disturbance. Weed taxa that are closely allied to economically important plants or indigenous plants e.g., Poaceae should not be excluded from consideration due to the high level of host specificity demonstrated by some organisms. Australian native plants that are weeds outside their natural range may also make suitable targets for biological control, particularly where substantial geographical barriers exist between their introduced and native range. The protocols for conducting such programs are not developed, but require attention before they should be undertaken.

The ultimate criteria for the successful control of environmental weeds, regardless of the techniques used, should be measured as either the level of replacement of the target infestations with other vegetation, or the level of protection provided to uninfested vegetation by a reduction in the rate of spread. Control programs that fail to reduce the fitness of weed infestations to levels below the 'critical ecological threshold' that allows natural regeneration, or significantly reduce dispersal rates cannot be regarded as successful. Where the target weed is replaced by undesirable vegetation with an equal or greater weed status, limited success may be claimed but the contribution of the control program to the protection or enhancement of biological conservation must be rated as negligible. In this respect, biological control programs for environmental weeds should be incorporated into integrated management plans that aim to manipulate post-control succession from weedy to native vegetation. Evaluation processes that record changes in vegetation composition and structure and the reproductive fitness of the target weed as well as the more traditional measures of plant density, biomass and area of distribution are required to determine success of environmental weed control programs.

Overview and use of biological control in pasture situations

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Summary

A number of successful biological control programs against pasture weeds are discussed and related to the state of the programs in Australia. Factors that affect the establishment of biological control agents and how biological control can be integrated into pasture management programs are discussed.

How successful have biological control programs been against pasture weeds?

There have been a number of examples of successful biological control of pasture weed species around the world. St. John's wort, *Hypericum perforatum* L., occupied more than 1 424 300 hectares in North America (Tisdale 1976). Biological control was started in 1946 with the introduction of two chrysomelid beetles, *Chrysolina quadrigemina* (Suffrian) and *Chrysolina hyperici* (Forster). Significant reductions were observed by 1954 and St. John's wort now occupies less than 3% of its original density over much of its former distribution in California. The beetles only feed on St. John's wort in sunny situations, so its distribution has now been largely restricted to shaded locations. Biological control programs against St. John's wort have been most successful in areas with summer droughts, where defoliated plants succumb to water stress and die. It is still a problem in localities with summer rainfall such as British Columbia in Canada, as the plant will regenerate and recover after defoliation and its seed will germinate more readily (Williams 1985).

An excellent example of biological control in Australia is the spectacular success of the moth, *Cactoblastis cactorum* (Berg), in controlling prickly pear cactus, *Opuntia stricta* Haw. Prickly pear once occupied more than 20 million hectares of pastoral and agricultural land in south west to central Queensland and was invading new country at the rate of two hectares every minute (Waterhouse 1978). Fifty one biological control agents were introduced over a 22 year period (1913–1935) of which seventeen were released and 12 established. *C. cactorum* was introduced in 1925 and had controlled most of the prickly pear infestations by 1932 (Wilson 1960).

Another pasture weed, ragwort, *Senecio jacobaea* L., has been biologically controlled in Western Oregon in North America. It has been estimated that ragwort populations have been reduced by 60–70% through the combined actions of the cinnabar moth, *Tyria jacobaeae* (L.), the ragwort flea beetle, *Longitarsus jacobaeae* (Waterhouse) and the ragwort seed fly, *Botanophila seneciella* (Meade) (Brown 1990).

Biological control of blackberry, *Rubus constrictus* Lef & M., has been successful in Chile where the rust fungus, *Phragmidium violaceum* (Shulz), has significantly reduced infestations (Oehrens and Gonzalez 1977). The rust fungus builds up its innoculum over summer and heavy rust infestations defoliates blackberry plants. This allows light to penetrate through the blackberry thicket, enabling seed from competing plant species to germinate and start growing up through the blackberry. This gradually takes nutrients and light away from the blackberry until it is displaced by other plant species.

Musk thistle, *Carduus nutans* L. has been successfully controlled by the weevil *Rhinocyllus conicus* Froel. in Virginia. The weevil has reduced musk thistle density by 95% and six years after release the weevil had spread 32 km (Kok and Surles 1975).

Biological control of pasture weeds in Victoria

Table 1 provides a summary of the current status of biological control projects against pasture weeds in Victoria.

