SESSION 1

Successes in Biological Control of Weeds

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Abstract

There have been many successes world-wide in the biological control of weeds. Forty-one weeds are listed which have been successfully controlled using introduced agents (insects and pathogens) and a further three which are controlled using native fungi applied as mycoherbicides. Many of the successes have been repeated in subsequent programs in different countries or continents. Biological control programs have saved millions of dollars and, despite the high initial costs, are very cost-effective. Why then are biological control successes not more generally recognised? This can be attributed to: failures from poorly resourced programs; long time lag (20 years or more) required to achieve full success; failure to record or remember the full extent of the pre-biocontrol weed infestations. Biocontrol scientists need to publicize their successes so that biological control is appreciated as a truly successful, cost-effective and environmentally-sustainable method of weed control.

Keywords: Biological control, successes, weeds

Introduction

When I told one of my colleagues (not a biocontrol scientist!) that I was writing a talk on successes in weed biocontrol, he replied “that will be a short paper.” My aim in this talk is to counteract this quite unjustified but unfortunately common negative view, and to remind all of us, biocontrol workers as well as the world in general, that there have been a long list of successes in the biological control of weeds, and very few failures. In all seriousness, the perception that biological control is always uncertain, costly and slow, and often if not usually unsuccessful, is a serious handicap to the adoption of the method. Decisions on whether weeds are suitable targets for biocontrol programs are based partly on the likely benefits, and partly on estimates of the probability of success (Cullen 1995; Peschken and McClay 1995; Wapshere *et al.* 1989). Consequently, if the probability of success is wrongly judged to be very low, the decision will be made to invest resources into other control methods, and biocontrol will not be attempted until the other methods have failed. By this time, the weed and the control methods used may have caused severe environmental as well as economic damage (McFadyen 1992).

Ignorance of past successes can also lead to untested theories becoming established dogma which again wrongly affect the decisions made (Chaboudez and Sheppard 1995). For example, it has been believed that biocontrol of trees is particularly difficult, yet there are several examples of trees controlled by insects (Dennill and Donnelly 1991; Mack 1996). Classical biocontrol has been seen as unsuitable for weeds of annual crops or other frequently disturbed environments (Duke 1997; Reznik 1996), yet there are examples of successful control of crop weeds (Chippendale 1995; Marsden *et al.* 1980). Other writers take the same data to show that the "weeds most susceptible to biocontrol are short lived herbaceous plants" and they therefore conclude that successful control of a perennial shrub is unlikely (Rea 1998). Plants reproducing sexually were judged hard to control because of their genetic variation (Burdon and Marshall 1981), but further analysis has shown this to be untrue (Chaboudez and Sheppard 1995). The probability of success is presumed to be reduced where the weed has close relatives of economic or conservation value, because agents selected must be monophagous (Olckers *et al.* 1995). However, true monophagy is not as rare as is sometimes supposed; the gall fly Procecidochares connexa responsible for the successful biocontrol of Chromolaena odorata in Indonesia, and its congeners P. alani and P. utilis used for control of their host plants, are all genuinely restricted to a single host species (Julien and Griffiths 1998). The chrysomelids Leptinotarsa texana and L. defecta introduced into South Africa to control the weed Solanum elaeagnifolium do not attack closely related crop plants in the genus Solanum (Hoffmann *et al.* 1998). Pathogens are also often specific to a single plant species or even strain (Evans and Tomley 1996; Hasan 1972).

Definitions

Any consideration of successes is bedevilled by the problem of assessment - when is control "successful"? As in my earlier review (McFadyen 1998), I propose to follow Hoffmann's (1995) definitions for success: complete, when no other control method is required or used, at least in areas where the agent(s) is established; substantial, where other methods are needed but the effort required is reduced (eg less herbicide or less frequent application); and negligible, where despite damage inflicted by agents, control of the weed is still dependent on other control measures. "Complete" control does not mean the weed is eradicated, or is no longer an important component of the weed flora, but that control measures are no longer required solely against the target weed, and that crop or pasture yield losses cannot be chiefly attributed to this weed (Chippendale 1995; McEvoy et al 1991). "Substantial" control includes cases where control may be "complete" in some seasons and/ or over part of the weed's range, as well as situations where the control achieved is widespread and economically significant but the weed is still a major problem.

