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Biological control of weeds in the tropics and sustainability

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1.1 Introduction

Efforts to manage weeds using biological control have been gaining momentum throughout the world, especially in the recent past (Delfosse, 2004). Developed countries, which are principally distributed in the temperate regions, have been practicing classical biological control efficiently, whereas developing countries, most of which are distributed in the tropical regions and have more limited resources, have not adopted deliberate measures for biological control of invasive plants to the same extent as developed nations. The first documented case of biological control of weeds in the tropics was in 1795 and involved the invasive plant *Opuntia monacantha* (Wildenow) Haworth (Cactaceae), which was controlled serendipitously in India due to the inadvertent introduction of *Dactylopius ceylonicus* (Green) (Hemiptera: Dactylopiidae) from Brazil in mistaken identity for *Dactylopius coccus* Costa (Hemiptera: Dactylopidae) (Rabindra and Bhumannavar, this volume; Zimmerman *et al*., this volume). Thereafter, it took more than a century for biological control of weeds to be rigorously adopted (e.g. biological control of lantana in Hawaii in 1902; biological control of cactus in Australia in 1912; Julien *et al*., 2007) and for invasive weed species to be recognized as an international problem (Harris, 1979).

Since the early 1900s, work has been predominantly carried out on weeds of the temperate regions in countries such as Canada, New Zealand, Australia, South Africa, and the USA. The USA, Australia, and South Africa, which include tropical segments (e.g. states of Florida, Hawaii, Queensland, Northern Territory, KwaZulu-Natal, Mpuma Langa, Limpopo) have developed programs on biological control of tropical weeds. Only a few developing countries in the tropics have attempted biological control, and this has been sporadic. Moreover, most efforts have been limited to technology-transfer activities of some projects that have already been trialed and implemented in developed countries. Clearly, there is a need for developing countries to receive support from donor agencies or regional and international organizations in the form of methods for creating awareness, knowledge, technical information, training, and financial resources to implement biological control of invasive species and to maintain sustainable programs in the future.

Biological Control of Tropical Weeds using Arthropods, ed. R. Muniappan, G. V. P. Reddy, and A. Raman. Published by Cambridge University Press.

This book attempts to consolidate and present biological control activities that have been carried out in different parts of the tropical world on invasive weeds. It includes chapters on biological, ecological, and economic management of 20 "top-priority" weeds, of which 19 have invaded from their epicenters to other parts of the tropical world, causing serious ecological damage to the local environment and economic problems to the people. *Striga* is the singular nonexotic weed treated in this volume; it is a parasitic species and a native of the Old World tropics. Of these 19 species, 16 have been introduced from the New World into the Old World, and one each from Australia into Africa, from Asia into Australia, and from Africa into the Pacific. They include 15 terrestrial (two herbs, seven shrubs, four trees, and two vines) and five aquatic elements. Their habitats vary from arid tropical (e.g. *Parthenium hysterophorus*, Asteraceae; cacti, Cactaceae; species of *Acacia*, Mimosaceae; and species of *Striga*, Orobanchaceae) to humid tropical (e.g. *Chromolaena odorata*, Asteraceae; *Clidemia hirta*, Melastomataceae; *Coccinia grandis*, Cucurbitaceae; and *Mimosa diplotricha* and *M. pigra*, Mimosaceae). *Lantana camara* (Verbenaceae) is cosmopolitan, whereas *Passiflora mollissima* (Passifloraceae) and *Solanum mauritianum* (Solanaceae) are subtropical–tropical elements. *Ageratina adenophora* (Asteraceae) is temperate and *Azolla filiculoides* (Azollaceae), *Cabomba caroliniana* (Cabombaceae), *Eichhornia crassipes* (Pontederiaceae), *Pistia stratiotes* (Araceae), and *Salvinia molesta* (Salviniaceae) are aquatic. All of these species are weeds that have either already invaded or have the potential to invade tropical countries. Of these, 14 species are adapted to lowlands; four species lowland to mid-level altitudes (*C. odorata* and *P. mollissima*, 1000 m asl); one species (*L. camara*) lowland to higher altitudes (2000 m asl); and one species higher altitudes (*A. adenophora*) (Table 1.1). In addition to the 20 chapters on individual weeds, three chapters provide overviews of activities pertaining to biological control of tropical weeds carried out in India; by a regional organization, Secretariat of the Pacific Community (SPC); and by an international organization, International Institute of Tropical Agriculture (IITA).

Several volumes available today deal with biological control in general of insect pests and weeds (e.g. DeBach, 1974; Huffaker and Messenger, 1976; Waterhouse and Norris, 1987; Nechols *et al.*, 1995; Waterhouse, 1998; Bellows and Fisher, 1999; Gurr and Wratten, 2000; Waterhouse and Sands, 2001; Neuenschwander *et al.*, 2003; Hajek, 2004) and a few relate to biological control of weeds specifically (e.g. Waterhouse, 1994; Coombs *et al.*, 2004). In such a context, the key aim of this book is to consolidate and present the past and current research and development work which is progressing in the area of biological control of tropical weeds.

