Biological control in the management of invasive alien plants in South Africa, and the role of the Working for Water programme

H.G. Zimmermann[a], V.C. Moran[b] and J.H. Hoffmann[b]

The first biological control project against invasive alien plants in South Africa was in 1913. Initially, invasive cactus species were the only plants in South Africa targeted for biological control. By the early 1960s, the emphasis expanded to include problem plants that threatened the 'Fynbos' biome, and latterly to invasive species in other types of natural habitats. Many of the South African projects have been innovative, for example: the use of gall-forming and seed-feeding insect species that have not been used elsewhere; the emphasis on weeds in conservation areas; and the predominance of woody invaders that have been targeted for biological control. Most of these woody plants originated as forestry or agro-forestry introductions, which has created a relatively high incidence of conflicts of interest between conservationists and growers. Recent benefit:cost analyses have demonstrated exceptionally high returns on investment for biological control, even for the least successful of the projects. The inception of the Working for Water programme in 1995 has significantly enhanced biological weed control in South Africa. The benefits include: sustainable funding; investment in research on emerging weeds; a well-organized implementation programme that has increased the impact of biological control in the field; improved international cooperation, particularly in Africa, in concert with the NEPAD initiative; and the recent re-organization of research personnel into cooperative teams that include entomologists, plant pathologists, resource economists and plant ecologists.

Introduction

This account provides a brief history of events and issues that have influenced the course of biological control of invasive alien plants in South Africa, and records the results that have been achieved. There is an emphasis on developments that have been a consequence of interventions by the Working for Water programme in weed biological control efforts in South Africa, since 1995.

The influx of alien plant species into South Africa began in the 1600s, when the Cape of Good Hope was a major refurbishing stop for European ships, sailing to and from the Spice Islands. Over many years, hundreds of species of plants were brought in and cultivated for various purposes. South Africa became a focal point in Africa for the establishment of alien plants from all over the world, especially from Australia and from South and Central America. Some of these plant species have become highly problematic.[1] Alien species of plants may become invasive when they are introduced into a new country without their natural suite of plant-feeding insects and pathogens that suppress them in their native regions. Relieved of this pressure, pre-adapted to conditions in the new country, and often with the ability to produce large numbers of seeds, they out-compete the local plants, form dense stands, spread rapidly and transform the landscape.

South Africa has an array of damaging invasive alien plant species that seem to be more prominent and overwhelming than those in many other countries. These plants (often referred to as 'weeds'), impact on both human well-being and biodiversity and are a problem in agricultural lands, river courses and catchments, and in wilderness and conservation areas. Since early in the 20th century, biological control has been used in South Africa to combat many species of invasive alien plants, encompassing a variety of forms, from cacti to large trees and water plants.

Biological control of weeds is a practice in which host-specific plant-feeding insects, mites and pathogens (that is, the plants' 'natural enemies') are transferred from their country of origin and released into a new country where the plants have become a problematic, in this case South Africa. Before the release of any natural enemies (also called biological control 'agents'), rigorous safety-tests are conducted under strict quarantine conditions. It may take several years to test a single agent species and ensure that it is sufficiently host-specific, that is, it can feed and maintain its populations on only one, or a very limited number of closely related species of host plants. Suitable agents cannot survive on species of plants other than the target weed, and they die if there are none of their host plants available.[2]

When they are successful, the damage inflicted by biological control agents causes a decline in population densities, distribution and, or, rates of spread of the problem plants, and reduces the costs of other management practices. For nearly 150 years, in many countries around the world, biological control has contributed to the suppression of invasive alien plants. More than 400 species of organisms have been deployed against approximately 280 weed species.[3] Biological control is a particularly attractive option as a management tool for weeds because: it is cost-effective and safe compared to herbicidal and mechanical operations; it can be successfully integrated with other management practices; and, most compelling of all, biological control is self-sustaining.