It is clear from this definition that success is the successful control of the weed, not the success of individual agents released against the weed. In most published analyses of weed biocontrol, there is confusion on this issue, and success rates are generally quoted as the % of agents which establish and contribute to successful control. Overall, about 60% of agents establish, with 33% of these resulting in control of the weed (Crawley 1989b, 1990; Williamson and Fitter 1996). The absurdity of using this as the measure of success can be shown by the famous prickly pear example. A total of 12 insects were released in Australia against prickly pear *Opuntia stricta (= inermis)* between 1921 and 1932 (Julien and Griffiths 1998). Of these, 7 established and 2 (*Dactylopius opuntiae* and *Cactoblastis cactorum*) were responsible for the successful control; that is, 42% of the agents failed and only 17% contributed to success. Many analyses would calculate this as a success rate of 17%. To me this is nonsense - the program to control the weed was successful and the success rate was therefore 100%. The time taken and additional unsuccessful agents introduced were equivalent to trials needed to perfect a new herbicide; they add to the development costs but do not enter into calculations of success rates.

This is not just a semantic issue; success rates quoted as "24% of agent releases were considered to impart effective weed control" become in the same review a "widely accepted 75% failure rate", which is then taken as a reason to question the whole practice and philosophy of biological control (Rea 1998). Yet when governments and others who make weed management decisions are considering biocontrol as a management option, the success rate of interest to them is the probability that the weed can be controlled biologically. They also need an estimate of the likely time factor to achieve success (10 to 20 years on average), and of the cost of the whole program. It is irrelevant whether 1 or 20 separate agents will be needed, except insofar as each extra agent increases costs and time delays. In South Africa, 6 weeds out of 23 targeted are under complete control and a further 13 are under substantial control, giving a success rate of 83% (Hoffmann 1995). In Hawaii, 7 weeds out of 21 are under complete control, and substantial control has been achieved for 3 more, giving a success rate of nearly 50% (Gardner et al 1995; Markin et al 1992). In Australia, of 15 completed programs, 12 resulted in complete control, ie 80%. Of 21 on-going programs commenced before 1986, 4 have achieved complete control and 3 substantial (and still improving) control, ie 33%, giving an overall success rate of 51% (numbers from the table in Briese 1999).

Failures are discussed in more detail in the next session led by Judy Myers, but in my view a program is a failure not when individual agents have failed, but only when the program as a whole has failed, ie the weed is still not adequately controlled.

Examples of Successful Biological Control of Weeds with Introduced Insects and Pathogens

Data from Olckers *et al.* 1998, Briese 1999, and Julien and Griffiths 1998. Plant order as in Julien and Griffiths except aquatic plants are grouped at the end.

Weed species	Agents introd./ contrib. to success	Countries
Ageratina adenophora	2/2	Hawaii
Ageratina riparia	3/3	Hawaii
Carduus acanthoides	3/2	USA
Carduus nutans	5/2	Canada, USA
Carduus tenuiflorus	4/1	USA
Centaurea diffusa	14/5	Canada, USA
Centaurea maculosa	13/4	Canada, USA
Chondrilla juncea	4/1	Australia, USA
Chromolaena odorata	3/2	Guam, Ghana, Indonesia, Marianas

Weed species	**Agents introd./ contrib. to success**	**Countries**
Senecio jacobaeae	6/4	Australia, Canada, New Zealand, USA
Xanthium strumarium (occidentale)	5/2	Australia
Harrisia martinii	2/1	Australia, S Africa
Opuntia aurantiaca	6/1	Australia, S Africa
Opuntia elatior	1/1	India, Indonesia
Opuntia ficus-indica	9/3	Hawaii, S Africa
Opuntia imbricata	1/1	Australia, S Africa
Opuntia leptocaulis	1/1	S Africa
Opuntia littoralis	1/1	USA
Opuntia oricola	1/1	USA
Opuntia streptacantha	6/2	Australia
Opuntia stricta	9/2	Australia, India, New Caledonia, Sri Lanka
Opuntia triacantha	3/2	West Indies
Opuntia tuna	3/2	Mauritius
Opuntia vulgaris	4/2	Australia, India, Mauritius, S Africa, Sri Lanka
Hypericum perforatum	11/2	Canada, Chile, Hawaii, S Africa, USA
Cordia curassavica	3/2	Malaysia, Mauritius, Sri Lanka
Euphorbia esula	18/3	Canada, USA
Sesbania punicea	2/2	S.Africa
Hydrilla verticillata	4/1	USA
Lythrum salicaria	4/2	USA
Sida acuta	2/1	Australia

