. (1994). Fireweed (*Senecio madagascariensis* Poir.) is not Part of the *Senecio lautus* Complex: Phylogenetic Evidence Using ITS 1 DNA Sequences. B.App.Sc. (Biotechnology) Honours Thesis, University of Queensland.

Scott, L.J., Congdon, C. and Playford, J. (1998). Molecular evidence that fireweed (*Senecio madagascariensis*, Asteraceae) is of South African origin. *Plant Systematic and Evolution* 213, 251-7.

Seawright, A.A. (1994). Toxic plant residues in meat. *In* 'Plant-associated Toxins: Agricultural, Phytochemical and Ecological Aspects', eds S.M. Colegate and P.R. Dorling, pp. 77-82 (CAB International).

Sheldon, J.C. and Burrows, F.M. (1973). The dispersal effectiveness of the achene-pappus units of selected Compositae in steady winds with convection. *New Phytologist* 72, 665-75.

Sheppard, A. and McFadyen, R. (2008). Research into the Biological Control of Fireweed. Presentation to the National Fireweed Conference, Bega RSL, 28 May 2008 (Bega Valley Fireweed Association, Bega) http://thebegavalley.org.au/fireweed.html (accessed 9/1/09).

Sindel, B.M. (1986). The ecology and control of fireweed (*Senecio madagascariensis* Poir.). *Plant Protection Quarterly*, 1, 163-72.

Sindel, B.M. (1987). Competition between fireweed *Senecio madagascariensis* and oats *Avena strigosa*. Proceedings of the 8th Australian Weeds Conference, eds. D. Lemerle and A.R. Leys pp. 171-4, Council of the Australian Weed Science Societies, Sydney.

Sindel, B.M. (1989). The Ecology and Control of Fireweed (*Senecio madagascariensis* Poir.). PhD Thesis, University of Sydney, 283 pp.

Sindel, B.M. (1996). Impact, ecology and control of the weed *Senecio madagascariensis* in Australia. Proceedings of the International Compositae Conference, Kew, 1994. Vol. 2. Biology and Utilization, eds P. Caligari and D.J.N. Hind, pp. 339-49. (Royal Botanic Gardens, Kew).

Sindel, B.M. and Michael, P.W. (1988). Survey of the impact and control of fireweed (*Senecio madagascariensis* Poir.) in New South Wales. *Plant Protection Quarterly*, 3, 22-8.

Sindel, B.M. and Michael, P.W. (1989). Frost as a limiting factor in the distribution of *Senecio madagascariensis* Poir. (fireweed) in Australia. Proceedings of the 12th Asian-Pacific Weed Science Society Conference, Taegu, Republic of Korea, pp. 453-9. Asian-Pacific Weed Science Society.

Sindel, B.M. and Michael, P.W. (1990). Competition between fireweed, *Senecio madagascariensis* Poir., and Italian ryegrass, *Lolium multiflorum* Lam. cv. Concord. Proceedings of the 9th Australian Weeds Conference, ed. J.W. Heap, pp. 369-72, Crop Science Society of South Australia, Adelaide.

Sindel, B.M. and Michael, P.W. (1992a). Spread and potential distribution of *Senecio madagascariensis* Poir. (fireweed) in Australia. *Australian Journal of Ecology*, 17, 21-6.

Sindel, B.M. and Michael, P.W. (1992b). Growth and competitiveness of *Senecio madagascariensis* Poir. (fireweed) in relation to fertilizer use and increases in soil fertility. *Weed Research*, 32, 399-406.

Sindel, B.M. and Michael, P.W. (1996). Seedling emergence and longevity of *Senecio madagascariensis* Poir. (fireweed) in coastal south-eastern Australia. *Plant Protection Quarterly,* 11, 14-9.