Progression in the biological control of invasive alien plants in South Africa

The period from 1913 to the late 1960s

Drooping prickly pear, *Opuntia monacantha,* from South America, which was already common in the Western Cape in 1772, spread rapidly and, by the 1890s, it was recognized as an important pest plant along the eastern coastal strip of South Africa. Biological control started in South Africa with the importation of plant-feeding cochineal insects, which were released against drooping prickly pear in 1913. This biological control programme was an outstanding success and within a few years drooping prickly pear had become localized and scarce in South Africa.[4] For the last ninety years, the cochineal insects have provided sustained, day-by-day, cost-free control of drooping prickly pear, and these benefits will continue indefinitely.

[a]Plant Protection Research Institute, Private Bag X134, Pretoria 0001, South Africa. E-mail: riethgz@plant2.agric.za
[b]Department of Zoology, University of Cape Town, Private Bag, Rondebosch 7701, South Africa. E-mail: vcmoran@iafrica.com and hoff@botzoo.uct.ac.za

Following this success against drooping prickly pear, little happened in weed biological control in South Africa until the advent of the extensive campaigns against various other invasive cactus species in the 1930s and 1940s.[5–7] The biological control of jointed cactus, *Opuntia aurantiaca,* in the Eastern Cape and Karoo[4] epitomizes the sequence of events and many of the basic principles of weed biological control. The plant originated in temperate South America and was introduced into South Africa in the early 1800s, because it was thought to have useful properties as a hedge plant or as a horticultural curiosity. By 1892 it had proliferated and formed dense thickets that were a problem in grazing lands. Eventually, at its worst, nearly a century later, jointed cactus infested about 850 000 ha. In spite of mechanical clearing efforts and the application of arsenic herbicides from the early 1900s, the weed continued to spread and increase in density until public and political pressure motivated research into biological control.

In 1933, the famous cactus moth, *Cactoblastis cactorum,* which had proved so successful against invasive opuntias in Australia, was being mass-reared near Uitenhage and released against sweet prickly pear, *Opuntia ficus-indica,* in South Africa. The moth also attacked jointed cactus to a limited extent but the damage caused was largely inconsequential. Two years later, in 1935, a cochineal insect, *Dactylopius austrinus,* was released at a time when jointed cactus had severely inhibited grazing by livestock on many properties, and land prices were decreasing. This cochineal insect proved particularly effective, and by 1946 biological control was the recommended method of management. However, decreases in the abundance of the host plant were followed by consequent decreases in the numbers of the cochineal insects, allowing the plant populations to recover.

The resurgence of the weed caused concern among property owners, who became disillusioned with the cochineal insects and with biological control and assumed that the insects would not provide permanent control of jointed cactus. As a result, subsidized herbicidal applications, at a huge cost, became the official management tool from 1957. The use and misuse of herbicides (the kerosene base was used for many purposes for which it was not intended) also acted against biological control. This situation persisted until a study was undertaken which clearly showed that the cochineal and the weed go through fluctuating population cycles in which jointed cactus populations increase and collapse approximately every 10–12 years.[4] These findings restored the credibility of the cochineal insects, and biological control gradually returned to favour. State subsidies on herbicides for jointed cactus control have now been greatly reduced. This has opened the way for cochineal insects to be maximally effective again in the management of jointed cactus and the insects are now being mass-reared near Uitenhage and provided free of charge for manual re-distribution when and where they are needed. Individual landowners and taxpayers are the beneficiaries.

These early efforts against problem cacti resulted in the release of six agent species, some of which made use of more than one species of cactus as host plants. There was then a complete hiatus in weed biological control in the 1950s, and only seven more releases were made in the 1960s. With the exception of one South African venture with the Commonwealth Institute of Biological Control, that culminated in the release, in 1948, of a stem-boring weevil against sweet prickly pear, all of the other biological control programmes from 1913 until the late 1960s were dependent on the importation of agents that had already been used in other countries. These agents had been tested for host-specificity and proved to be effective against various invasive cactus species, lantana (*Lantana camara*) and St John's wort (*Hypericum perforatum*), and all came to South Africa via Australia.[3] Close cooperation with biological control scientists from many countries (Australia in particular) continues to this day. However, from the late 1960s, weed biological control research in South Africa gained its independence, with projects that were initiated and researched entirely by South African scientists to counter uniquely South African weed problems.

