One agent is usually sufficient for successful biological control of weeds

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Summary

A review of the recent literature reveals ten new cases of successful biological control of weeds. In each of these a single species of biological control agent has apparently caused the decline in the density and biomass of the target weed. Each of these agents also dramatically damages the plants and reduces their survival. While it remains difficult to predict which species of insect herbivore or plant fungus will be successful, history suggests that those that cause serious damage to the plants are most likely to reduce target weed biomass and density. Clearly single agents can be successful.

Key words: biological control efficacy, natural enemies, invasive plants

Introduction

Recent, highly publicized examples of non-target impacts in biological control of weeds programmes (Louda *et al.*, 2003) have resulted in more stringent regulations and public apprehension about the introduction of new, exotic biological control agents. In addition, interest in the conservation of natural biodiversity calls attention to the potential impacts of more introductions of exotic species such as occurs in biological control of weeds programmes. Given these concerns, in the future it will be important for the practice of biological control to be conservative in terms of the number of agents introduced, and to be efficient in regard to the degree of control achieved with each new species introduced.

Although it is a commonly held view that biological control success requires the introduction of several species of agents attacking different parts of a target weed, we have shown in the past that a majority of biological control of weed successes has been attributed to a single species of agent (Denoth *et al.*, 2002). To determine if the pattern in more recent biological control of weeds successes is in accordance with the earlier analysis, I have reviewed the recent literature for successful weed control projects to determine if single or multiple agents were required to achieve biological control success.

Methods

The definition of success that I have used in this evaluation is that the population density of the target weed was greatly reduced by the activity of the introduced agent. Even if the scale at which the agent had established was small and geographically limited, I considered this to be successful control if plant density at sites with established agents declined significantly as compared to control sites lacking the agent. Other definitions of success might include factors such as the geographical extent of the impact of the control agent or other biological parameters such as the reduction of seed production (review in Myers and Bazely, 2003).

The recent literature was searched using Biosis and Science Citation Index and the key words "biological control success". I also reviewed the journal Biological Control from 2003 to the present for examples of successful control programs.

Results

Nine cases were found of biological control of weeds programmes recorded in the recent literature and we have been studying an additional example that is successful (Table 1). In all these cases, success was attributed to a single agent and in no recent cases were multiple agents reported to be necessary or involved in success. These examples are briefly described below.

Mimosa, *Mimosa pigra,* L.

Mimosa pigra is a woody legume that creates impenetrable stands in the Northern Territory of Australia (Paynter, 2005). Six biological control agents were introduced and established, but of these, only the twig boring moth, *Carmenta mimosa* Echlin and Passoa, has been found to reduce the density of *M. pigra*. Attack by *C. mimosa* can cause severe defoliation and kill twigs and branches and this can reduce seed production by 90%. Reduced seed banks are associated with increased under storey from competing plants and this further declines in seedling success. Higher densities of under storey plants also increase fuel loads and the susceptibility of mimosa to fire. Mimosa populations did not expand in any of the nine sites in which *C. mimosa* was established and three of the sites contracted in size. In contrast, mimosa populations expanded in four of eight areas that lacked *C. mimosa.* From this study (Paynter, 2005) it appears that *C. mimosa* has the potential to be a successful biological control agent.

Bridal creeper, *Asparagus asparagoides,* L. Druce,

Bridal creeper, *Asparagus asparagoides,* is a South African vine that has invaded natural areas with Mediterranean climates in Australia. Initially it was considered that multiple agents would be required for biological control success and three agents were introduced: a rust, *Puccinia myrsiphylli* (Thüm); a leafhopper in the genus *Zygina*; and a beetle in the genus *Crioceris* (Morin and Edwards, 2006). Of these the rust has become widely established in coastal areas and has significantly reduced bridal creeper populations (Morin *et al*., 2006). Although defoliation by the leafhopper also appears to have the potential to reduce the population density of bridal creeper, an egg parasite has reduced its success and populations are unstable. It may have a greater impact in drier, interior sites where the conditions may be less favourable for the fungus (Morin and Edwards, 2006). Presently it appears that the fungus is able to achieve successful biological control on its own in coastal areas of Australia.

