Impact evaluation of weed biological control in Australia: lessons from a quantitative review

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Summary  Evaluation of the impact of biological control programs is often neglected due to inadequate time and resources, or the perception that any successful outcomes will be clearly noticeable. In this paper, the biocontrol literature was quantitatively reviewed to assess the methodologies used in past evaluation studies and to estimate the overall impact of biocontrol in Australia. Impact of biological control agents have been mainly measured in terms of damage on individual plants and reductions in weed population densities, but other broader ecological impacts are rarely evaluated. This review highlights that biological control agents have had considerable impact on both individual target weeds and populations in Australia. However, the methodology used influences the extent to which impacts are detected.

Keywords  Quantitative review, weed biological control, impact evaluation, methodology.

INTRODUCTION

Quantitative studies focusing on evaluating impacts of agents are essential to assess the true benefits of weed biological control programs in Australia. Impact evaluation studies are particularly important to justify continued investment in biological control and to provide crucial knowledge to make informed decisions in future programs. Lack of adequate funding and resources is the main reason that impact studies of released agents are not systematically undertaken (Dhileepan 2003a). As a result, post-release studies are frequently confined to short-term assessments of agent establishment (McClay 1995).

There are many ways to evaluate biological control programs using a range of demographic, economic and social indicators (Syrett et al. 2000). Nevertheless, many biological control programs in Australia have not been quantitatively and objectively evaluated (McFadyen 1998). For example, programs against Opuntia stricta (Haw.) Haw. (prickly pear) and Salvinia molesta D.S.Mitch. were branded as successful within relatively short time frames, with limited quantitative data (Dhileepan 2003a). In most programs, however, impact of agents are more subtle and gradual and long-term monitoring across a number of sites is required to demonstrate impact of the agents against a background of environmental and temporal variability (McClay 1995).

In this paper, I present a review of the published biological control literature, where the impacts of released agents have been evaluated in Australia. By analysing these studies following a vote counting approach (Hedges and Olkin 1985) the overall impact of biocontrol in Australia is estimated. The strengths and weaknesses of various methodologies used in past evaluation studies are also discussed.

MATERIALS AND METHODS

Literature search  Weeds targeted for biological control in Australia for which establishment of at least one agent has been confirmed were identified from Julien and Griffiths (1998), with updates (to 2004) provided by J.K. Scott and M. Julien (unpublished). The citation database ‘Web of Science’ (1986–2006), and Proceedings of the Australian Weeds Conferences (1990–2004) and Proceedings of the International Symposium on the Biological Control of Weeds (1985–2003) were then searched for evaluation studies investigating each weed-agent combination. The majority of studies focused on single agent impacts, although some noted the presence (and/or negligible impact) of other agents. Four studies used chemical exclusions to examine multiple agent impacts (from either insects or fungi) rather than individual agent impacts.

Categorisation of studies  Studies were considered only if agent impacts had been statistically analysed at the individual plant, population or community levels. Studies focusing on individual plants were categorised according to type of measurements taken, including above-ground components (combining the number, size and biomass of above ground parts), below-ground components (including number, size or biomass of below ground parts) and reproduction (such as the number and biomass of flowers, fruits and seeds). Studies investigating population or community responses were categorised according to measurements made on seed, seedling and weed densities or the number and density of other plant species. The methodology used in each study was also categorised, including study type (experiment or survey), conditions (laboratory...
or field) and design (control versus treated or before versus after comparisons). These categories were then used to determine the predominant methodologies and types of measurements used in the literature.

**Vote counting analysis** When analysing the effect of biological control on weeds, different sites and measurements (within studies) were considered as independent observations and only data collected at the end of the study were included (where you would expect the greatest impact from biocontrol). Therefore, 40 studies generated 228 observations which were analysed using a vote counting methodology (Hedges and Olkin 1985) to determine the number of significant positive and negative responses of individual weeds, weed populations or communities exposed to biological control agents.

**RESULTS**

**Overall impact of biocontrol** In this review, the efficacy of 79 established biocontrol agents (including insects, pathogens and mites) for 20 weed species (across 40 studies) were assessed (see Julien and Griffiths 1998, J.K. Scott and M. Julien unpublished). There was quantitative data available for 85% of the weeds covered in this review, although this covered only 37% of established agents. Across all studies and weed species, significant reductions in all weed measurements (including individual and population measures) due to biocontrol were recorded for 59% of observations. In contrast, an increase in weed measurements was recorded in only 2% of studies after biocontrol was implemented.

**Types of measurements** Sixty five percent of studies comprised measurements at the individual plant level, while only 30% of studies included measurements at the population level. Only two studies incorporated community or ecosystem level measurements. The majority of individual plant measurements were made on above-ground components (75% of studies), reproductive output (66% of studies) and below-ground components (28% of studies). The number, size or biomass of above-ground components mainly declined in response to attack by biological control agents, although these impacts did not always lead to reductions in reproductive output (Figure 1). The impact of biological control agents on below-ground parts were less than for above-ground components, although this may not be accurate because fewer studies included these measurements (Figure 1).

Only 30% of studies occurred at the population level and showed that weed, seed and seedling densities were generally reduced after biological control (Figure 1). The indirect effects of biological control agents on the plant communities associated with the target weed (e.g. abundance of other plant species) were only measured in two studies, making it impossible to draw any generalisations.