The period from the early 1970s

In the early 1970s, at the instigation of the late David P. Annecke, a weed biological control research group was formed within the Plant Protection Research Institute (PPRI), bolstered by recruits from some universities. As a result, weed biological control in South Africa became properly organized and activity increased greatly. The number of releases of new agents in South Africa[8] may be used as a measure of activity in biological control against invasive alien plants. There were 22 releases of new agents in the 1970s, 30 in the 1980s, and 33 in the 1990s. This impetus has grown. There have already been 10 releases of new agents from 2000 to 2003, and more are in prospect.

South African researchers obviously face the same matters of principle and conventional technical problems as their counterparts in biological control in other parts of the world. The host-specificity of the agents, the safety of biological control, risks and non-target effects, and legislative procedures that govern the introduction and release of biological control agents were, and still are, major issues. Researchers in South Africa, and in other countries where biological control is practiced, devote energy and thought to the technical aspects of biological control, including exploration, quarantine procedures, release strategies, monitoring and evaluation. They are concerned with predicting and optimizing success in biological control, choosing the most effective agents and the most vulnerable stage of the target plant, and analysing why biological control has succeeded or why it has failed. There is a copious amount of literature on the technical aspects of biological control and these topics comprise the agenda for regular international meetings on weed biological control.[9–11]

In South Africa, a single agency, the PPRI, has been responsible for all the essential preparatory aspects leading to the releases of biological control agents, while subcontracting certain projects and long-term evaluative work to researchers at a few participating universities (mainly at Rhodes University and the University of Cape Town). This commonality brought coherence and encouraged cooperation on a national level and contrasts with the situation in many other countries where inter-agency rivalries have fragmented and even hampered biological control endeavours. South African weed biological control priorities were largely determined by political and pragmatic considerations, and by the intuitions of the senior and leading researchers at the time.

By the early 1970s, South Africa was gradually changing its emphasis from exclusively agriculturally driven biological control to a focus that was increasingly motivated by deep concerns about the plight of conservation areas. In this respect, South Africa was ahead of the times. South African scientists became involved in a number of unique projects, and in innovative approaches to biological control. For example:

- South Africa took the lead in the biological control of invasive tree species, particularly in conservation and riparian areas. The use of agents that reduce the seeding of target trees has proved successful in supplementing management practices. The successful use of two species of gall-forming pteromalid wasps against long-leaved wattle, *Acacia longifolia,* and golden wattle, *A. pycnantha,* respectively, are cases in point.[12–14] Conventional dogma had rejected gall-forming species as ineffective in biological control. In particular, seed-destroying agents have helped to defuse conflicts of interest, that is, in cases where the trees are useful to some sectors of the community but problematical to others.[12] South Africa has also had outstanding success using a fungus that has been deployed against an Australian invasive tree, Port Jackson willow, *A. saligna.*[15] In addition, following continuing consultations with the forestry industry, a cone-feeding weevil species that has the potential to reduce seeding in cluster pine, *Pinus pinaster,*[16] is currently being tested in quarantine in South Africa.

- It is the first country to have released agents against invasive species of plants in the family Solanaceae, namely, satansbos (*Solanum eleagnifolium*), wild tomato (*Solanum sisymbriifolium*), and bugweed (*Solanum mauritianum*). This plant-family includes potatoes, tomatoes, eggplant, tobacco and a number of other beneficial plants, a fact that obviously increases the risk and puts added pressure on the quality of the tests and on the scientists that establish the safety of the agents.[17,18]
- Currently, South Africa is the leading nation in the exploration and release of agents for the biological control of three weeds of major international significance, namely lantana, *Lantana camara,*[19] water hyacinth, *Eichhornia crassipes,*[20] and triffid weed, *Chromolaena odorata.*[21]

Since the 1970s, a small, dedicated and cooperative team of researchers has accumulated an impressive track record on a relatively small budget. The question is: what have these releases of biological control agents and all these activities actually achieved in the management of invasive alien plants in South Africa?