Weed species	Agents introd./ contrib. to success	Countries
Clidemia hirta	7/1	Fiji, Hawaii, Palau
Acacia saligna	1/1	S Africa
Mimosa invisa	2/1	Australia, Cook Islands, Micronesia, PNG
Emex australis	4/1	Hawaii
Tribulus cistoides	2/2	Hawaii, PNG, West Indies
Tribulus terrestris	2/2	Hawaii, USA
Alternanthera philoxeroides	3/1	Australia, China, New Zealand, USA
Pistia stratiotes	1/1	Australia, Botswana, Ghana, PNG, S Africa, USA, Zambia, Zimbabwe
Salvinia molesta	1/1	Australia, Fiji, Ghana, India, Kenya, Malaysia, Namibia, PNG, S Africa, Sri Lanka, Zambia, Zimbabwe
Eichornia crassipes	7/2	Australia, Benin, India, Indonesia, Nigeria, PNG, S Africa, Thailand, Uganda, USA, Zimbabwe

The listed 41 weeds have been successfully controlled somewhere in the world using introduced insects and pathogens (Table 1). A further three are regularly controlled using indigenous fungi applied as a mycoherbicide: northern jointvetch *Aeschynomene virginica* in the USA using the fungus *Colletotrichum gloeosporoides*, milkweed vine *Morrenia odorata* also in the USA using the fungus *Phytophthora palmivora*, and broomrape *Orobanche ramosa* in the Ukraine and Hungary using *Fusarium* spp. (Julien and Griffiths 1998). With many of these weeds, the successful control has been repeated in several countries and regions of the world, and the savings to agriculture and the environment are enormous. Economic evaluations of classical biocontrol, for both arthropod and weed pests, have been recently reviewed for Australia (Cullen and Whitten 1995). The successful biocontrol of Noogoora burr in Queensland resulted in annual benefits (in 1991) of US$720,000, a return of 2.3:1 (Chippendale 1995). Evaluations of the successful control of skeleton weed (*Chondrilla juncea*) (Marsden *et al.* 1980) and of tansy ragwort (Coombs *et al.* 1995), have demonstrated benefit-cost ratios of 112 and 15. In South Africa, it is estimated that biocontrol programs have already saved $276 million in weed control costs (Olckers *et al.* 1998). Biocontrol programs also result in substantial non-economic benefits, in sustainability of the success, and in equity, in that benefits are not limited to those who can afford the product (Doeleman 1989). Costs are the risk of failure, and possible damage to non-target species (Cullen and Delfosse 1985).

Major successes in the last two decades include tansy ragwort (*Senecio jacobaea*) in the USA (McEvoy *et al.* 1991), and nodding thistle *Carduus nutans* in Canada and the USA (Frick 1978; Harris 1984). Less well known examples are the successful control of *Cordia curassavica* in Malaysia after the earlier success in Mauritius (Ooi 1992), of the annual weed Noogoora burr in Australia (Chippendale 1995; Morin *et al.* 1996), of Harrisia cactus, *Eriocereus martinii*, in Australia (McFadyen 1986) and of the annual weed *Mimosa invisa* in Australia, Papua New Guinea (Ablin 1995, Kuniata 1994), and the Cook Islands. The perennial shrub *Chromolaena odorata* has been successfully controlled in the Marianas (Siebert 1989) and now in large areas of northern Sumatra (R Desmier de Chenon and A Sipayung unpublished data). The perennial shrubs Hamakua pamakani *Ageratina riparia*, and Klamath weed *Hypericum perforatum*, are now under complete control in Hawaii (Gardner *et al.* 1995; Markin *et al.* 1992). The trees *Acacia saligna* and *Sesbania punicea* have been successfully controlled in South Africa (Morris 1997; Hoffmann and Moran 1998). Immediately following in this session, a paper by Flanagan *et al.* will describe the successful control of *Sida acuta* in northern Australia, another by Mic Julien will present results from the successful control of water hyacinth in PNG, and Kroschel *et al.* will describe the successful development of mycoherbicides to control parasitic weeds in crops in Africa.