![Figure 1](image-url) The number of observations where individual weeds, weed populations or community measures significantly decreased (black), were not affected (grey) or significantly increased (white) in response to biological control.
Types of studies  Field manipulative experiments were the most common methodology used in studies (45% of studies), followed by laboratory/glasshouse experiments (27.5% of studies) and field surveys (27.5% studies). Field manipulative experiments compare sites where the agents have been excluded, using either repeated chemical application (65% of studies) or cages (35% of studies), to sites where the biocontrol agent is present. A study was categorised as a field survey (rather than field manipulative experiment) either because comparisons (of control and impacted plants or sites) did not involve any direct manipulation of the agent or where no formal controls in real time were used (as for before/after comparisons). The majority of field surveys consisted of temporal comparisons of sites before and after release of biocontrol agents (42%). In 33% of cases, field surveys consisted of spatial comparisons between ‘control’ plants or sites (which are free of biocontrol agents without the use artificial exclusion techniques) and plants or sites attacked by agents. The remaining field surveys (25%) either correlated agent density with impact (at plant level) or involved monitoring sites where the agent had established over time (without any before-release data). The negative impact of biocontrol agents on individual weeds was highest when experiments were conducted in the laboratory/glasshouse, followed by field surveys (Figure 2). No impact was detected in almost 55% of observations made in field manipulative experiments that utilised insecticide or fungicide to exclude biocontrol agents in control plots (Figure 2).

DISCUSSION
The first measure of success for a biological control program is whether the released agent has established (Syrett et al. 2000), but true success is judged by the impact on the target weed and its population dynamics (McFadyen 1998).

From the review, the impact of only 37% of established biocontrol agents were evaluated in the laboratory or field. In these studies, biological control agents generally caused significant reductions in the vegetative components of individual weeds. In some weed-agent combinations a reduction of plant vegetative parts translated into significantly reduced seed output (Dhileepan et al. 2000); however, reproductive capabilities were not always affected, particularly when agent densities varied spatially or temporally due to environmental fluctuations or competition from other biocontrol agents (see Briese and Jupp 1995).

Impact data on individual weeds provides some indication of agent effectiveness; however, it is necessary to monitor weed population densities over several sites and years to judge the success of a biocontrol agent (Dhileepan 2003a). While the review identified some studies where agents exerted a negative impact on weed populations (e.g. Lonsdale et al. 1995), only 30% of studies involved population level measurements.

The indirect effects of biocontrol agents on non-target species and ecosystem processes are also important components of the evaluation process (Blossey 2002). For example, does a highly effective biocontrol agent for a weed lead to weed substitution or restoration of native species? Simply removing or reducing the dominant target weed may not promote native species colonisation, particularly if the community has become fundamentally altered prior to or since invasion (Thomson and Leishman 2004).

The majority of studies used experimental manipulations, in either the laboratory or field, to evaluate impacts of biocontrol agents. Laboratory/glasshouse experiments are useful for exploring the interaction between the weed and its agent under controlled conditions, but they have a tendency to overestimate impact (McCay 1995). On the other hand, manipulative field experiments are recommended to obtain a more accurate assessment of agent impacts (McCay 1995); however, they too have their drawbacks. Manipulative field experiments involving chemical exclusion of agents are costly and difficult to maintain and are invariably performed over relatively short time periods (Crawley 1989, Dallapaan 2003a). Additionally, exclusion experiments can interfere with fundamental plant processes (such as pollination and seed set when insecticides are used; Lonsdale and Farrell 1998).

Field surveys have commonly been used by biocontrol practitioners to assess agent impact. Field surveys are particularly convincing if they include before-release measurements of plant population

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**Figure 2.** The number of observations, based on study type, where individual weed or population measures significantly decreased (black), were not affected (grey) or significantly increased (white) in response to biological control.
parameters to provide base-line data and subsequently document consistent declines in weed densities over time and across sites. However, without the inclusion of a formal control, where the agent was not released and/or excluded, it is difficult to separate the effect of the agent from other confounding factors (McClay 1995).

This review indicates that biological control has had considerable impacts on both individual weeds and weed populations. However, we still lack the data to evaluate the true success of biological control for many weed species in Australia (McFadyen 1998). Essentially, the evaluation phase of biological control programs should move beyond short-term measures of agent establishment and individual plant damage to quantifying impacts of agents on weed populations and associated plant and animal communities (Blossey 2002, McClay 1995).

This review was limited to published studies, which inevitably under-estimates highly successful agents, such as Cactoblastis sp. released on prickly pear (Dhileepan 2003a). More importantly it did not include failures, which are rarely documented in the literature. Vote counting methods only consider significant results, which are biased towards studies with large sample sizes and statistical power (Hedges and Olkin 1985). A future review of the impacts of biological control agents will employ meta-analysis techniques (Hedges and Olkin 1985) to calculate the effect size of all studies regardless of their statistical significance.

ACKNOWLEDGMENTS
Funding for this project was generously provided by the CRC for Australian Weed Management. I would also like to thank Louise Morin, Ricky Spencer and an anonymous referee for their thoughtful comments on the manuscript.

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