The successes achieved

The numbers of species of biological control agents established

The information in Table 1 has been updated from a list of invasive alien plants that have been targeted for biological control in South Africa,[8] and provides a summary of the biological control of 44 target plant species (counting *Prosopis* hybrids as one species) on which biological control agents have become successfully established. Altogether, 86 species of biological control agents have been released in South Africa since 1913, of which 23 failed to establish (see Table 1). Some details of the 63 successfully established agents are provided in Table 2; namely, the types of organisms used, how they feed (i.e. the feeding guilds) and how they damage their target plants.

Biological control in the management of invasive alien plants

In some instances the reductions in distribution, rate of spread and density of the target weed brought about by biological control agents are obvious and spectacular. It is easy to categorize these instances of biological control as highly successful. In the case of drooping prickly pear, for example, a former pervasive weed has almost disappeared. In another, more recent case, using a single species of weevil as the agent, biological control of the red water fern, *Azolla filiculoides,* resulted in almost complete elimination of the weed over its entire area of distribution within a few years.[22,23] By contrast, in some cases biological control agents have become established on their target plants, but after many years their contribution to management has been negligible. For example, the release, over more than 50 years, of 21 different species of agents on lantana, has resulted in notable and impressive damage to some cultivars of the plant in certain areas, but generally the levels of control achieved have been disappointing. Several other examples fall between these extremes, and while the agents are contributing to control, the weeds remain a problem in some circumstances, albeit at lower levels than before biological control.

The assessment of the contribution of biological control to management of invasive alien plants is difficult and complex.[24] Overall, South African practitioners have classified success in weed biological control[8,25] as follows:

- *'complete'*; no other control methods are needed to reduce the weed to acceptable levels, at least in areas where the agents are established;
- *'substantial'*; other management methods are needed to supplement biological control and reduce the weed to acceptable levels, but these management efforts are less than they were prior to biological control (for example, lower volume of herbicide or fewer applications, because the weed infestation is reduced in size and/or density);
- *'negligible'*; in spite of obvious damage to the weed by the agent management efforts are entirely reliant on other measures, not biological control; and
- *'?'*; the impact of the agents is unknown either because no follow-up evaluations were done at the time or because it is too early for the programme to be meaningfully evaluated.

According to this classification of success, for those weed biological control programmes in South Africa where agents have established (Table 1), 11 of 44 (25%) of the target plant species have been completely controlled biologically. Sixteen (36%) have been substantially controlled. The agents have had a negligible impact on the target weed species in 12 (27%) of the cases, and for 5 (11%) of the programmes, the outcome of biological control is uncertain. These results are highly satisfactory and compare favourably with results in weed biological control from other parts of the world.[26–29] Biological control is not a panacea; it is mostly a tool for enhancing the management of invasive alien plants, which are very costly to the South African economy.[30] It has been estimated that biological control has already reduced the overall budget for the management of problem plants in South Africa by about 19.8%. This represents a saving of about US$276 million.[31] Further impressive savings will accrue in future, as biological controls become more effective and widespread.

The contribution of the Working for Water programme to biological control of invasive alien plants in South Africa

Recent political developments

Following the change in political circumstances in South Africa since 1994, the country has ratified several international conventions that deal with the issue of invasive plants and their control. Article 8(h) in the Convention on Biological Diversity is most significant in this respect, in that it commits participating countries to 'prevent the introduction of, to control, or to eradicate those alien species which threaten ecosystems, habitats or species'. South Africa has recently become increasingly involved in these efforts internationally and particularly in other parts of Africa.[32]

In retrospect, there seems little doubt that 1996 will be seen as the start of a new era for conservationists, and for the biological control of invasive alien plants in South Africa. The Constitutional Assembly accepted the Constitution of the Republic of South Africa in October 1996. Item 24 of the Bill of Rights states that everyone has 'the right to have the environment protected, for the benefit of present and future generations, through reason-

Table 1. A list of invasive alien plants in South Africa on which biological control agents have become successfully established, updated to July 2003.