Dalmatian toadflax, *Linaria dalmatica*, L. (Mill.)

Dalmatian toadflax, *Linaria dalmatica* infests large areas of rangeland in western North America. The stem-boring weevil, *Mecinus janthinus,*Germar, has been highly successful in reducing densities of Dalmatian toadflax, particularly in British Columbia, Canada (De Clerk-Floate and Harris, 2002; Nowerski, 2004; Hansen, 2004; McClay and Hughes, 2007). In some areas such as Alberta, Canada, the climate is less favourable for the weevils and they do not have sufficient time to develop to the over wintering adult stage (McClay and Hughes, 2007). Thus *M. janthinus* is an example of a species that is a successful biological control agent on its own in some regions, but it is not adapted to all of the areas invaded by the target weed.

Red floating fern, *Azolla filiculoides,* Lam.

Red floating fern, *Azolla filiculoides,* is native to South America but became a serious aquatic weed in South Africa. The frond-eating weevil *Stenopelmus rufinasus,* Gyllenhall was introduced from Florida, USA to South Africa in 1997 and caused extinction of the water fern at 81% of the original 112 release sites usually within seven months of its release (McConnachie *et al*., 2004). This program with a single species of agent is considered to be highly successful.

Mist flower, *Ageratina riparia* (Regel) R.M.King & H.Rob

Mist flower, *Ageratina riparia,* is an ornamental that is native to Central America. It has been spread to many tropical areas where it reaches dense stands in warm, moist habitats along forest edges, wetlands, and poorly managed pastures. In Hawai'i four species of biological control agent were introduced and success was attributed to all of them, although no quantitative data were collected (Trujillo, 1985). Two species of biological control agents were introduced to New Zealand; the white fungus *Entyloma ageratinae* Barreto and Evans, in 1998, and a gall fly, *Prococidochares alani*, Steyskal, in 2001. The fungus spread rapidly and within several years mistflower cover declined from 81% to 1.5% in heavily infested sites, and apparently before the gall flies were widely established (Barton *et al*., 2007). The success of *E. ageratinae* in reducing mistflower suggests that this species may be sufficient for successful biological control, and the contribution of other agents in Hawai'i may have been overestimated.

Banana poka, *Passiflora tarminiana,* Copens and Barney

Banana poka, *Passiflora tarminiana,* , is native to the high Andes and became a major weed in high elevations of Hawai'i where it infested more that 50,000 ha (Trujillo, 2005). In 1993 a fungus, *Septoria passiflorae,* Syd. was introduced to Hawai'i from Columbia for host range testing under quarantine. After it was shown to be specific, *S. passiflorae* was sprayed on banana poka in the Hilo Forest Reserve. Densities of the weed were reduced by 95% within four years in many areas but not in regions in which the fungus was killed by acid rain (Trujillo, 2005). This plant pathogen has preserved endangered species and allowed the regeneration of koa forests at high elevations on the islands of Kauai, Maui, and Hawai'i.

Houndstongue, *Cynoglossum officinale* L.

Houndstongue, *Cynoglossum officinale*. is a native of Europe and Asia-minor and a serious rangeland weed in British Columbia, Canada. The seeds of this plant attach to the faces and hides of cattle and the foliage is very toxic to large mammals. The root-boring weevil *Mogluones cruciger* Herbst. was introduced in 1997 and became effectively established at many sites where it may attack over 90% of flowering plants and kill over half the rosettes it attacks in the autumn. *Mogluones cruciger* has reduced the density of houndstongue at most of the release sites (De Clerck-Floate and Schwarzländer, 2002; De Clerck-Floate *et al*., 2005) and thus is considered to be a successful biological control agent.