The programs against floating water weeds have been the outstanding success of the last two decades. Three water weeds - water lettuce *(Pistia stratiotes)*, water hyacinth (*Eichhornia crassipes)* and salvinia *(Salvinia molesta)* - have been successfully controlled where they have been major weeds in the tropics and sub-tropics (Chikwenhere and Forno 1991; Harley 1990; Harley *et al.* 1990; Julien *et al.* 1996; Room *et al.* 1981; Thomas and Room 1985), and a fourth alligator weed *(Alternanthera phileroxoides*) successfully controlled in aquatic habitats in sub-tropical climates (Julien and Chan 1992). These successes are particularly noteworthy because they illustrate almost every major theme in biological control of weeds: doubts regarding the chances of success; initial failures; successes transferable world-wide; enormous financial and social benefits.

At the start, F.O. Wilson, leader at the time of biological control of weeds in Australia, expressed doubts (which he admitted were based largely on lack of adequate information) regarding the host-specificity of aquatic plant-feeding insects (Wilson 1964). Ten years later, these doubts were still being expressed although host-testing of the insects ultimately successful against alligator weed and water hyacinth was largely completed by then (Andres and Bennett 1975). There was early success with water hyacinth in the USA, but implementation of successful biocontrol in other countries has been slow, and is only now gaining momentum (Table 1) (Julien and Griffiths 1998; Julien this session). The program against salvinia was a failure initially as the agents tested and introduced from northern South America, including the weevil *Cyrtobagous singularis*, were not successful. Ten years later, new surveys in southern Brazil found the weevil *Cyrtobagous salviniae*, initially thought to be a host-race of the first species but subsequently shown to be a new species with a different biology which was significantly more damaging to the host plant (Sands and Schotz 1985). This weevil has since successfully controlled salvinia in all tropical and sub-tropical countries where it has been introduced (Table 1) (Julien and Griffiths 1998).

Financial and social benefits from control of water hyacinth and salvinia in particular have been enormous. Because waterways are used for transport as well as fisheries, irrigation, and water supply, the entire society can be disrupted or even destroyed if movement between villages is prevented by dense mats of floating water weeds. This was the situation caused by salvinia in the Sepik river in PNG, and by water hyacinth in the rivers of southern Irian Jaya on the same island, as well as many other areas of the world. Control by chemical or mechanical means was impossible, as the areas involved were so large and the weed multiplied so fast. It is hard therefore to place a dollar cost on the benefits from the successful control of these weeds, but the value of the continued prosperity and production of the villages must be several million dollars annually. When the weevil was used to control salvinia in Sri Lanka, the benefit/ cost ratio was calculated to be 1675:1! - costs were low because the weevil had already been tested and used in Australia (Doeleman 1989).

Why then, in view of this long list of successes, can my colleague, and so many like him, continue to believe that biological control of weeds has seldom worked? One major problem is that people forget, and early successes are forgotten. Sometimes the actual example is forgotten, *eg* the successful control of the small tree *Cordia curassavica* in Mauritius and then Malaysia has been almost totally forgotten, and few people now remember that a perennial woody tree can be successfully controlled by a defoliating beetle. More usually, a success is quoted from time to time, but the community has forgotten just how serious was the weed problem, and how much damage to ecosystems was being caused by the massive infestations of the weed.

Forgetting happens quickly - how many people are aware how serious were the salvinia infestations in the Sepik river in PNG in the 1970s and 80s? And how rapidly they were controlled by the release of the cyrtobagous weevil in 1982? Other examples are klamath weed in the western USA and thistles in Canada and the USA, where most people no longer realise just how serious, widespread and invasive these weeds were. Reports published at the time are seen as out of date, and the success then questioned by later authors with no experience of the original infestations of the weed (Shea and Kelly 1998). In other instances, the community may not even realise that they are benefitting from successful biocontrol. For example, in the Brisbane river system in northern Australia, water hyacinth has been a problem since the early 1900s. Water hyacinth does not grow in the stretches through Brisbane city, where the river is tidal and brackish. However, it grows readily in the creeks, side channels and dams in the catchment of the Brisbane and its tributary the Bremer rivers, and in the past would periodically block these completely. Then heavy rain in the catchments would cause flooding, and the water hyacinth would be washed down to form dense mats in the city reaches of the river, blocking ferries, threatening bridges, and causing amazement to the locals. Major infestations occurred in the 1900s, in the 1940s and the 1960s, and in the major flood of 1974. Since then, although climatic conditions have been ideal, with dry summers in the 1980s and 1990s interspersed with floods in 1992 and again early in 1999, there have been no dense infestations of water hyacinth in the upper catchment and no floating mats coming downstream with the floods. The introduction and rapid establishment of the weevils *Neochetina eichhorniae* in 1975 and *N. bruchi* in 1990 (Wright 1996) has resulted in the effective control of the weed in the areas where it used to proliferate. Yet because of the sporadic nature of the problem, even Brisbane's weed scientists are largely unaware of this success, and unfortunately, this is not unusual.