In the backdrop of brief taxonomic notes, origin, distribution, ecology, economic usefulness/uselessness and ecological criticality of the weed, biology and behaviour of the biological control agents selected, trials relating to introduction, establishment, spread, interference by local parasitoids and predators, and efficacy have been discussed at length, citing specific examples. Most importantly, benefit-cost analyses referring to the environmental and economic sustainability in the biological management of each weed have also been considered, wherever appropriate data are available.

Table 1.1. *Status of biological control of invasive weeds addressed in this volume*

Invasive weed	Origin	Invaded regions	Form	Altitude	Ecological niche where invasive	Considered invasive in:	State of the program
Acacia nilotica (Mimosaceae)	India	Australia	Tree	Lower	Arid tropics	Australia	Early stages
Ageratina adenophora (Asteraceae)	Neotropics	Australia, Asia, Africa, Hawaii, and New Zealand	Shrub	Higher	Humid temperate	Australia, New Zealand, India, China, Nepal, South Africa	In operation for 30 years
Australian *Acacias* (Mimosaceae)	Australia	South Africa	Tree	Lower	Arid tropics	France, India, Italy, New Zealand, Portugal, Reunion, South Africa, Spain, Uganda, USA	
Azolla filiculoides (Azollaceae)	Neotropics	South Africa	Aquatic herb	Lower	Tropics to subtropics	South Africa	
Cabomba caroliniana (Cabombaceae)	Neotropics	Australia and South Africa	Aquatic herb	Lower	Tropics to subtropics	Australia, Canada, China, India, Japan, Netherlands, USA	
Chromolaena odorata (Asteraceae)	Neotropics	Humid tropical Africa, Asia, Pacific, and Australia	Shrub	Lower	Humid tropics to subtropics	Western Africa, Southern Africa, South and Southeast Asia, Micronesia, Papua New Guinea, Australia	In operation for 40 years
Clidemia hirta	Neotropics	Pacific Islands	Shrub	Lower	Humid tropics	Hawaii, Fiji, Samoa, and American Samoa	In operation for 50 years
Coccinia grandis (Cucurbitaceae)	Africa	Hawaiian and Mariana Islands in the Pacific	Vine	Lower	Humid tropics	Hawaii and Mariana Islands in the Pacific	In operation for 10 years

Table 1.1. (cont.)

Invasive weed	Origin	Invaded regions	Form	Altitude	Ecological niche where invasive	Considered invasive in:	State of the program
Eichhornia crassipes (Pontederiaceae)	Neotropics	Old World, Australia and the Pacific Islands	Aquatic herb	Lower	Tropics	Australia, tropical South and North America, and Old World tropics	In operation for 60 years
Lantana camara (Verbanaceae)	Neotropics	Old World, Australia, and the Pacific Islands	Shrub	Cosmopolitan	Tropics, subtropics and temperate. Adapted to arid and humid conditions	Australia and Old World tropics	In operation over 100 years
Mimosa diplotricha (Mimosaceae)	Neotropics	Australia, Asia, and the Pacific Islands	Shrub	Lower	Humid tropics	Australia and Pacific Islands	In operation over 40 years
Mimosa pigra (Mimosaceae)	Neotropics	Australia, Southeast Asia	Tree	Lower	Humid tropics	Australia, Thailand, Philippines, and Indonesia	In operation over 30 years
Cactaceae	New World	Old World, Australia and the Pacific Islands	Shrub to tree	Lower	Arid tropics	Australia, India, Sri Lanka, South Africa, Madagascar, Hawaii, Ethiopia, Eritrea, Kenya, Yemen, Saudi Arabia, Morocco, Canary Islands, Zimbabwe, Namibia, and West Indies	In operation over 200 years

Table 1.1. (cont.)

Invasive weed	Origin	Invaded regions	Form	Altitude	Ecological niche where invasive	Considered invasive in:	State of the program
Parthenium hysterophorus (Asteraceae)	Mexico	Australia, South Asia, Eastern and Southern Africa, and some Pacific Islands	Herb	Lower	Arid tropics	Australia, India, Ethiopia, Kenya, South Africa, Botswana, Mauritius, and Madagascar	In operation for 30 years
Passiflora tripartita (Passifloraceae)	South America	Hawaii	Vine	Lower to middle	Humid tropics and subtropics	Hawaii, New Zealand	
Pistia stratiotes (Araceae)	South America	Old World, Australia, and Pacific Islands	Aquatic herb	Lower	Tropics	Old and New World tropics	
Prosopis sp. (Mimosaceae)	North America	Africa, Asia, and Australia	Tree	Lower	Arid tropics	Australia, India, South Africa, Kenya, and Ethiopia	
Salvinia molesta (Salviniaceae)	South-eastern Brazil	Old World, and Australia	Aquatic herb	Lower	Tropics	Old and New World tropics	In operation over 40 years
Solanum mauritianum (Solanaceae)	South America	Old World	Shrub	Lower to middle	Tropics to subtropics	South Africa and Australia	
Striga spp. (Orobanchaceae)	Old World	Old World	Parasitic herb	Lower	Arid tropics	Old World tropics	

Interest in ecologically sound management of invasive species is currently on the rise, among both scientists and the general public (e.g. Drake *et al.*, 1989; Devine, 1998). Among the many diverse invasive organisms, alien plants induce serious economic losses to humankind by competing for natural resources, especially in an agricultural context, which includes not only grain production but also the pasture and forestry industry, by reducing overall yield and quality through allelopathy and contamination (Dhileepan, this volume; Zachariades *et al.*, this volume). Weeds also increase the likelihood of fires, reduce property values, poison domestic and wild animals, reduce quality of milk and meat, interfere in the movement of wild animals and their breeding habits, endanger native vegetation, interfere with irrigation, navigation and recreational water bodies, inflict allergies, enhance chances for disease incidence in humans, animals, and crops by harboring disease-agent vectors, and reduce market access because of strict quarantine practices (Culliney, 2005).