Purple loosestrife, *Lythrum salicaria* L.

Purple loosestrife, *Lythrum salicaria,* is a European plant that has become widely spread in wetland areas across southern Canada and the northern USA. Two species of leaf-feeding beetles have been introduced widely as biological control agents, *Galarucella calmariensis* and *G. pusilla,* Dust. and in some locations the root-boring beetle *Hylobius transversovittatus* Goeze has also been introduced. In southern British Columbia the species composition of releases is not certain but is likely to have been dominated by *G. calmariensis* (DeClerk-Floate, personal communication). This has effectively reduced loosestrife at several sites that were monitored (Denoth and Myers, 2005). Similarly, in Manitoba *G. calmariensis* reduced loosestrife populations at several locations (Lindgren, 2000). In Michigan both species of beetles were introduced but only *G. calmariensis* became established and here too the species effectively reduced loosestrife density at many locations (Landis *et al*., 2003). Both *Galarucella* spp. were established in western Oregon and were considered to be ecological equivalents. They contributed to a dramatic decline in loosestrife plant size and density over three years (Schooler, 1998). In New York *G. pusilla* was the dominant species at many locations, but neither species together or alone had an apparent impact on loosestrife density

(Grevstad, 2005). After five years *G. calmariensis* was spreading and increasing in density compared to *G. pusilla*. In another study in New York the two species of leaf-feeding beetles were introduced and after five years a significant decline in loosestrife densities occurred (Albright *et al*., 2004). The species composition of the two beetle populations was not monitored over time in this study so it is not clear if both species were involved in the decline of host plant density. Comparisons of the impacts of *H. transversovittatus* and *G. calmariensis* showed that the leaf-feeding beetle had the greatest impact on loosestrife reproductive effort and above ground biomass and this damage allowed improved growth of other plants in plots (Hunt-Joshi *et al*., 2004). In conclusion, reduction of purple loosestrife density has been achieved in programs involving only *G. calmariensis* and this shows that a single agent can be successful. The failure of Grevstad (2005) to find a reduction in loosestrife density in programs that initially involved both leaf feeding beetle species may suggest that there can be a negative interaction of the species or that the environment in New York is less conducive to control by these leaf-feeding beetles. The two species were successful in combination in western Oregon however.

Spotted knapweed, *Centaurea stoebe* Linnaeus *micranthos* (S. G. Gmelin ex Gugler) Hayek

Spotted knapweed, *Centaurea stoebe micranthos,* is a serious rangeland weed in western North America where it infests over three million ha. Twelve Eurasian insect species have been introduced as potential biological control agents. Seven of these species are considered to have an impact through the reduction in seed production. This has not however, been translated into successful reduction of plant density. One species, the root-boring beetle *Cyphocleonus achates* Fahraeus can kill spotted knapweed plants and caused a significant reduction in plant density, 99% and 77% over 11 years, at two sites where it reached high densities (Story *et al.*, 2006). This weevil does not fly so its spread is slow, but nevertheless the population did expand on average by 99 m per year. Thus, this species is capable of at least local control of spotted knapweed.

Diffuse knapweed, *Centaurea diffusa* Lamarck

Diffuse knapweed, *Centaurea diffusa*, like spotted knapweed, is a rangeland weed in western North America. It infests drier areas at lower elevations than spotted knapweed, and shares some of the introduced biological control agents with spotted knapweed (Bourchier *et al.*, 2002). Twelve species of exotic, potential control agents have been introduced for this species as well and the most widely established agents include two gall flies, *Urophora affinis* Frauenfeld, and *U. quadrifasciata*, the root-boring beetle *Sphenoptera jugoslavica* Obenberger, and most recently the weevil *Larinus minutus* Gyllenhal. Since the establishment and spread of *L. minutus* in the late 1990's, densities of diffuse knapweed have declined in many sites in British Columbia, Canada and Colorado and Montana in the USA (Myers unpublished; Smith ,2004; Saestedt *et al.*, 2003). While the other established biological control agents reduce seed production of diffuse knapweed, *L. minutus* reduces both seed production and plant survival. Damage to flowering plants can be severe particularly in dry summers. The impact of *L. minutus* on diffuse knapweed in British Columbia was demonstrated after a fire removed both knapweed and biological control agents from a site. The seed bank of knapweed was sufficient for a resurgence of dense plant populations and over three years *L. minutus* returned to once again suppress the knapweed (Myers unpublished). These observations suggest that *L. minutus* is an effective control agent and sufficient to reduce the density of diffuse knapweed.