The Future

Many analyses of success rates suffer from the inclusion of data from recent programs before equilibrium has been reached. As effective agent establishment may take many years (REC McFadyen unpublished data; Vitelli *et al.* 1996) and control up to 10 years after that (Hoffmann 1995), no program should be judged a success or failure until at least 10 years after the release of the last agent. However, there are some current programs with very promising early indications of success. Rubbervine (*Cryptostegia grandiflora*) is being very heavily damaged in north Queensland by the introduced rust disease *Maravalia cryptostegiae* and the moth *Euclasta ahelleyi* (M.Vitelli pers. comm. 1999), and there are promising results with the control of *Solanum eleagnifolium* in South Africa (Hoffmann *et al.* 1998). Also in South Africa, the recent introduction of a better-adapted host race of the cochineal *Dactylopius opuntiae* from Australia has resulted in greatly improved control of the prickly pear *Opuntia stricta* (Volchansky *et al.* 1999)

There are also some partial successes that have already resulted in major benefits, even though work is continuing in the hope of achieving complete success (Hoffmann 1995). For example, in the program against parthenium weed in Australia, nine insects and a rust have been introduced (Navie *et al.* 1998), with a second rust introduced later in 1999 (Seiers and Tomley this proceedings). Despite successful establishment of most of the agents, parthenium weed remains a major problem and the program is not yet regarded as a success. However field experiments using insectide-treated check plots have demonstrated that the reduction in parthenium already achieved is responsible for increased pasture growth worth between $1 million per annum, depending on climatic conditions and beef prices. Calculated over the 50 years since the program began, the cost/benefit ratio for even this partial success is 2:1 with a 6% discount rate, or 3.7:1 with a 2% discount rate (Adamson and Bray 1999). Many other programs could demonstrate similar results if resources were made available for the necessary field experiments.

Discussion

To sum up, there have been many successes in the biological control of weeds. I have listed 44 weeds which have been successfully controlled and where biological control is now the only or preferred method of control used. These are 44 separate weed species; for many of them, this represents successful programs in several countries on different occasions. For example, cordia was successfully controlled in both Mauritius and Malaysia, *Mimosa invisa* in Australia, PNG and Pacific countries, and the water weeds in many countries over three continents. Overall, I would suggest that there is an 80 or even 90% probability that a properly resourced and conducted program of biological control will result in satisfactory control of the weed.

So what is the problem? Why is biological control still seen as unreliable, with a poor success rate and an uncertain future? I believe there are three main reasons:

- too many programs are poorly resourced. A program against a new weed, where there is no previous information and overseas exploration is required, will cost between $200,000 and $500,000 per year for 5 to 15 years, ie a total of about $3 to $8 million. This still represents very good value for money, but too often countries which cannot afford this outlay attempt to run programs on limited resources or for a few years only, and this necessarily reduces the probability of success.

- successful control may develop gradually and take up to 20 years for full results. Political and financial time frames are usually much shorter than this, and as a result, many programs are prematurely declared failures.

- memories and working lives are also short, often less than 20 years, consequently few scientists involved at the start of weed control programs are still there when success is achieved. Early photographs are not properly archived and consequently the full extent of the success may not be appreciated.

If I am right, it is up to us as biological control scientists to publicise our successes. We owe it to the environment to promote biological control for what it is - the only safe, cost-effective, and sustainable method of weed control, with a success rate of at least 80% overall.

References

Ablin, M.P. 1995. *Heteropsylla* sp. (Psyllidae) successfully controls pasture infestations of *Mimosa invisa* within three years of release in Australia. *In* Delfosse ES, Scott RR [eds.], 1995. Proc. 8th Int. Symp. Biol. Control Weeds. Melbourne: CSIRO. pp. 435-6

Adamson, D., and S. Bray. 1999. Re-economic benefit from investing in parthenium (*Parthenium hysterophorus*) inext biological control. Unpubl. rept., June 1999. RDE Connections, V. Qld., Bristane, Australia

Andres, S.A., and F.D. Bennett. 1975. Biological Control of Aquatic Weeds. Annu. Rev. Ent. 20:31-46.