1.2 Management strategies

The major weed management strategies usually applied are prevention, eradication, and control (Mack *et al.*, 2000; Monaco *et al.*, 2002; Culliney, 2005). Quarantine laws promulgated with assistance from regional and international organizations regulate movement of weeds and products from weed-infested areas in intra- and intercountry transportation. In developed countries, clamping of strict quarantine regulations is common whenever an impending threat from an invasive species becomes obvious. Such regulations in developing countries are either rare or nonexistent. As an effort to assist smaller countries in the Pacific, such as Fiji, Kiribati, Samoa, Tonga, and Vanuatu, Pest-Alert Bulletins appear from the Secretariat of the Pacific Community (SPC) whenever a “pest” problem becomes evident in the region. This practice is done so that the member countries of SPC can promulgate their own regulations (SPC–PPS, 2003). Eradication is possible when the introduction and consequent spread of a weed species is spotted early and sustained efforts to monitor it are made. For example, when *C. odorata* and *Mikania micrantha* Kunth (Asteraceae) infestations occurred in northern Queensland in 1994 and 1998, respectively, Australia instituted immediate monitoring programs (Galway and Brooks, 2007), which paved the way for possible eradication. Early detection and determination to eradicate, backed by an adequate budget and human resources, are critical to achieve a successful program. Eradication becomes economically unviable when the weed spread is extensive (Myers and Bazely, 2003; Culliney, 2005). To prevent the spread of *P. hysterophorus* in the state of Karnataka (India), a quarantine act was passed in 1975 declaring it a noxious weed; and notices were issued to remove this weed once or twice in the 1980s by the Bangalore Municipal Corporation (Bhan *et al.*, 2007). Because of the failure to initiate the correct action in the most appropriate manner, management of *P. hysterophorus* was a failure, as it was not supported by adequate funds, human resources, nor by commitment from either people or the administration. Furthermore, the neighbouring states paid either little or no attention to the establishment and spread of *P. hysterophorus*. Examples of such failure to implement and follow up the correct measures (e.g. quarantine regulations) in developing countries exist plentifully.

When a weed escapes quarantine and exceeds the eradication stage, the next level of options available for management are: mechanical, chemical, cultural, and biological. Mechanical control varies from the use of hand tools to the use of heavy machinery in the removal of weeds. Slashing the weeds such as *Chromolaena odorata* in India and *Coccinia grandis* in Mariana Islands proved futile as the stubbles sprouted and the operation had little impact. Burning is one of the methods used extensively for the control of some weeds, especially in forests and rangelands; but fire is a factor that supports *C. odorata* spread. In *C. odorata*-infested areas, fire killed most of the adjoining vegetation but not the stubbles of *C. odorata*, inducing their immediate sprout soon after rains and invasion of the land occupied by native vegetation (Muniappan *et al.*, 2005). In Hawaii, *A. adenophora* was cleared from a vast spread of grazing land by farmers between 1920 and 1948 at great expense without much relief, whereas the introduction of the gall fly *Procecidochares utilis* Stone (Diptera: Tephritidae) enabled an impressive control of the weed, eliminating the need for mechanical control (Bess and Haramoto, 1958). Chemical control is widely used in croplands and rangelands, and along roadsides (Monaco *et al.*, 2002). Cultural control involves the use of mulch, cover crops, and competitive suppression. This practice is used in annual and perennial cropping systems and, to a limited extent, in vacant land areas (Mahadevappa and Ramaiah, 1988). However, these methods have only a limited effect. They are expensive and entail several repeats. Moreover, herbicides cause health problems to humans and domesticated animals, and adversely affect the environment. Most infestations of these invasive weeds are either too extensive or the land value infested by them is too marginal, thus rendering physical, cultural, and chemical control methods uneconomical and unsustainable. Benefit–cost analysis of different control options of *Salvinia molesta* in Zimbabwe showed that physical and chemical control measures were expensive and ineffective, whereas biological control was effective and inexpensive (Chikwenhere and Keswani, 1997).

1.3 Biological control

Classical biological control is the most sustainable method used in biological control of invasive, exotic weeds. This method employs the introduction of arthropod natural enemies that exist naturally in their places of origin. The method, however, involves importation, colonization, and establishment of exotic natural enemies, which include predators and parasitoids (McFadyen, 1998). This method provides long-lasting and affordable management, either alone or in combination with other methods. It is usually useful in the control of perennial weeds that infest low-productivity cropland areas, rangelands, and disturbed forests. Whereas other methods are either expensive or impractical in specific circumstances, biological control methods are affordable, safe to the environment, and economical as well.