Family	Invasive alien plant species	Year of release of first agent	Number of insect (+pathogen) species established	Degree of control
ARACEAE	*Pistia stratiotes* (water lettuce)	1985*	1	Complete
ASTERACEAE	*Ageratina adenophora* (crofton weed)	1984	1 (+1)	Negligible
	Ageratina riparia (creeping crofton weed)	1989	0 (+1)	Negligible
	Cirsium vulgare (spear thistle)	1984	1 [1 failed]	Negligible
AZOLLACEAE	*Azolla filiculoides* (red water fern)	1997	1	Complete
BIGNONIACEAE	***Macfadyena unguis-cati* (cat's claw creeper)**	**1999**	**1**	**Negligible**
CACTACEAE	*Cereus jamacura* (queen of the night)	1990	2	Substantial
	Harrisia martinii (moon cactus)	1983	2	Complete
	Opuntia aurantiaca (jointed cactus)	1935	2 [3 failed]	Substantial
	Opuntia exultata (long-spine cactus)	?	1	Negligible
	Opuntia ficus-indica (sweet prickly pear)	1933	4	Substantial
	Opuntia fulgida (rosea cactus)	1970	1	Negligible
	Opuntia imbricata (imbricate prickly pear)	1970	1 [1 failed]	Substantial
	Opuntia leptocaulis (finger cactus)	1977	1	Complete
	Opuntia linheimeri (small round-leaved prickly pear)	1938	2	Substantial
	Opuntia monacantha (drooping prickly pear)	1913	3	Complete
	Opuntia salmiana (no common name)	?	1	Substantial
	Opuntia spinulifera (saucepan cactus)	?	1	Negligible
	Opuntia stricta (Australian pest pear)	1980s*	2	Complete
	***Pereskia aculeata* (Barbados gooseberry)**	**1991***	**1**	**Negligible**
CAESALPINIACEAE	***Caesalpinia decapetala* (Mauritius thorn)**	**1999**	**1**	**?**
CLUSIACEAE	*Hypericum perforatum* (St John's wort)	1960	2 [4 failed]	Complete
HALORAGACEAE	*Myriophyllum aquaticum* (parrot's feather)	1994	1	Complete
MIMOSACEAE	***Acacia cyclops* (rooikrans)**	**1994***	**2**	**Substantial**
	***Acacia dealbata* (silver wattle)**	**1994***	**1**	**?**
	***Acacia decurrens* (green wattle)**	**2001***	**1**	**?**
	Acacia longifolia (long-leaved wattle)	1982	2	Complete
	***Acacia mearnsii* (black wattle)**	**1993***	**1**	**?**
	***Acacia melanoxylon* (Australian blackwood)**	**1986***	**1**	**Substantial**
	***Acacia pycnantha* (golden wattle)**	**1987***	**1**	**Substantial**
	***Acacia saligna* (Port Jackson willow)**	**1987***	**1 (+1)**	**Substantial**
	Leucaena leucocephala (leucaena)	1999	1	?
	Paraserianthes lophantha (stink bean)	1989*	1	Substantial
	***Prosopis* species (mesquite various hybrids)**	**1987***	**2 [1 failed]**	**Negligible**
MYRTACEAE	***Leptospermum laevigatum* (Australian myrtle)**	**1994***	**2**	**Negligible**
PAPILIONACEAE	*Sesbania punicea* (red sesbania)	1970s	3	Complete
PONTEDERIACEAE	***Eichhornia crassipes* (water hyacinth)**	**1974***	**5 (+1)**	**Substantial**
PROTEACEAE	***Hakea gibbosa* (rock hakea)**	**1975***	**1**	**Negligible**
	***Hakea sericea* (silky hakea)**	**1970***	**3**	**Substantial**
SALVINIACEAE	*Salvinia molesta* (Kariba weed)	1985	1	Complete
SOLANACEAE	*Solanum elaeagnifolium* (satansbos)	1979	2 [2 failed]	Substantial
	***Solanum mauritianum* (bugweed)**	**1999***	**1**	**Negligible**
	Solanum sisymbriifolium (dense-thorned bitter apple)	1994	1	Substantial
VERBENACEAE	***Lantana camara* (lantana)**	**Before 1961**	**9 (+1) [11 failed]**	**Substantial**

Asterisks indicate ongoing research projects. The degree of control is recorded (see text for details). Projects supported by the Working for Water programme are indicated in bold type.

able legislative and other measures that (i) prevent pollution and ecological degradation; [and] (ii) promote conservation;....'. Item 27 in the Bill of Rights stipulates that everyone in South Africa has 'the right to have access to sufficient water...' and that 'The State must take reasonable legislative and other measures to achieve the progressive realization of each of these rights'.