Briese, D.T. 1999. Classical biological control. In Australian Weed Management Systems, B. Sindel [ed.]. RG and FJ Richardson Publ., Melbourne (in press).

Burdon, J.J., and D.R. Marshall. 81. Biological control and the reproductive mode of weeds. J. Appl. Ecol. 18: 49-58

Chaboudez, P., and A.W. Sheppard. 1995. Are particular weeds more amenable to biological control? - a reanalysis of mode of reproduction and life history. *In* Delfosse ES, Scott RR [eds.], 1995. Proc. 8th Int. Symp. Biol. Control Weeds. Melbourne: CSIRO. pp. 95-102

Chikwenhere, G.P., and I.W. Forno. 1991. Introduction of *Neohydronomus affinis* for biological controlof *Pistia stratiotes* in Zimbabwe. J. Aquat. Plant Manage. 29:53-5

Chippendale, J.F. 1995. The biological control of Noogoora burr *(Xanthium occidentale)* in Queensland: an economic perspective. *In* Delfosse ES, Scott RR [eds.], 1995. Proc. 8th Int. Symp. Biol. Control Weeds. Melbourne: CSIRO. pp. 185-92

Coombs, E.M., D.L. Isaacson, and R.B. Hawkes. 1995. The status of biological control of weeds in Oregon. *In* Delfosse ES, Scott RR [eds.], 1995. Proc. 8th Int. Symp. Biol. Control Weeds. Melbourne: CSIRO. pp. 463-71

Crawley, M.J. 1989b. The successes and failures of weed biocontrol using insects. Biocontr. News Inf. 10:213-23

Crawley, M.J. 1990. Plant life-history and the success of weed biological control projects. *In* Delfosse ES [ed.], 1990. Proc. 7th Int. Symp. Biol. Control Weeds. Rome: Min. Agric. Forest. pp. 17-26

Cullen, J.M. 1995. Predicting effectiveness: fact and fantasy. *In* Delfosse ES, Scott RR [eds.], 1995. Proc. 8th Int. Symp. Biol. Control Weeds. Melbourne: CSIRO. pp. 103-9

Cullen, J.M., and E.S. Delfosse. 1985. *Echium plantagineum:* catalyst for conflict and change in Australia. *In* Delfosse ES [ed.], 1985. Proc. 6th Int. Symp. Biol. Control Weeds. Ottawa: Agriculture Canada. pp. 249-92

Cullen, J.M., and M.J. Whitten. 1995. Economics of classical biological control: a research perspective. *In* Biological Control: Benefits and Risks [eds.], HMT Hokkanen, JM

Lynch, 270-6. Cambridge: University Press

Dennill, G.B., and D. Donnelly. 1991. Biological control of *Acacia longifolia* and related weed species (Fabaceae) in South Africa. Agric. Ecosyst. Environ. 37:115-35

Doeleman, J.A. 1989. Biological control of *Salvinia molesta* in Sri Lanka: an assessment of costs and benefits. ACIAR Technical Reports 12, Canberra

Duke, S.O. 1997. Weed science directions in the USA: what has been achieved and where the USA is going. Plant Prot. Quart. 12:2-6

Evans, H.C., and A.J. Tomley. 1996. Greenhouse and field evaluations of the rubber vine rust, *Maravalia cryptostegiae,* on Madagascan and Australian Asclepiadaceae. *In* Moran VC, Hoffmann JH [eds.], 1996. Proc. 9th Int. Symp. Biol. Control Weeds. Stellenbosch, University of Capetown. pp. 165-9

Frick, K.E., ed. 1978. Biological Control of Thistles in the genus Carduus in the United States. USDA. 50 pp.

Gardner, D.E., C.W. Smith, and G.P. Markin. 1995. Biological control of alien plants in natural areas of Hawaii. *In* Delfosse ES, Scott RR [eds.], 1995. Proc. 8th Int. Symp. Biol. Control Weeds. Melbourne: CSIRO. pp. 35-40

Harley, K.L.S. 1990. The role of biological control in the management of water hyacinth, *Eichhornia crassipes.* Biocontr. News Inf. 11:11-22

Harley, K.L.S., R.C. Kassulke, D.P.A. Sands, and M.D. Day. 1990. Biological control of water lettuce, *Pistia stratiotes* (Araceae), by *Neohydronomus affinis* (Coleoptera: urculionidae). Entomophaga 35:363-74

Harris, P. 1984. *Carduus nutans* L., nodding thistle, and C. *acanthoides* L., plumeless thistle (Compositae). *In* Biological Control Programmes against Insects and Weeds in Canada 1969-1980, ed. JS Kelleher, MA Hulme, 115-26. Farnham Royal: Commonw. Agric. Bur.