Biological control of weeds plays a key role in the management of natural resources in Oceania (Julien *et al*., 2007) and other parts of the world. It will usually require a long period of research and a high initial investment of capital and human resources (Culliney, 2005). A program typically requires 10–20 years to achieve satisfactory results and can easily cost US$3–8m (McFadyen, 2000). Over 350 species of natural enemies, including arthropods, pathogens, and vertebrates have been released for the biological control of weeds (Julien and Griffiths, 1998) with nearly 1000 releases made from the mid nineteenth century to the end of 1996 to control 133 weed species (Culliney, 2005). The success rate of biological control of weeds programs on the whole was 33% (Culliney, 2005). Benefit–cost analysis of weed biological control projects in Australia has been reported by Page and Lacey (2006). They quantified the overall return on investment in the form of a benefit-cost ratio of 23.1, implying that for every dollar invested in biological control of weeds there is $23.1 returned as benefits. Benefit–cost ratios available for the biological control of weeds covered in this book are given in Table 1.2.

1.4 Technology transfer

Government agencies in the USA, Canada, Australia, New Zealand, and South Africa were able to initiate new biological control projects for invasive weeds starting with identification of the native range, searching for potential natural enemies, screening for host specificity, assessing acceptable risk, establishing the agents, and evaluation of impact. Most developing countries lack the knowledge, capital, human resources, and infrastructure to carry out different steps involved in biological control. Programs on biological control of weeds carried out in developing countries involved mostly technology transfer supported by donor countries, assisted by international organizations like CAB International or through bilateral and reciprocal arrangements. Exploration, screening, introduction, and evaluation of the natural enemies introduced into these countries have already been carried out either by the developed countries or by international organizations. The advantage in such technology transfer is that only the natural enemies that have been tried elsewhere and proven effective may be selected for introduction. As noted in this volume, some spectacular successes have been achieved in controlling the invasive weeds by technology transfer, such as *Opuntia* spp. in Australia, Hawaii, Sri Lanka, and South Africa (Zimmermann *et al*., this volume); *S. molesta* in Africa, Fiji, Papua New Guinea (PNG), Malaysia, and India (Julien *et al*., this volume); *C. odorata* in Micronesia (Zachariades *et al*., this volume); *M. diplotricha* in PNG, Fiji, Samoa, Solomon Islands, Pohnpei, and Yap (Kuniata, this volume); *C. hirta* in Fiji (Conant, this volume); and *E. crassipes* in PNG, and Africa (Coetzee *et al*., this volume; Beed and Dubois, this volume). It is hoped that the information presented on the 20 tropical weeds will assist in sparking an interest to start biological control projects in developing countries through bilateral programs with the resources available within the

Table 1.2. *Benefit-cost analysis for the biological control of invasive weeds in the tropics*

Weed	Country	Benefit/cost ratio	Reference
Acacia longifolia (Andr.) Willd	South Africa	104	van Wilgen *et al.*, 2004
Acacia pycantha Benth	South Africa	665	van Wilgen *et al.*, 2004
Acacia saligna (Labill.) Wendl.)	South Africa	800	van Wilgen *et al.*, 2004
Azolla filiculoides Lamarck	South Africa	2.5	McConnachie *et al.*, 2003
		13	Hill and McConnachie, this volume
Eichhornia crassipes (Mart.) Solms-Laub.	Benin	124	De Groote *et al.*, 2003
	Australia	27.5	Page and Lacey, 2006
Lantana camara L.	South Africa	22	Van Wilgen *et al.*, 2004
	Australia	5.6	Page and Lacey, 2006
		9	AEC group, 2007
Mimosa diplotricha	Australia	17.6	Page and Lacey, 2006
Mimosa pigra	Australia	0.8	Page and Lacey, 2006
Opuntia aurantiaca Lindley	South Africa	709	van Wilgen *et al.*, 2004
Opuntia spp.	Australia	312.3	Page and Lacey, 2006
Parthenium hysterophorus L.	Australia	7.2	Page and Lacey, 2006
Pistia stratiotes	Australia	27.5	Neuenschwnader *et al.*, this volume
Prosopis spp.	Australia	0.5	Page and Lacey, 2006
Salvinia molesta D. S. Mitchell	Australia	27.5	Page and Lacey, 2006
	Sri Lanka	53	Doeleman, 1989
	Zimbabwe	10.6	Chikwenhere and Keswani, 1997

host countries; and regional and international programs with the assistance of donor agencies.

1.5 Economics of biological control of weeds

As a concept classical biological control is for the public good (Tisdell and Auld, 1990) and it is not amenable for individual profit (Culliney, 2005). Whereas chemical, cultural, and mechanical control methods benefit only the users and the geographical localities in which it is used, biological control benefits the public at large (Cullen and Whitten, 1995). Because it usually has a high initial investment and is unlikely to recover research and development expenses, biological control is unattractive as a private entrepreneurial effort (Hill and Greathead, 2000; Coombs *et al*., 2004). Although developing countries are unable to initiate biological control programs because of the need for a high initial investment, the technology transfer of the programs developed in other countries has benefited low-income farmers and the environment (Greathead, 1995). The economic evaluation of benefits of biological control of weeds involves considerations of esthetics, health, and natural resources (Culliney, 2005). Only in recent years has biological control of weeds been subjected to rigorous economic analysis, mostly in USA, South Africa, and Australia (van Wilgen *et al*., 2004; Culliney, 2005; Page and Lacey, 2006). The success rate of weed biological control programs is estimated at 17%, based on the characterization of the small number of outstanding successes and large number of failures (Crawley, 1989), which could be due to bias in the way success has been measured traditionally. Culliney (2005) estimated the success rate of biological control to be 33% based on analysis focusing on the outcomes achieved by each program. Walton (2005) has estimated the success rate to be 80%. Success rates have varied in individual countries: Hawaii – 50% (Markin *et al*., 1992), Australia – 51% (McFadyen, 2000), South Africa – 61% (Zimmermann *et al*., 2004), Mauritius – 80% (Fowler *et al*., 2000), and New Zealand – 81% (Fowler, 2000).