St. John's wort has been partially controlled by biological control in Victoria, especially in agricultural areas experiencing Mediterranean conditions. The best results have occurred when farmers have improved their pasture management practices by sowing strong competing pasture and by keeping it well fertilized (Parsons 1957). It appears that the combination of stress imposed by the biological control agents and the competition from the improved pasture, displaces the weed. St. John's wort is still a serious weed in many areas of Victoria and research is currently being carried out on the host specificity of a fungus, *Colletotrichum gloeosporioides*, and introduction of a mite, *Aculus hyperici*, for its control.

There are three insect species established on ragwort in Victoria. These are the ragwort leaf and crown boring moth, *Cochylis atricapitana* (Stephens), and the ragwort flea beetles, *Longitarsus flavicornis* Ste. and *L. jacobaeae*. Thus far, the flea beetles have only established in high altitude, high rainfall locations. Where the flea beetles have established, they have reduced ragwort infestations but have spread slowly and taken a long time to control the weed. The ragwort leaf and crown boring moth is building up at established sites and is expected to start having an impact on ragwort infestations (McLaren 1992).

An illegal introduction of a strain of the blackberry rust fungus, *P. violaceum*, was found in Victoria in 1984 (Marks *et al.* 1984). This rust only attacks four of the nine blackberry species in Victoria but has been shown to have a significant impact on these species (E. Bruzzese personal communication). A strain of *P. violaceum* that attacks the most widespread blackberry species (*Rubus procerus*) was released in 1990 and observations suggest that this could have a considerable impact on blackberry populations in the next decade.

Biological control of Paterson's curse re-commenced in 1988 with the release of the Paterson's curse leaf miner, *Dialectica scalariella* (Zeller). This insect is now established in the warmer parts of the state but has yet to have an impact on Paterson's curse infestations. Several other biological control agents are currently being reared for release or are being tested for host specificity. These include a root boring weevil, *Mogulones geographicus* (Goeze), a crown boring weevil, *M. larvatus* Shultze and two sap sucking bugs, *Dictyla echii* Schrank and *D. nassata* Puton.

Strains of the thistle receptacle weevil *Rhinocyllus conicus* are being mass reared and released to control spear, slender and variegated thistle. This insect has been very difficult to rear and has yet to establish in the field. A fly, *Urophora stylata* (F.) that galls the heads of spear thistle is currently being reared, but has yet to be released.

A biological control project on horehound began in 1991 with the introduction of a plume moth, *Pterophorus spilodactylus* (Curtis) whose larvae defoliate horehound. It has undergone host specificity testing and it is anticipated that the first release of this moth will occur late in 1993.

What are our chances of success and what factors affect the likelihood of successfully controlling a pasture weed?

The overall figure on worldwide success in biological control programs on weeds is 24% (Julien 1989). In Australia, it has been estimated that biological control has saved in excess of $1 billion dollars (Harley and Forno 1992). Factors that will determine the likelihood of success are:

Climate, host range, agent strain

Biological control agents have evolved with their host in their country of origin for many thousands of years. As a consequence, many insects have become specifically adapted to particular sets of climatic conditions and in many cases formed strains that will only survive in particular environmental locations. Outside this climatic range, the species strain may not reproduce or complete their life cycle. It is therefore important that searches are made for biological control agents in areas that have similar climatic conditions to those that the insect species will encounter when released on plant infestations in Australia.

Climate may impact on establishment of biological control agents in a number of ways. It has been shown for St. John's wort that locations that have summer "droughts" are more likely to enable successful biological control than locations with cooler, moister conditions that allow plants to recover and for seed to germinate. In areas of the world where St. John's wort has become a serious weed, it has only been well controlled in locations where there is a true Mediterranean climate (i.e., California in North America and parts of north east Victoria or southern NSW in Australia.)

Another good example of how climate and host range can affect a biological control agent is the Paterson's curse leaf miner, *D. scalariella.* In its countries of origin, *D. scalariella* is oligophagous and will survive on other Boraginaceae species when Paterson's curse is not available (Wapshere 1985). As these host plants do not occur in Australia, *D. scalariella* is restricted to climatic zones or locations where some Paterson's curse plants are actively growing all year round.