Hasan, S. 1972. Specificity and host specialization of *Puccinia chondrillina.* Annals Appl. Biol. 72:257-63

Hoffmann, J.H. 1995. Biological control of weeds: the way forward, a South African perspective. Proc. BCPC Symp. 1995, 64: Weeds in a Changing World. pp. 77-89. Brighton: BCPC

Hoffmann, J.H., and V.C. Moran. 1998. The population dynamics of an introduced tree, Sesbania punicea, in South Africa, in response to long-term damage caused by different combinations of three species of biological control agents. Oecologia 114:343-348.

Hoffmann, J.H., V.C. Moran, and F.A.C. Impson. 1998. Promising results from the first biological control programme against a solanaceous weed (Solanum elaeagnifolium). Agric. Ecosyst. Environ. 70: 145-150

Hosking, J.R., R.E.C. McFadyen, and N.D. Murray. 1988. Distribution and biological control of cactus species in eastern Australia. Plant Prot. Quart. 3:115-23

Julien, M.H., and M.W. Griffiths. 1998. Biological Control of Weeds: a World Catalogue of Agents and their Target Weeds. Wallingford, Oxford: CAB Int. 4th ed. 223 pp.

Julien, M.H., K.L.S. Harley, A.D. Wright, C.J. Cilliers, and M.P. Hill, 1996. International cooperation and linkages in the management of water hyacinth with emphasis on biological control. *In* Moran VC, Hoffmann JH [eds.], 1996. Proc. 9th Int. Symp. Biol. Control Weeds. Stellenbosch, University of Capetown. pp. 273-82

Kuniata, L.S. 1994. Importation and establishment of *Heteropsylla spinulosa* (Homoptera: Psyllidae) for the biological control of Mimosa invisa in Papua New Guinea. Int. J. Pest Manage. 40:64-5

Mack, R.N. 1996. Biotic barriers to plant naturalization. *In* Moran VC, Hoffmann JH [eds.], 1996. Proc. 9th Int. Symp. Biol. Control Weeds. Stellenbosch, University of Capetown. pp. 39-46

Markin, G.P., P-Y Lai, and G.P. Funusaki. 1992. Status of biological control of weeds in Hawai'i and implications for managing native ecosystems. In Alien Plant Invasions in

Native ecosystems of Hawai'i: Management and Research, eds. CP Stone, CW Smith, JT Tunison, 466-82. Honolulu: Univ. Hawaii Press

Marsden, J.S., G.E. Martin, D.J. Parham, T.J. Risdill-Smith, and B.G. Johnston. 1980. Skeleton weed control. Returns on Australian Agricultural Research. pp. 84-93. Canberra, CSIRO Division of Entomology

McEvoy, P.B., C.S. Cox, and E.M. Coombs. 1991. Successful biological control of ragwort. Ecol. Applic. 1:430-2

McFadyen, R.E.C. 1986. Harrisia cactus in Queensland. *In* The Ecology of Exotic Animals and Plants in Australia, R. Kitching [ed.], 240-61. Brisbane: Jacaranda-Wiley.

McFadyen, R.E. 1992. The harrisia cactus eradication scheme: policy-making by technocrats. Thesis, M.Pub. Admin., Univ. Qld. 103 pp.

McFadyen, R.E.C. 1998. Biological control of weeds. Annu. Rev. Entomol. 43:369-93

Moran, V.C., and H.G. Zimmermann. 1991. Biological control of jointed cactus, *Opuntia aurantiaca* (Cactaceae) in South Africa. Agric. Ecosyst. Environ. 37:5-27

Morin, L., B.A. Auld, and H.E. Smith. 1996. Rust epidemics, climate and control of *Xanthium occidentale*. *In* Moran VC, Hoffmann JH [eds.], 1996. Proc. 9th Int. Symp. Biol. Control Weeds. Stellenbosch, University of Capetown. pp. 385-91

Morris, M.J. 1997. Impact of the gall-forming rust fungus *Uromycladium tepperianum* on the invasive tree *Acacia saligna* in South Africa. Biological Control 10:75-82

Olckers, T., H.G. Zimmermann, and J.H. Hoffmann. 1995. Interpreting ambiguous results of host-specificity tests in biological control of weeds: assessment of two *Leptinotarsa* species (Chrysomelidae) for the control of *Solanum elaeagnifolium* (Solanaceae) in South Africa. Biol. Cont. 5:336-44

Olckers, T., H.G. Zimmermann, and J.H. Hoffmann. 1998. Integrating biological control into the management of alien plant invaders in South Africa. Pesticide Outlook 1998.