Biological control of invasive weeds is economical. In most countries, data on the agricultural and environmental impact of one or more weeds, as well as any costing done towards control, are unavailable. Whereas the benefit-cost analysis method is reliable in a broad-brush context, analyses need to be done independently for each country, because the impact of one or more weeds on agriculture and the environment is bound to vary. The cost of control will be far less and the benefit-cost ratio will be high in countries where the program had been transferred from other countries. For example, natural enemies of *L. camara* introduced into Guam, Micronesia, and the Solomon Islands were already host-specificity and field tested in Hawaii. Similarly, exploratory work and most of the host-specificity testing for natural enemies of *Coccinia grandis* introduced into Guam and Saipan were done in Hawaii. McConnachie *et al*. (2003) reported a benefit to cost ratio for controlling *Azola filiculoides* in South Africa at 2.5:1 in the year 2000, which was increased to 13:1 for 2005 by adjusting for the value of the South African R and for inflation (Hill and McConnachie, this volume). In some instances, it may not be possible to separate benefits, as examples such as *Eichhornia crassipes, Salvinia molesta*, and *Pistia stratiotes* occur in the same water bodies and locations (Julien *et al*., this volume). Doeleman (1989) estimated a benefit cost ratio of 53:1 in terms of money and 1671:1 in terms of labor for the complete control of the weed *Salvinia molesta* in Sri Lanka. These examples highlight the substantial "economic" benefits of using biological control in weed management (Julien *et al*., this volume). Biological control of invasive weeds is a better investment than the remaining procedures that apply to management of invasive weeds and it is needed more than ever before with the rise in the traffic of introductions of diverse plant species through extensive and rapid human movements across the continents.

1.6 Conflict of interest resolution

Conflict of interest occurs when some sectors of a community find either a use or a relevance regarding a weed or when the biological control agent begins to attack nontarget but economically important organisms (Culliney, 2005). Such a conflict usually entails sociological, political, and scientific complexities. Conflict of interest has been extensive in six out of the 20 weeds dealt with in this volume; i.e., *Chromolaena odorata* (Zachariades *et al*., this volume) species of cacti (Zimmermann *et al*., this volume), species of the Australian *Acacia* (Impson *et al*., this volume), *Acacia nilotica* (Dhileepan, this volume), species of *Prosopis* (van Klinken *et al*., this volume), and *Solanum mauritianum* (Olckers, this volume). *Opuntia elatior* has invaded Kenya and biological control was contemplated; however, commercial cultivation of *O. ficus-indica* has restricted the adoption of the currently available biological control agents. Moreover, neighboring Ethiopia decided against biological control because several rural communities depend on *O. ficus-indica* for food. Biological control of *Solanum mauritianum* has been taken up in South Africa, but most countries that either raise solanaceous crops or have other native species of *Solanum* do not consider the biological control option, because of the concern that the introduced agents may invade either the economic crops or the native species (Olckers, this volume). For biological control of the Australian *Acacia* in South Africa and *Prosopis* in Australia and South Africa, amicable resolutions have been reached. A regional project up to a value of a million dollars towards the biological control of *C. odorata* in western Africa with the prospect for funding from the Inter-African Development Bank was blocked due to a perception that this invasive plant species was considered a valuable fallow species by farmers who used shifting cultivation techniques (McFadyen, 1996). The report of feeding by *Zygogramma bicolorata* Pallister (Coleoptera: Chrysomelidae), a natural enemy introduced for the biological control of *P. hysterophorus*, on sunflower in India resulted in the cancellation of all projects for biological control of weeds for many years until it was proved that the beetle fed on sunflower leaves dusted with *P. hysterophorus* pollen from the neighborhood (Bhumannavar *et al*., 1998).

1.7 Sustainability

In Rio de Janeiro during the Earth Summit, the gathered nations adopted Agenda 21, which made sustainable development a universal goal in June 1992 (Moldan and Billharz, 1997). The World Bank has identified economic, sociocultural and ecological dimensions as the key perspectives for an environmentally sustainable development (Moldan, 1997). The generic concept of sustainability, including the subtler aspects of sustainable growth and sustainable development, is the singular choice for the future development of any nation (Xiaomin and Li, 1997). The alteration of the population and community structure of native ecosystems by the invasion of exotic species has led to the extinction of native species and reduced local biodiversity, and has placed a heavy burden of socioeconomic investment to achieve their control and/or management (Ramakrishnan, 1991). Chemical, cultural, and mechanical control methods are limited in their application and relevance and require repeated applications and/or adoptions and therefore are not cost effective. Chemical control is amenable to the disadvantage of causing environmental and human-health problems. Classical biological control is an economically viable measure; it is environmentally safe, is long lasting, and is a sustainable method available for management of invasive weeds. It could be implemented either independently or as a component of integrated pest management (IPM) as it readily and effectively integrates several other mechanisms.