Table 1. Biological control of pasture weeds in Victoria

Common name	Scientific name	Date of 1st release	Success
St. John's wort	*Hypericum perforatum*	1930	Partial
Ragwort	*Senecio jacobaea*	1930	Partial
Blackberry	*Rubus fruiticosus*	1984	Partial
Paterson's curse	*Echium plantagineum*	1988	Slight
Spear thistle	*Cirsium vulgare*	1991	Not established
Slender thistle	*Carduus pycnocephalus*	1993	Not established
Variegated thistle	*Silybum marianum*	1988-89	Not established
Horehound	*Murrubium vulgare*	Not released	

The ragwort flea beetle, *L. flavicornis* is another insect species that appears to be limited in its distribution by climate and insect strain. So far, *L. flavicornis* has only established in high altitude, high rainfall sites. Attempts were made to bring in several other strains of this flea beetle from a range of climatic localities in Europe. However, this species has still only established in higher altitude/rainfall localities. Another flea beetle species *L. jacobaeae* was introduced in 1988 and has established at some lower altitude sites.

Another way climate and insect strain may impact on effectiveness of biological control is shown by impact of the ragwort seed fly, *Botanophila jacobaeae,* on ragwort infestations in New Zealand. There is poor synchronization of emergence of the seed fly and the flowering period of ragwort, as it emerges approximately six weeks before the peak flowering period, resulting in 80–90% of ragwort seeds escaping predation (Dymock 1987). The milder climate in New Zealand enables ragwort to flower over a prolonged period. It may be possible to overcome this problem by importing seed flies from locations in Europe that have similar climates to those in New Zealand.

The genetic diversity of the weed

The way a weed reproduces may be an important factor in determining the likelihood of controlling the weed. It would be expected that a genetically uniform weed species would be easier to control than a species that exhibits wider genetic diversity (Burdon *et al.* 1980). For example, prickly pear cactus, *Opuntia* spp., reproduces asexually and clonally and when introduced into Australia, it essentially formed a huge monoculture of genetically uniform structure. Once an agent was found that would feed on and destroy prickly pear (the moth, *C. cactorum*), the plant was controlled in a relatively short time. The limiting factor of control being the temperature requirements of the insect (Wilson 1960).

Weed species that reproduce sexually (i.e., ragwort, Paterson's curse, thistles) may have a greater genetic diversity which gives these plant species a greater chance of survival from insect attack than species that primarily reproduce vegetatively (prickly pear cactus, St. John's wort). They have a greater probability of adapting through natural selection and producing strains that may be more resistant to insect attack in the future.

Another example of how genetic diversity of a weed can affect the success of a biological control program, is the biological control of skeleton weed *Chondrilla juncea* L., using the rust fungus *Puccinia chondrillina* Bubak & Syd. Skeleton weed is a widespread weed in wheat/fallow cultivations of south-eastern Australia.

In Australia, there are three main forms of skeleton weed which have been termed narrow leaf, intermediate leaf and broad leaf (Hull and Groves 1973). A rust fungus *P. chondrillina,* that was virulent against the most common "narrow leaf" form of skeleton weed was introduced and released in Australia in 1971 (Hasan 1972). It was extremely effective and significantly reduced skeleton weed infestations (Cullen *et al.* 1973). However, the narrow leaf form of skeleton weed was partially replaced by the intermediate and wide leaf forms which has necessitated the search for rusts that attack these skeleton weed forms (Hasan 1981).

Predators, parasites and disease

Biological control agents are cultured and screened for at least one generation in quarantine before they are released, to ensure that parasites and / or diseases are not introduced with them. However, predators, parasites and / or diseases have still played significant roles in preventing agent establishment. Repeated attempts at establishing the cinnabar moth for biological control of ragwort from 1930 to 1981 were prevented initially by disease and then by the action of a number of native insects, the most damaging being the scorpion fly, *Harpobittacus nigriceps* (Selis) (Bornemissza 1966). Attempts were made at protecting field cultures in cages. This was successful but once cages were removed, the cinnabar moth larvae were heavily predated upon and failed to establish (Bornemissza 1966).

Other important predators include birds, spiders, ants, and centipedes. To try and overcome some of these problems, increasing effort is being placed into doing caged releases. This helps protect the insects from predators while also keeping the insects together so they can mate, lay eggs and establish.

Increasing stress on the weed by introducing a variety of biological control agents that attack different parts of the weed at different times of the year

There is a deliberate strategy in most weed biological control projects to introduce a range of biological control agents that will attack different stages of the life cycle of the target weed at different times of the year. The aim is to accumulate stress on a weed species so it is unable to recover from agent attack and enable more desirable plant species to out compete the weed and replace it. McEvoy *et al.* (1989) have shown that the combined action of the cinnabar moth, *T. jacobaeae,* and the ragwort flea beetle, *L. jacobaeae,* led to faster and more effective ragwort control than when either agent attacked ragwort in isolation. The cinnabar moth attacks the reproductive plant stages in summer while the flea beetle attacks the vegetative plant stages in autumn, winter and spring. Attack by the flea beetle reduced the capacity of ragwort to recover from attack by the cinnabar moth.