Sindel, B.M., Michael, P.W., McFadyen, R.E. and Carthew, J. (2008a). The continuing spread of fireweed (*Senecio madagascariensis*) – the hottest of topics. Proceedings of the 16th Australian Weeds Conference, Cairns, 2008, eds R.D. van Klinken, V.A. Osten, F.D. Panetta and J.C. Scanlan, pp. 47-9, The Weed Society of Queensland Inc., Brisbane.

Sindel, B., Michael, P., McFadyen, R., Carthew, J., Lowe, A. and Dormontt, E. (2008b). The Spread and Distribution of Fireweed (*Senecio madagascariensis*) in Australia. Presentation to the National Fireweed Conference, Bega RSL, 28 May 2008 (Bega Valley Fireweed Association, Bega) http://thebegavalley.org.au/fireweed.html (accessed 9/1/09).

Sindel, B.M., Radford, I.J., Holtkamp, R.H. and Michael, P.W. (1998). The biology of Australian weeds. 33. *Senecio madagascariensis* Poir. *Plant Protection Quarterly* 13, 2-15.

Spencer, K.A. (1977). 'A Revision of the Australian Agromyzidae (Diptera)'. Western Australian Museum, Special Publication No. 8.

Starr, F., Martz, K., Loope, L., (1999). Fireweed (*Senecio madagascariensis*). An Alien Plant Report. United States Geological Survey Biological Resources Division. http://hear.org/species/reports/senmad_fskm_awwa_report.pdf (accessed 9/1/09).

Thompson, I.R., (2005). Taxonomic studies of Australian *Senecio* (Asteraceae): 5. The *S. pinnatifolius*/*S. lautus* complex. *Muelleria* 21, 23-76.

Tracanna, N., Catullo, J., Sosa, C. and Rodríguez, M. (1983). Influence of the timing of treatments on control of *Senecio madagascariensis* (Poir). Paper presented at the 9th Argentinian Meeting on Weeds and their Control. Santa Fé August 1982. *Malezas* 11, 230-1.

Turner, B.L. (1970). Chromosome numbers in the Compositae. XII. Australian Species. *American Journal of Botany* 57, 382-9.

Verona, C.A., Fernández, O.N., Montes, L. and Alonso, S.I. (1982). Agroecological and biological aspects of *Senecio madagascariensis* Poiret (Compositae) (In Spanish). *Ecología Argentina* 7, 17-30.

Volkart, I. (1984). Leaf, stem and root anatomy of *Senecio madagascariensis* Poir. (Compositae) (In Spanish). *Revista de la Facultad de Agronomía, Universidad Nacional de La Plata* 60, 27-41.

Walker, K.H. and Kirkland, P.D. (1981). *Senecio lautus* toxicity in cattle. *Australian Veterinary Journal* 57, 1-7.

Warwick, S.I. (1991). The influence of intraspecific variation on the biology and control of agricultural weeds. Brighton Crop Protection Conference - Weeds, pp. 997-1006.

Watson, R., Allan, H., Munnich, D., Launders, T. and Macadam, J. (1994). Fireweed. Agfact P7.6.26. Second Edition. NSW Agriculture.

Watson, R., Launders, T. and Macadam, J. (1984). Fireweed. Agfact, P7.6.26, New South Wales Department of Agriculture.

Whittet, J.N. (1958). 'Weeds.' (New South Wales Government Printer, Sydney).

Wilson, I.M., Walshaw, D.F. and Walker, J. (1965). The new groundsel rust in Britain and its relationship to certain Australasian rusts. *Transactions of the British Mycological Society* 48, 501-11.

Appendix 1 - About the Author

Dr Brian Sindel is Professor of Weed Science at the University of New England (UNE). Along with his students, he has undertaken projects on the ecology and management of over a dozen weed species in Australia over the last 15 years. Professor Sindel received his training under two of Australia's leading experts on alien plant invasions, firstly at the University of Sydney under Dr Peter Michael and then at CSIRO Plant Industry under Dr Richard Groves.