When effective, classical biological control provides the most sustained suppression of an invasive plant. The inadvertent introduction of *Dactylopius ceylonicus* into India nearly 200 years ago has effectively controlled the prickly pear (*Opuntia monacantha*), and the landscape infested by *O. monocantha* became suitable for cultivation within five to six years. The control was permanent and required no further efforts to manage the weed. Subsequent introduction of *Dactylopius ceylonicus* and similar other natural enemies into Sri Lanka, Australia, South Africa, Madagascar, and Hawaii have yielded similar sustained control of the cactus (Zimmermann *et al.*, this volume; and Rabindra and Bhumannavar, this volume). The benefit-cost ratios of 800 for control of *Acacia saligna* and 709 for control of *Opuntia aurantiaca* in South Africa (Table 1.2) are far better returns for the money invested. Biological control has offered similar results for *S. molesta* in Australia, Botswana, Congo, Fiji, Ghana, India, Kenya, Papua New Guinea, South Africa, Malaysia, Mauritania, and Namibia; for *P. stratiotes* in Australia, South Africa, Papua New Guinea, North America, Congo, Senegal, Ghana, Ivory Coast, Kenya, Benin, and Mauritania; *E. crassipes* in Papua New Guinea, Benin, Malawi, India, and Lake Victoria; *A. filiculoides* in South Africa; *C. odorata* in Micronesia; and *L. camara* in Guam and Solomon Islands. Release of the weevil *Stenopelmus rufinasus* Gyllenhal (Coleoptera: Curculionidae) for control of *Azolla filiculoides* in South Africa has completely eliminated the threat of this weed to aquatic ecosystems (Hill and McConnachie, this volume). Farmers in Maui, Hawaiian Islands, stopped controlling the Crofton weed, *Ageratina adenophora* by mechanical and chemical means about three years after establishment of the gall fly *Procecidochares utilis* Stone.

1.8 Conclusion

Classical biological control is the best among the viable options available for sustainable management of invasive weeds, especially where other technologies such as chemical and mechanical control are unacceptable due to cost and adverse impact on the environment. Available benefit-cost ratios for biological control trials made for some of the most serious weeds indicate that classical biological control has given the highest returns for the monies spent (Page and Lacey, 2006). Such ratios could be improved further in technology-transfer programs wherein the initial expenses for research and development have already been incurred elsewhere.

The techniques described for biological control of weeds in this volume could be safely and efficiently transferred to developing countries with minimal expense for the initial institutional and human-capacity building. There is a greater opportunity for individual countries and regional and international organizations to play a constructive role in implementing biological control of invasive weeds. Some of the developing countries in Asia and Africa are implementing independently or with assistance from donor agencies. The United States Agency for International Development (USAID) is assisting Ethiopia and South Africa with the biological control of *Parthenium hysterophorus*. Australian Centre for International Agricultural Research (ACIAR) is assisting in East Timor and Papua New Guinea in biological control of *Chromolaena odorata*. The World Bank is supporting biological control of *Eichhornia crassipes* in Lake Victoria. Commonweath Agricultural Bureaux International is assisting India, China, Taiwan, and Secretariat of the Pacific Community (SPC) in biological control of *Mikania micrantha*. Regional and international organizations such as SPC and International Institute of Tropical Agriculture (IITA) are also actively assisting their clientele in this activity. The role of classical biological control in sustainable integrated invasive weed management is well recognized. While there is a need for increased funding for research and development of biological control of newly emerging invasive species in the tropical world, attention should also be given to technology transfer of successful biological control programs achieved elsewhere to solve the problems of invasive species in the developing world.

References

AEC group (2007). *Economic Impact of Lantana on the Australian Grazing Industry*. Final Report for Queensland Department of Natural Resources and Water. Brisbane, Australia: AEC Group Limited, 39 pp.

Bellows, T. S. and Fisher, T. W. (1999). *Handbook of Biological Control*, Academic Press, 1046 pp.

Bess, H. A. and Haramoto, F. H. (1958). Biological control of pamakani, *Eupatorium adenophorum*, in Hawaii by a tephritid gall fly, *Procecidochares utilis*. 1. The life history of the fly and its effectiveness in the control of the weed. In *Proceedings of the Tenth International Congress of Entomology*, held in Montreal, August 17–25, 1956, Vol. 4, ed. E. C. Becker. Ottawa: Mortimer, pp. 543–548.

Bhan, V. M., Sushilkumar and Raghuwanshi, M. S. (2007). *Future strategies for Effective Parthenium Management* (www.iprng.org/IPRNG-parthenium_a&w19.htm).

Bhumannavar, B. S., Balasubramanian, C. and Ramani, S. (1998). Life table of the Mexican beetle *Zygogramma bicolorata* on parthenium and sunflower. *Journal of Biological Control*, **12**, 101–106.