Discussion

These examples of recent biological control successes can be incorporated with the data previously summarized by Denoth *et al*. (2002) (Figure 1). In that review, based on Julien and Griffiths (1998) catalogue of biological control agents and weeds, diffuse knapweed control was attributed to the combined impact of eight agent species. This is curious because diffuse knapweed densities in British Columbia, upon which this value was based, had not declined prior to 1998. Therefore I suggest that this be changed since the decline of diffuse knapweed occurred following the establishment of *L. minutus* that is likely the agent most responsible for the successful control of diffuse knapweed, and I have incorporated this change in Figure 1.

One situation in which multiple species of agents may be necessary is when the target weed has a greater environmental range than the agent. For example the failure of *M. janthinus* to survive in Alberta, Canada suggests that another agent or strain of control agent may be necessary in the toadflax control programme (McClay and Hughes, 2007).

In this review I only considered published cases of biological control success. Less successful programs are unlikely to be described in publications and thus we cannot evaluate the impacts of the biological control agents in these. Cases of modest control by several agents may therefore be overlooked and understudied (Julien, personal communication). An exception is a recent report on the impact of the mite *Tetranychus lintearius* Dufor, on gorse, *Ulex europaeus* L. (Davies et al. 2007). This agent was originally recommended for use in gorse control by Zwölfer (1963) who observed dead plants in their native habitat that he thought had been killed by the mites. In the study of Davies et al. (2007) and others reviewed there, the mites have been found to reduce the growth and sometimes flower production of gorse. Damage from *T. lintearius* and 5 other species of biological control agents has been insufficient however to successfully control gorse measured as a reduction in the density of plants (Hill et al. 2000).

Although a majority of successful weed programmes can be attributed to a single agent, this observation does not help to identify the characteristics that will allow agents to be successful prior to their release. One factor that does stand out however is the ability of the agent to kill the target weed. It appears that accumulated impact of several types of feeding damage from different agents is not necessary for successful control. To reduce the number of releases of exotic species for biological control, the paradigm should change from the assumption that multiple agents are required to a greater focus on identifying potential biological control agents that can kill host plants. Introducing fewer agents per programme would make biological control of weeds more efficient, less costly, and more environmentally benign. More focus on the potential efficacy of biological agents could be cost effective (McClay and Balciunas 2005).

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Table 1. Summary of recently reported successful biological control of weed programs. **Est.** is the number of agents that are established in the program. Successful agents are those to which success has been attributed.

Weed	**Country**	**Est.**	**Successful Agents**	**Reference**
Mimosa pigra	Australia	8	*Carmenta mimosa*	Paynter (2005)
Asparagus asparagoides	Australia	3	*Puccinia myrsiphylii*	Morin and Edwards (2006)
Linaria dalmatica	Canada – BC USA	1	*Mecinus janthinus*	De Clerck-Floate and Harris (2002) Nowerski (2004) Hansen (2004)
Azolla filiculoides	South Africa	1	*Stenopelmus rufinasus*	McConnachie *et al*., (2004)
Ageratina riparia	New Zealand Hawaii	2 3	*Entyloma ageratinae*	Barton *et al*., (2007) Trujillo (2005)
Passiflora tarminiana	Hawaii	1	*Septoria passiflorae*	Trujillo (2005)
Cynoglossum officinale	Canada	1	*Mogluones cruciger*	De Clerck-Floate and Schwarzländer (2002)
Lythrum salicaria	Canada	1	*Galerucella calmariensis*	Lindgren *et al*., (2002) Denoth and Myers (2005)
Centaurea stroebe	Montana	12	*Cyphocleonus achates*	Story *et al*., (2006)
Centaurea diffusa	British Columbia, Colorado, Montana	12	*Larinus minutus*	Myers unpublished) Saestedt *et al*., (2003) Smith (2004)