Professor Sindel is editor and author of three chapters of the first Australian textbook on weeds 'Australian Weed Management Systems' published through the Weeds CRC in 2000, in which he was an active researcher over the last 13 years. Professor Sindel has successfully conducted weed research programs for LWA, GRDC, MLA, RIRDC, CRDC, and NHT, as well as the Cotton and Weed CRCs.

International recognition led to an invitation to contribute, as one of only two Australians to the Handbook of Sustainable Weed Management (Haworth Press, USA), published in 2006. Other publications are in some of the highest ranking journals in the world in the discipline, including Weed Research and Plant and Soil as well as the prestigious Australian journals, Australian Journal of Experimental Agriculture and Australian Journal of Agricultural Research.

He has most recently lead two national survey projects through LWA on the pathways by which weeds spread within Australia, and on the best ways for farmers and weed inspectors to detect new weeds on their properties. He is familiar with weed risk analysis methods, having been involved in the process to assess the weed risks of genetically modified canola and other GMOs in Australia for LWA. In a recent MLA funded project with nearly a thousand graziers, on barriers and incentives to adoption of weed management in southern Australia, Professor Sindel and his colleagues identified several key criteria likely to lead to better adoption of weed control.

Professor Sindel was the first person in Australia to conduct detailed research on the ecology and management of fireweed for his PhD at the University of Sydney in 1989 and developed the principles for effective control based on the utilisation and management of competitive pasture species. The quality of this work on fireweed has been recognised with a prize in the Research Paper Award at the 12th Conference of the Asian-Pacific Weed Science Society in 1989 for 'An Outstanding Contribution to Weed Science', the inclusion of his work in the book series Biology of Australian Weeds, and an invitation to present a paper on fireweed at the International Compositae Conference at Kew Gardens in the UK in 1994 and at various seminars and workshops on fireweed within Australia.

As one of the world authorities on fireweed, Professor Sindel has provided expertise to researchers from Japan, Uruguay, Guatemala, Hawaii, France and Australia in their attempts to deal with this weed and has reviewed many of the publications on this and related *Senecio* species from around the world in the last few years.

Professor Sindel served on the Executive of the Weed Society of NSW for 11 years, and from 1995-1999 as Editor of the Society's newsletter. He is a reviewer for the USDA National Research Initiative Competitive Grants Program, the National Sciences and Engineering Council of Canada grant program, 19 high ranking journals, and has examined postgraduate theses for 12 Australian and overseas universities. He has for ACIAR run week-long in-country courses on Agricultural Research Management for senior researchers and research directors from Vietnam, Fiji, Indonesia, Papua New Guinea, the Philippines and from various African countries.

Appendix 2 - Description of Fireweed

Description

This description of fireweed has been built up using information from various authors (Poiret 1817, Humbert 1963, Hilliard 1977, Nelson 1980, Verona *et al.* 1982, Daniel 1984, Volkart 1984, Watson *et al.* 1984, Radford 1997a) and observations by Sindel *et al.* (1998). Based on Australian herbarium specimens, Thompson (2005) has provided the most recent description, as well as for the *S. pinnatifolius*/*S. lautus* complex.

Habit
A glabrous or very sparsely hairy bush or herb up to c. 60 cm tall. Rarely decumbent, most commonly found as an erect plant, stem often simple and weakly lignified at the base, often much branched above (Figure 17).

Figure 17 *A mature branched fireweed plant.*

Leaves
Bright green, alternate, variable, up to 12 x 2.5 cm but often much smaller. Cauline leaves mostly linear-lanceolate to elliptic-lanceolate, apex acute, margins denticulate to coarsely and irregularly toothed, tapering to a narrow petiole-like half-clasping base, sometimes minutely eared. Upper leaves occasionally pinnately lobed, reduced petiolate, subsessile or sessile (Figure 18 and 19). Possesses predominantly α2-type leaves according to the classification of leaf forms of the *S. lautus* (now *S. pinnatifolius*) complex given by Ali (1964b).