Chikwenhere, G. P. and Keswani, C. L. (1997). Economics of biological control of kariba weed (*Salvinia molesta* Mitchell) at Tengwe in north-western Zimbabwe – a case study. *International Journal of Pest Management*, **43**, 109–112.

Coombs, E. M., Clark, H. K., Piper, G. L. and Cofrancesco, Jr., A. F., eds. (2004). *Biological Control of Invasive Plants in the United States*. Corvallis OR: Oregon State University Press, 467 pp.

Crawley, M. J. (1989). The successes and failures of weed biocontrol using insects. *Biocontrol News and Information*, **10**, 213–223.

Cullen, J. M. and Whitten, M. J. (1995). Economics of classical biological control: a research prespective. In *Biological Control: Benefits and Risks*, ed. H. M. T. Hokkanen and J. M. Lynch. Cambridge, UK: Cambridge University Press, pp. 270–276.

Culliney, T. W. (2005). Benefits of classical biological control for managing invasive plants, *Critical Reviews in Plant Science*, **24**, 131–150.

DeBach, P. H. (1974). *Biological Control by Natural Enemies*. New York: Cambridge University Press.

De Groote, H., Ajuonu, O., Attignon, S., Djessou, R. and Neuenschwander, P. (2003). Economic impacts of biological control of water hyacinth in Southern Benin. *Ecological Economics*, **45**, 105–117

Delfosse, E. S. (2004). Introduction. In *Biological Control of Invasive Plants in the United States*, ed. E. M. Coombs, J. K. Clark, G. L. Piper and A. F. Cofrancesco, Jr. Corrallis, OR: Oregon State University Press, pp. 1–11.

Devine, R. S. (1998). *Alien Invasion: America's Battle with Non-Native Animals and Plants*. Washington, DC: National Geographic Society, 280 pp.

Doeleman, J. A. (1989). *Biological Control of* Salvinia molesta *in Sri Lanka: An Assessment of Costs and Benefits*. Economic Assessment Series 1. Canberra, Australia: Australian Centre for International Agriculture Research.

Drake, J. A., Mooney, H. A., di Castri, F., *et al*., eds. (1989). *Biological Invasions: A Global Perspective*. SCOPE 37. New York: John Wiley, 525 pp.

Fowler, S. V. (2000). Trivial and political reasons for the failure of classical biological control of weeds: a personal view. In *Proceedings of the X International Symposium on Biological Control of Weeds*, ed. N. R. Spencer. Great Falls, MT: Advanced Litho Printing, pp. 169–172.

Fowler, S. V., Syrett, P. and Hill, R. L. (2000). Success and safety in the biological control of environmental weeds in New Zealand. *Austral Ecology*, **25**, 553–562.

Galway, K. E. and Brooks, S. J. (2007). Control recommendations for mikania vine (*Mikania micrantha*) 106 and Siam weed (*Chromolaena odorata*) in Australia. In *Proceedings of the Seventh International Workshop on Biological Control and Management of* Chromolaena odorata *and* Mikania micrantha, ed. P-Y. Lai, G. V. P. Reddy and R. Muniappan. Taiwan: National Pingtung University of Science and Technology, pp. 106–115.

Greathead, D. J. (1995). Benefits and risks of classical biological control. In *Biological Control: Benefits and Risks*, ed. H. M. T. Hokkanen and J. M. Lynch. Cambridge, UK: Cambridge University Press, pp. 53–63.

Gurr, G. and Wratten, S., eds. (2000). *Biological Control: Measures of Success*. Boston, MD: Kluwer Academic Publishers, 429 pp.

Hajek, A., ed. (2004). *Natural Enemies: An Introduction to Biological Control*. Cambridge, UK: Cambridge University Press, 378 pp.

Harris, P. (1979). Cost of biological control of weeds by insects in Canada. *Weed Science*, **27**, 242–250.

Hill, G. and Greathead, D. (2000). Economic evaluation in classical biological control. In *The Economics of Biological Invasions*, ed. C. Perrings, M. Williamson and S. Dalmazzone. Cheltenham, UK: Edward Elgar Publishing, pp. 208–223.

Huffaker, C. B. and Messenger, P. S., eds. (1976). *Theory and Practice of Biological Control*. New York: Academic Press, 788 pp.

Julien, M. H. and Griffiths, M. W. (1998). *Biological Control of Weeds: A World Catalogue of Agents and Their Target Weeds*. Wallingford, UK: CABI Publishing 223 pp.

Julien, M. H., Scott, J. K., Orapa, W. and Paynter, Q. (2007). History, opportunities and challenges for biological control in Australia, New Zealand and the Pacific Islands. *Crop Protection*, **26**, 255–265.

Mack, R. N., Simberloff, D., Lonsdale, W. M., *et al.* (2000). Biotic invasions: causes, epidemiology, global consequences, and control. *Ecological Applications*, **10**, 689–710.

Mahadevappa, M. and Ramaiah, H. (1988). Pattern of replacement of *Parthenium hysterophorus* plants by *Cassia serecia* in waste lands. *Indian Journal of Weed Science*, **20**, 83–85.

Markin, G. P., Lai, P. Y. and Funasaki, G. Y. (1992). Status of biological control of weeds in Hawaii and implications for managing native ecosystems. In *Alien Plant Invasions in Native Ecosystems of Hawaii: Management and Research*, ed. C. P. Stone, C. W. Smith and J. T. Tunison. Honolulu, HI: University of Hawaii Cooperative National Park Resources Studies Unit, pp. 466–482.