Ooi, P.A.C. 1992. Biological control of weeds in Malaysian plantations. Proc. Internatl. Weed Contr. Congr., 1st, Melbourne, pp. 248-55. Melbourne: Weed Sci. Soc. Victoria

Peschken, D.P., and A.S. McClay. 1995. Picking the target: a revision of McClay's scoring system to determine the suitability of a weed for classical biological control. *In* Delfosse ES, Scott RR [eds.], 1995. Proc. 8th Int. Symp. Biol. Control Weeds. Melbourne: CSIRO. pp. 137-43

Rea, N. 1998. Biological control: premises, ecological input and Mimosa pigra in the wetlands of Australia's Top End. Wetlands Ecol. Manage. 5:227-242.

Reznik, S. Ya. 1996. Classical biocontrol of weeds in crop rotation: a story of failure and prospects for success. *In* Moran VC, Hoffmann JH [eds.], 1996. Proc. 9th Int. Symp. Biol. Control Weeds. Stellenbosch, University of Capetown. pp. 503-6

Room, P.M., K.L.S. Harley, I.W. Forno, and D.P.A. Sands. 1981. Successful biological control of the floating weed salvinia. Nature 294:78-80

Sands, D.P.A., and M. Schotz. 1985. Control or nocontrol: a comparison of the feeding strategies of two salvinia weevils. pp. 551-6. *In* E.S. Delfosse [ed.], Proc. 6th Int. Symp. Biol. Control Weeds. Agric. Canada, Ottawa, Canada.

Siebert, T. 1989. Biological control of the weed *Chromolaena odorata* (Asteraceae) by *Pareuchaetes pseudoinsulata* (Lep.: Arctiidae) on Guam and the Northern Mariana Islands. Entomophaga 34:531-9

Shea, K., and D. Kelly. 1998. Estimating biocontrol agent impact with matrix models: *Carduus nutans* in New Zealand. Ecol. Appl. 8: 824-832

Thomas, P.A., and P.M. Room. 1985. Towards biological control of salvinia in Papua New Guinea. *In* Delfosse ES [ed.], 1985. Proc. 6th Int. Symp. Biol. Control Weeds. Ottawa: Agriculture Canada. pp. 567-74

Vitelli, M., P. James, J. Marohasy, R.E. McFadyen, M. Trevino, and M. Hannan-Jones. 1996. Field establishment - how long does it take? *In* Moran VC, Hoffmann JH [eds.], 1996. Proc. 9th Int. Symp. Biol. Control Weeds. Stellenbosch, University of Capetown. pp.

421 (Abstr.)

Volchansky, C.R., J.H. Hoffmann, and H.G. Zimmermann. 1999. Host-plant affinities of two biotypes of *Dactylopius opuntiae* (Homoptera: Dactylopiidae): enhanced prospects for biological control of *Opuntia stricta* (Cactaceae) in South Africa. J. Appl. Ecol. 36:85-91

Wapshere, A.J., E.S. Delfosse, and J.M. Cullen. 1989. Recent developments in biological control of weeds. Crop Protection 8:227-50

Williamson, M., and A. Fitter. 1996. The varying success of invaders. Ecology 77:1661-8

Wilson, F.O. 1964. Biological Control of Weeds Annu. Rev. Ent. 9:225-244

Wright, A.D. 1996. An outline of water hyacinth control in Australia. *In* Charudattan, R., Labrada, R., Center, TD, and Kelly-Begazo, C. [eds.], Strategies for Water Hyacinth Control: Report of a Panel of Experts Meeting, 11-14 September 1996\5, Fort Lauderdale, Florida USA. Rome, FAO, pp.115-122.

Zimmermann, H.G., and V.C. Moran. 1991. Biological control of prickly pear, *Opuntia ficus-indica* (Cactaceae) in South Africa. Agric. Ecosyst. Environ. 37:29-35