Figure 18 *Leaves of young rosette (top) and seedling (bottom) fireweed.*

Inflorescence

Heads heterogamous, radiate, few to many on bracteate peduncles arranged in open, corymbose panicles, terminal or axillary, the small decurrent bracts similar to the calycular bracts of the capitulum (Figures 19, 20 and 21). Involucre campanulate, 3-5 mm diam., principal bracts or phyllaries c. 20-21, herbaceous with membranous edges, 4-5(-6) mm long about equalling or a little shorter than the disc, width 0.8-1.3 mm, keeled, nerves 1-3, resinous, attenuated to an acute apex. Calycular bracts c. 8-12, 1/4 to 1/3 length of upper bracts, often purple-tipped. Total disc and ray florets c. 100-120, rays c. 12 or 13, ray

corolla length 8-14 mm, often revolute with 4 resinous lines, particularly obvious on upper surface. Ray and disc florets canary-yellow.

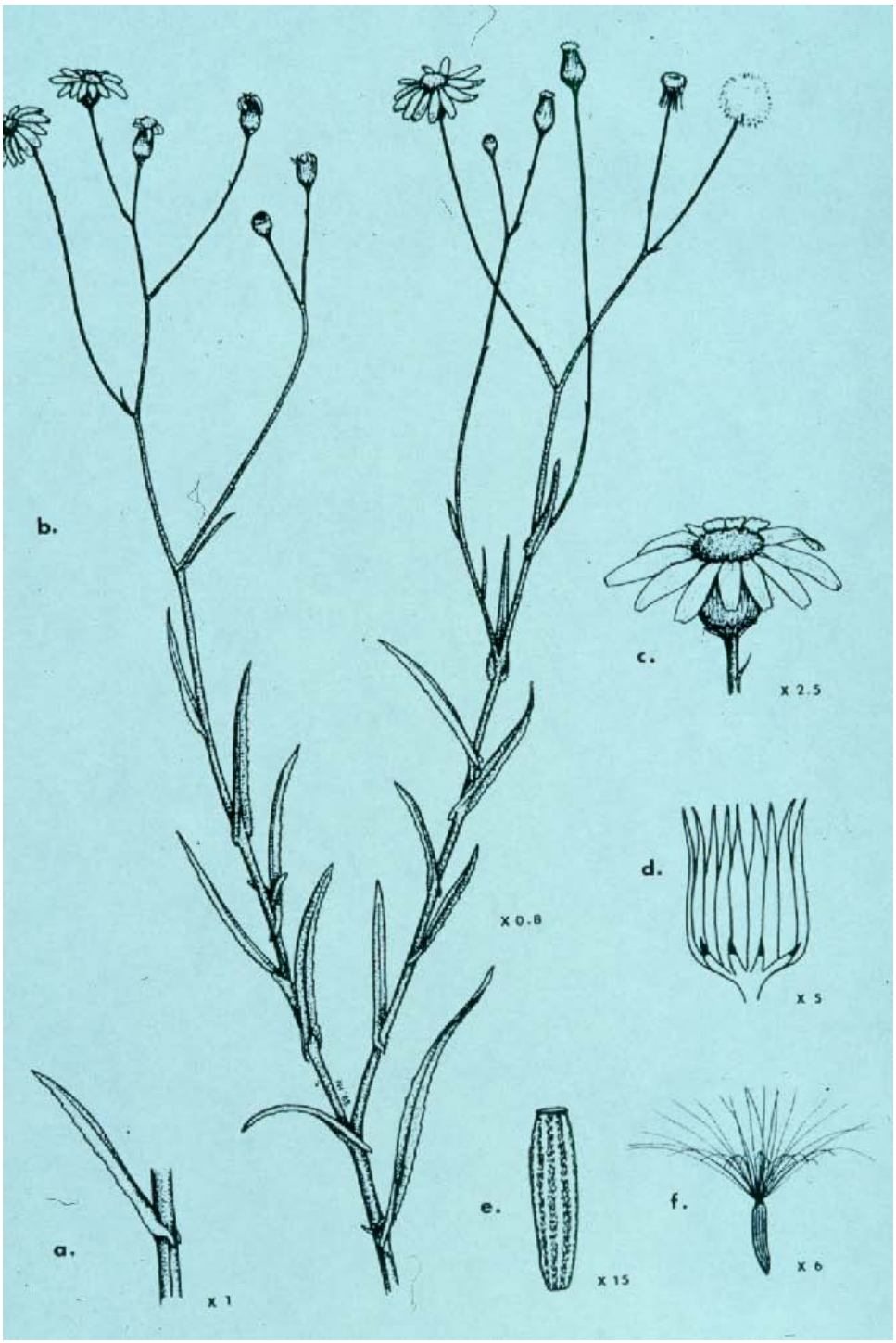

Figure 19 *a) Leaf axil, b) inflorescence and habit, c) capitulum, d) involucre of the capitulum, e) achene, and f) achene and pappus, of fireweed.*

Figure 20 *Inforescences of fireweed.*

Figure 21 *Capitula of fireweed showing the 20-21 involucral bracts.*

Fruits
Achenes 1.4-2.2 mm long, 0.30-0.45 mm wide, cylindrical, shallowly ribbed, with short hairs or bristles c. 0.025 mm long in c. 9-10 longitudinal lines or bands, each band 0.03-0.05 mm wide. Achenes dark brown, light brown or green with light brown being most abundant. Pappus 3.5-6.5 mm long (Figures 11 and 19).

Roots
Shallow, branched, annual or perennating taproot with numerous fibrous roots, growing from 10 to 20 cm deep.

Anatomy
Anatomical characteristics of leaves, stems and roots similar to those generally possessed by other herbaceous *Senecio* species.

Differentiation from *S. pinnatifolius* and *S. brigalowensis*