McConnachie, A. J., de Wit, M. P., Hill, M. P. and Byrne, M. J. (2003). Economic evaluation of the successful biological control of *Azolla filiculoides* in South Africa. *Biological Control*, **28**, 25–32.

McFadyen, R. E. (1996). Biocontrol of *Chromolaena odorata*: divided we fail. In *Proceedings of the IX International Symposium on Biological Control of Weeds*, ed. V. C. Moran and J. H. Hoffmann. Cape Town, South Africa: University of Cape Town Press, pp. 455–459.

McFadyen, R. E. C. (1998). Biological control of weeds. *Annual Review of Entomology*, **43**, 369–393.

McFadyen, R. E. C. (2000). Successes in biological control of weeds. In *Proceedings of the X International Symposium on Biological Control of Weeds*, ed. N. R. Spencer. Great Falls, MT: Advanced Litho Printing, pp. 3–14.

Moldan, B. (1997). World Bank perspectives on sustainable development. In *Sustainability Indicators. Report of the Project on Indicators of Sustainable Development*, ed. B. Moldan, S. Billharz and R. Matravers. New York: John Wiley, pp. 138–141.

Moldan, B. and Billharz, S. (1997). Introduction. In *Sustainability Indicators. Report of the Project on Indicators of Sustainable Development*, ed. B. Moldan, S. Billharz and R. Matravers. New York: John Wiley, pp. 1–5.

Monaco, T. J., Weller, S. C. and Ashton, F. M. (2002). *Weed Science: Principles and Practices*. Fourth edn. New York: John Wiley.

Muniappan, R., Reddy, G. V. P. and Lai, P. Y. (2005). Distribution and biological control of *Chromolaena odorata*. In *Invasive Plants: Ecological and Agricultural Aspects*, ed. Inderjit. Basel, Switzerland: Birkhauser Verlag, pp. 223–233.

Myers, J. H. and Bazely, D. R. (2003). *Ecology and Control of Introduced Plants*. Cambridge, UK: Cambridge University Press.

Nechols, J. R., Andres, L. A., Beardsley, J. W., Goeden, R. D. and Jackson, C. G., eds. (1995). *Biological Control in the Western United States: Accomplishments and Benefits of Regional Research Project W-84, 1964–1989*. Publication 3361. Berkeley, CA: University of California Press, Division of Agricultural and Natural Resources.

Neuenschwander, P., Borgemeister, C. and Langewald, J. (2003). *Biological Control in IPM Systems in Africa*. Wallingford, UK: CABI Publishing, 414 pp.

Page, A. R. and Lacey, K. L. (2006). *Economic Impact Assessment of Australian Weed Biological Control*. Technical Series 10. Adelaide, Australia: CRC for Australian Weed Management, 150 pp.

Ramakrishnan, P. S., ed. (1991). *Ecology of Biological Invasion in the Tropics*. New Delhi: International Scientific Publications, 195 pp.

SPC-PPS. (2003). Incursion of parthenium weed (*Parthenium hysterophorus*) in Papua New Guinea. Pest Alert 30. Suva, Fiji Islands: Secretariat of the Pacific Community, Plant Protection Service, 1 p.

Tisdell, C. A. and Auld, B. A. (1990). Evaluation of biological control projects. In *Proceedings of the VII International Symposium on Biological Control of Weeds*, ed. E. S. Delfosse. Rome, Italy: Instituto Sperimentale per la Patologia Vegetale (MAF), pp. 93–100.

van Wilgen, B. W., de Wit, M. P., Anderson, H. J., *et al*. (2004). Costs and benefits of biological control of invasive alien plants: case studies from South Africa. *South African Journal of Science*, **100**, 113–122.

Walton, C. (2005). *Reclaiming Lost Provinces: A Century of Weed Biological Control in Queensland*. Brisbane, Australia: Department of Natural Resources and Mines, 104 pp.

Waterhouse, D. F. (1994). *Biological Control of Weeds: Southeast Asian Prospects*. Monograph 26. Canberra, Australia: ACIAR, 302 pp.

Waterhouse, D. F. (1998). *Biological Control of Insect Pests: Southeast Asian Prospects.* Monograph 51. Canberra, Australia: ACIAR, 548 pp.

Waterhouse, D. F. and Norris, K. R. (1987). *Biological Control Pacific Prospects*. Melbourne, Australia: Inkata Press. 454 pp.

Waterhouse, D. F. and Sands, D. P. A. (2001). *Classical Biological Control of Arthropods in Australia*. Monograph 77. Canberra, Australia: ACIAR, 560 pp.

Xiaomin, G. and Li, G. (1997). Application of indicators of sustainable development in China. In *Sustainability Indicators. Report of the Project on Indicators of Sustainable Development*, ed. B. Moldan, S. Billharz and R. Matravers. New York: John Wiley, pp. 334–339.

Zimmermann, H. G., Moran, V. C. and Hoffmann, J. H. (2004). Biological control in the management of invasive alien plants in South Africa, and the role of the working for water programme. *South African Journal of Science*, **100**, 34–40.