From a conservation and biological control point of view, these progressive, even inspired, items in the Bill of Rights give legitimacy, strength and purpose to a range of legislation in respect of the management of invasive alien organisms and particularly their management in conservation and riparian areas. This legislation includes the National Environment Management Act, the Environment Conservation Act, the Water Act, the National Veld and Forest Fire Act, and most relevant to this paper, the regulations promulgated in terms of the Conservation of Agricultural Resources Act. The last categorizes invasive plants and stipulates what must be done in respect of their management and control.

The objectives of Working for Water are explained elsewhere in this issue, but in essence they are the removal and control of invasive alien plants from the South African environment, particularly trees in water catchments, rivers and conservation areas. The motivation for Working for Water is improved stream flow, the provision of less costly water supplies to the people, and the protection of biodiversity in natural ecosystems.[30,31,33,34] The managers of Working for Water have understood, from the outset, that the task that they had set themselves is daunting, logistically difficult, expensive and long term. Those involved, including politicians, managers and implementers, have come to realize more and more starkly, that satisfactory, sustainable and affordable management of invasive alien plants in South Africa will be impossible without the integration of biological control as a supplement to other management practices.

The consequences of the interventions by Working for Water since 1995

There is little doubt, in retrospect, that if it had not been for the active intervention of Working for Water, the practice of weed biological control in South Africa would have languished, perhaps almost stopped. Weed biological control research and support personnel at the PPRI are beleaguered by numerous regulatory, political and financial restraints, but the funding and support from Working for Water has at least stabilized the situation, and, in many respects, has invigorated the practice. From a Working for Water perspective, support of biological control is imperative. Without biological control as an aid in the management of invasive alien plants the whole enterprise of weed control would be far more costly and, in the long term, ineffective. Current mechanical and chemical control procedures cannot be financed at present levels in perpetuity and biological control has to play an increasingly important role if Working for Water is to succeed.

Table 2. Statistics on the (i) taxonomic group, (ii) guild, and (iii) plant-parts damaged, for the 63 species (58 insect species and five pathogens) that have become established as biological control agents on invasive alien plants in South Africa (see text and Table 1 for further details).

(i) **Taxonomic group**	Number of species	Percentage
Weevils and close relatives (Coleoptera: Apionidae, Bruchidae and Curculionidae)	21	33.3
Other families of beetles (Coleoptera)	11	17.5
Sucking bugs (Hemiptera: Heteroptera and Homoptera)	10	15.9
Butterflies and moths (Lepidoptera)	7	11.1
Flies (Diptera)	7	11.1
Pathogenic fungi (Basidiomycetes and Hyphomycetes)	5	7.9
Plant-feeding wasps (Hymenoptera: Pteromalidae)	2	3.2
(ii) **Guild**		
Adults or larvae chew and devour the plant tissues	26	41.3
Adults or larvae mine or bore into the plant	16	25.4
Adults and immature stages suck the sap	10	15.9
The agents (including one pathogen species) induce plant-galling	7	11.1
Pathogenic agents produce necroses and spots	4	6.4
(iii) **Plant parts damaged**		
Vegetative tissues (leaves, petioles, stalks, stems)	31	49.2
Reproductive tissues (buds, flowers, seeds, pods)	22	34.9
Sap drained from the phloem vessels	10	15.9

Obviously, funding from Working for Water (amounting to about R7 million per annum over the last three years, increasing to over R12 million per annum from August 2003) has been the principal support for weed biological control in South Africa.