Because *S. madagascariensis* has fitted, in general terms, the descriptions of the similar native *S. lautus* (known in Australia as variable groundsel) complex given in many of the earlier Australian floras, but now known principally as *S. pinnatifolius* (Radford *et al.* 2004, Thompson 2005), it is important to differentiate between the species. This is especially relevant since members of the *S. pinnatifolius* complex are mostly non-weedy (Radford 1997a) and often occur in areas where fireweed is not expected to grow (Figure 3). The content of alkaloids, which cause poisoning in livestock, may also vary widely between the two species (Walker and Kirkland 1981). However, because of the variability that occurs within the *S. pinnatifolius* complex and the possibility of hybridisation and gene exchange between its different forms (Ornduff 1964, Ali 1966, Radford 1997a, Prentis *et al.* 2007), differentiation from fireweed can sometimes be difficult.

Ali (1964a,b) was able to show that in Australia five main ecological groups were able to be recognised in the *S. lautus* complex, namely: coastal, moist gully, mallee, montane and desert. After consideration of the genetic system within the complex (Ali 1966), he later gave these taxa subspecies status, with the exception of the desert group (Ali 1969). They are respectively subspp. *maritimus*, *lanceolatus*, *dissectifolius* and *alpinus*. Because of the similarity to members of the mallee and coastal groups, the desert population was described as 'aff. subsp. *dissectifolius* and subsp. *maritimus'*. These subspecies were distinguished predominantly on the basis of leaf shape.

While Ali did not recognise *S. madagascariensis*, it is known from a study of herbarium specimens (Nelson 1980) that he included it among his group of plants known as *S. lautus* aff. subsp. *lanceolatus* (Ali 1969).