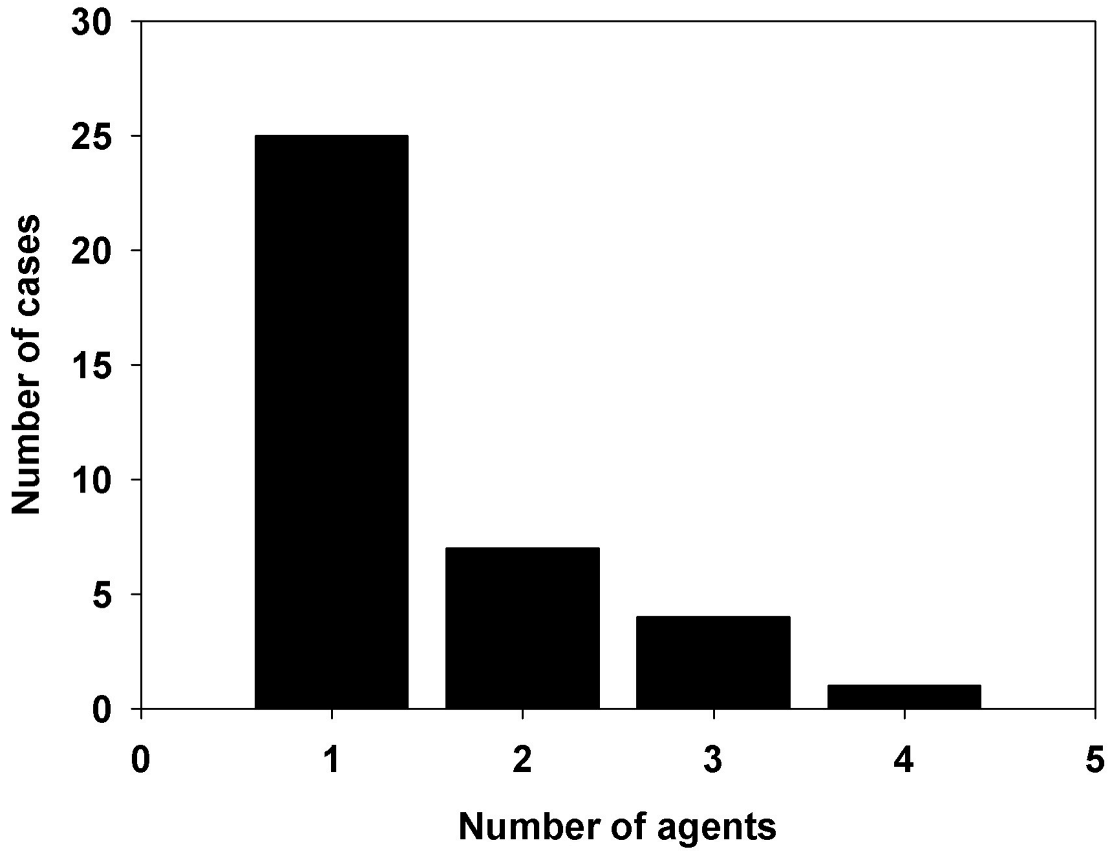

Figure 1. Number of agents considered to have contributed to the successful biological control of weeds. In this figure 10 new successful projects are added to those summarized by Denoth *et al*., (2002) and instead of attributing success to the eight agents established in biological control of diffuse knapweed programs, with the success of *L. minutus*, this project is moved to the category in which one agent was successful.