However, there have been a number of other benefits, including the following:

- *Improved international recognition and cooperation.* Working for Water has become a well-known programme in many countries that are involved in the management of invasive alien plant species.[35] Weed biological control in South Africa has always been well regarded in its own right but the international status of the discipline has been vicariously advanced through association with the Working for Water programme. Since its inception, Working for Water has hosted a major bi-national meeting with the United States and has hosted a visiting Australian delegation. Biological control has featured prominently during these interactions. Working for Water has close links with the International Union for Conservation of Nature and Natural Resources (IUCN), the United Nations Environment Programme (UNEP), the Global Environment Facility (GEF) and with the Global Invasive Species Programme (GISP). These contacts are of obvious strategic importance, with strong potential to enhance weed biological control efforts in this country.
- *Cooperative ventures in Africa.* Support and funding from the Working for Water programme has contributed to the development of cooperative exchanges between biological control scientists in South Africa and their counterparts in other African countries. Experts from Africa have visited laboratories and field sites in South Africa, and scientists from South Africa have been reciprocally hosted elsewhere in Africa. South African weed biological control experts serve on committees and contribute to workshops that deal with the problems of invasive alien plants in Africa, and South Africa has become an informal 'clearing house' for weed biological control on the continent. The overall objective is the use of appropriate technological advances in biological control, that have been developed in Africa, and that are used to help solve Africa's weed problems. Examples include South African technological inputs into management plans against invasive cacti and mesquite (*Prosopis*) in Ethiopia, and the much-publicized South African technological and scientific contributions to the management of water hyacinth on Lake Victoria.[36]

  In the latter case, expertise in biological control developed in South Africa benefited East African countries and, more recently, all other African countries, north and south of the Equator, where water hyacinth threatens human livelihoods. These sorts of productive exchanges are imperative for the effective management of invasive plants whose spread takes no cognizance of political boundaries. These cooperative ventures support the South African president's vision for advancement in Africa in the NEPAD plan (that is, 'New Partnership for Africa's Development').
- *Strategic planning, capacity building and transformation.* Working for Water has guided planning and strategic thinking in weed biological control in South Africa.[37,38] These processes have been inclusive, in that people in a number of different agencies in South Africa have been involved, including experts in weed biological control, ecology, conservation and forestry. The process has been enriched by the participation of politicians and leading international experts. Funding from Working for Water has enabled recruitment of new staff and particularly has broadened the demographic composition of those involved in weed biological control research and implementation in South Africa.
- *Integrated management practices.* The philosophy of Working for Water and of cooperating conservation departments and agencies (including the forestry industry, and the Land Care movement of the National Department of Agriculture) in South Africa supports the optimal integration of all management practices against invasive alien plants.[32] Most importantly, Working for Water holds a long-term view of management (20 years or more). These views are compatible with the practice of biological control, which has always been undermined by unrealistic expectations for quick results and the 'eradication' rather than control of problem plants.
- *Benefit:cost analyses.* Traditionally, weed biological control has been the ambit of entomologists and plant pathologists, who usually lack the expertise to provide economic evidence that supports their claims of 'outstanding', or 'spectacular' or 'complete' successes for biological control. Recently, however, the benefits and costs of managing invasive alien trees in South

Africa have led to a number of economic studies,[39,40] some of which have been initiated and funded by Working for Water. Estimates of benefit:cost ratios for weed biological control ranged from 8:1 for lantana (one of the least successful and most expensive programmes in South Africa), to 709:1 for the programme against jointed cactus. Projected benefit:cost estimates range from 34:1 for lantana, up to an extraordinary 4333:1 for golden wattle.[40] These values are exceptionally encouraging and present a compelling case for biological control, but they are dependent on models that incorporate a number of arguable assumptions.

By contrast, the study on the economics of biological control of the red water fern[23] is, as yet, the only full benefit:cost analysis of an actual biological control project in South Africa, from its inception. As such, it sets a precedent indicating the wisdom of investment in biological control and in research aimed at establishing, species-by species, the costs and benefits of this management practice.

- *The biological control implementation programme.* Working for Water has funded processes that have enhanced the application of biological control research by managers in the field. The biological control 'implementation programme' has been an important development and has resulted in the appointment of skilled staff, the mass-rearing of biological control agents in four provinces and improved liaison between state departments, researchers and Working for Water implementation officers in the field, private forestry, and the wider public.