The number of involucral bracts or phyllaries (20-21) is of major importance as a distinguishing characteristic of fireweed (Nelson 1980). Only the desert genoecodeme of what he described as *S. lautus* and a recently described weedy ecotype from central and southern Queensland (Noble *et al.* 1994), *S. brigalowensis (*Thompson 2005*)*, have a similar number of involucral bracts (ca. 19) per capitulum (Ali 1964b, Radford 1997a, Thompson 2005). Geographical separation of these variants from fireweed means that confusion between them in the field is unlikely, though not out of the question, as described earlier in this report. Also, the achenes of the desert genoecodeme (686 μg) (Ali 1968) are much heavier than those of fireweed (135 μg) and seed length is greater for plants from the central Queensland *S. brigalowensis* (mean 2.2 mm) than for fireweed (mean 1.8 mm)

(Radford 1997a). It is also possible to distinguish desert variants and weedy *S. brigalowensis* by their dissected or pinnatisect leaf shape compared with fireweed, which has entire or finely toothed leaf margins (Radford 1997a). In Argentina, the number of involucral bracts was also found to be critical in the correct identification of fireweed (Verona *et al.* 1982). The shape of the phyllaries, achene morphology, calycular bract morphology and leaf shape are also important. For example, Thompson (2005) noted that the stereome (central herbaceous part) of phyllaries and bracteoles of fireweed are sometimes suffused purple (Figure 21) while this character has not been observed in the native lautosoid species in Australia.

Appendix 3 - Enhancing the Capacity of Livestock to Destroy Pyrrolizidine Alkaloids

Exerpt from John Edgar's presentation at the National Fireweed Conference (Edgar 2008)

One approach to the problem of fireweed being considered at this meeting is the introduction of biological agents to help control the level of the weed. I would like to spend a few minutes mentioning another potential approach to the problems of fireweed. That is, to enhance the ability of ruminants, such as sheep and goats, to destroy PAs and ideally to make some ruminants completely resistant to PAs and useful as biological control agents for PA plants such as fireweed.

It has been known since the 1970s, as a result of the work of a colleague of mine at CSIRO, George Lanigan, that a bacterium which he isolated from the rumen of sheep and cattle and which he named *Peptostreptococcus heliotrinreducans*, breaks PAs into two non-toxic components. This is why sheep and some other ruminants such as goats and, to a lesser extent, cattle are much more resistant to PAs than monogastric animals such as horses, chickens, pigs and humans. Sheep for example can destroy around 85% of the PAs they ingest in their rumen, prior to absorption. In many parts of Australia sheep have traditionally been used to control PA plants however sheep are not completely resistant to PAs and do succumb over about 2 seasons of exposure and their productive life is shortened by several years. Their new born lambs also suffer liver damage.

George Lanigan found that destruction of PAs by *Peptostreptococcus heliotrinreducans* requires free hydrogen to be available in the rumen. Unfortunately, most of the hydrogen in the rumen is used by other rumen bacteria to produce methane. Methane-producing bacteria compete for available hydrogen with the PA-destroying bacterium. George reasoned that if we could stop methane production the increased availability of hydrogen might increase the efficiency of PA destruction from 85% to 100% and the animals would then be completely protected and the PAs they ingested would be completely destroyed. There would also be no PAs left to be transferred into products such as milk. A fully protected cow, sheep or goat, for example, would be a very effective agent for controlling PA plants such as fireweed.

In recent years methane production by ruminants has been recognised as a major contributor to climate change. In fact methane is considered to be a much stronger green house gas than carbon dioxide. If methane production in ruminants could be inhibited they would not add to green house gas levels and may, at the same time, become more effective destroyer of PAs. In modern parlance it would be a win, win situation. As well as being a greenhouse gas, it has long been recognised that methane also represents lost production. If the carbon lost as methane was instead converted into productive growth this would be a win, win, win situation all around!

Funding for such a project could come jointly from greenhouse gas abatement programs and from weed control programs thus spreading the cost burden. For a description of a CSIRO-patented antimethanogen that enhanced the destruction of heliotrope PAs in the rumen see:
http://www.pharmcast.com/Patents/Yr2001/June2001/062601/6251879_Antimethanogenic062601.htm