Pasture management and integrated control

Farmers should not rely on biological control as a total cure for weed problems, as biological control cannot achieve weed eradication. Approximately 75% of biological control agents released, fail to control their target. If biological control does work and the farmer does not improve his pasture, then the weed controlled through biological control may well be replaced by another weed species.

Biological control should be viewed as part of an integrated approach to controlling weeds in pasture situations. To help aid competition from desirable plant species, the pasture should be improved through application of fertilizer, sowing new grasses or adjusting stocking rates. Farmers must rehabilitate their pasture while biological control is taking place or they may only be removing one weed species and replacing it with another.

Biological control should not be used as an excuse by farmers not to do weed control on the rest of their properties. If biological control agents are released at a particular location on a property, then they should allow a 50 metre buffer area around the release site and control weeds on the rest of the property.

Improving the competitiveness of desirable pasture species will take nutrients and resources away from weeds being damaged and weakened by biological control agents. This "pasture improvement" will aid in the displacement of the weed and will also help prevent re-infestation by preventing germination of weed seed or from the weed being replaced by other undesirable weed species.

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Summary and conclusion

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The speakers at this workshop gave an excellent overview of biological control programs in Victoria and the relationship to the National scene.

The following major points were made:

- Biological control programs may require 10–20 years to achieve an effective outcome.
- Strict protocols are in place to ensure the scientific integrity of the programs, to protect natural and modified ecosystems and to provide a mechanism for the resolution of conflict of interest where it arises in the community.
- The major benefit of successful biological control will be at the community level although some benefits will flow to individuals.
- Both government and industry organizations have provided significant funding over many years, but there is currently serious questioning of both the time span and level at which this funding will continue to be provided.
- A large number of control agents are being tested against a range of pest species. Are resources spread too thinly?
- The level of resources that are used to study plant and agent interactions should be reviewed with a view to increasing the availability of resources for mass rearing insects for field releases.
- Community expectations on the potential value of biological control vary, and "success" to the scientist may not be seen in the same light by farmers or others in the community.
- In many bushland situations biological control appears to offer the only chance of returning the vegetation to near natural condition.
- There is an exciting opportunity to link mass rearing and release programs to schools and community groups. This would give the benefits of increased availability of insects coupled with a better community understanding of the place of biological control in weed control.
- To be effective biological control programs must be linked to regional weed control strategies and not be seen as an add-on that may have some benefit.
- Although there is good communication and co-ordination between State and Commonwealth research workers, the impact of biological control would be enhanced through the development of a better National focus.

This workshop provides policy makers and managers at both the State and National level with information to review existing and proposed biological programs. Programs must have a stronger focus on producing effective outcomes with tangible results in the field.

The proceedings will also serve as a valuable tool both for promoting biological control and in increasing the level of understanding in the government, industry and the community. This will help the development of stronger links between workers in research and in the field, and provide for the integration of biological control into regional weed control strategies and programs.

With the current level of resourcing there is a need for a reduction, or at least a consolidation, in the number of target species and agents under study. It would be preferable to adopt a "best bet" approach with a view to achieving a limited number of recognized successes rather than maintaining a larger number of possibilities of success without adequate resources to complete the required work.

Professional publicity should be given to programs where success can be demonstrated. This publicity should not raise unrealistic expectations, but rather clearly spell out the level of success and the limitations. Publicity of this nature will help to sustain community, industry and political support to help the continued flow of the necessary long term funding. Effective integration of the community into rearing and release programs will also build and maintain support for programs.

Although there is excellent communication between research workers in State and Commonwealth agencies, the impact of programs could be enhanced through the development of a stronger National focus. The Australian Weeds Committee and the co-ordinator, recently appointed jointly by the Wool and Meat Research Industry Councils, are two avenues which could help in the development of this focus.

Finally, congratulations are due to both the members of the Weed Science Society of Victoria and the staff of the Department of Conservation and Natural Resources for their work in organizing and presenting this important workshop. Their efforts are well appreciated and I look forward to the continued co-operation between the Department and the Society in the coming years.