Working for Water and the way forward in weed biological control in South Africa

During 2002, Working for Water, together with the PPRI and participating universities, took the initiative in planning the way forward in research on the biological control of invasive alien plants in South Africa. Following a protracted process involving all interested parties, Working for Water has decided to fund five cooperative teams who will work on priority projects during the next three-year funding cycle, from 1 April 2003, as follows:

1. A team from the PPRI and Rhodes University will complete research on selected biological control agents against lantana (*Lantana camara*), continue research on Barbados gooseberry (*Pereskia aculeata*) and considerably increase the research effort on triffid weed (*Chromolaena odorata*).
2. A consortium of biological control researchers and ecologists from the PPRI, the University of Cape Town and the CSIR will concentrate on biological control of invasive Australian *Acacia* species. The team will also continue research on *Hakea* species and Australian myrtle (*Leptospermum laevigatum*), and complete screening of a prospective agent against cluster pine (*Pinus pinaster*).
3. A consortium of researchers from Rhodes University, the PPRI and the CSIR will continue research on the biological control of water hyacinth (*Eichhornia crassipes*).
4. A team from the PPRI will continue research on invasive tree hybrids of mesquite (*Prosopis* species). They will initiate research on invasive gum trees (*Eucalyptus* species) and on the biological control of jacaranda (*Jacaranda mimosifolia*), both of which are recognized as serious invasive trees in this country but which have not, as yet, been prioritized for biological control research.
5. Lastly, a team of researchers from the PPRI will start work on the biological control of selected species of plants that are recognized as important emerging weeds in this country. Five species have been chosen from a long list of incipient weeds; they are pompom weed (*Campuloclinium macrocephalum*), American bramble (*Rubus cuneifolius*), balloon vine (*Cardiospermum grandiflorum*), parthenium or feverfew (*Parthenium hysterophorus*), and yellow bells (*Tecoma stans*).

These developments, and the sustained support of Working for Water, bode well for the future of weed biological control in South Africa.

We are grateful for generous funding from the Department of Water Affairs and Forestry, through the Working for Water programme, the Plant Protection Research Institute of the Agricultural Research Council, and the University of Cape Town.

1. Henderson L. (2001). *Alien Weeds and Invasive Plants.* Plant Protection Research Institute Handbook No. 12. Agricultural Research Council, Pretoria.
2. Van Klinken R.D. and Edwards O.R. (2002). Is host-specificity of weed biological control agents likely to evolve rapidly following establishment? *Ecol. Lett.* **5**, 590–596.
3. Julien M.H. and Griffiths M.W. (1998). *Biological Control of Weeds. A world catalogue of agents and their target weeds,* 4th edn. CSIRO Entomology. CABI Publishing, Wallingford, Oxon.
4. Moran V.C. and Zimmermann H.G. (1991). Biological control of jointed cactus, *Opuntia aurantiaca* (Cactaceae), in South Africa. *Agric. Ecosyst. Environ.* **37**, 5–27.
5. Pettey F.W. (1948). The biological control of prickly pears in South Africa. *Sci. Bull. Dept Agric. For., Un. S. Afr.* **271**, 1–163.
6. Annecke D.P. and Moran V.C. (1978). Critical reviews of biological pest control in South Africa. 2. The prickly pear, *Opuntia ficus-indica* (L.) Miller. *J. Ent. Soc. sthn Afr.* **41**, 161–188.
7. Moran V.C. and Annecke D.P. (1979). Critical reviews of biological pest control in South Africa. 3. The jointed cactus, *Opuntia aurantiaca* Lindley. *J. Ent. Soc. sthn Afr.* **42**, 299–329.
8. Olckers T. and Hill M.P. (eds) (1999). Biological control of weeds in South Africa (1990–1998). *African Entomology Memoir* No. 1, 182 pp.
9. Delfosse E.S. and Scott R.R. (eds) (1995). Biological control of weeds. *Proc. VIII International Symposium on Biological Control of Weeds.* 1992. Lincoln University, Canterbury, New Zealand; CSIRO, Melbourne.
10. Moran V.C. and Hoffmann J.H. (eds) (1996). *Proc. IX International Symposium on Biological Control of Weeds,* Stellenbosch, South Africa. University of Cape Town, South Africa.
11. Spencer N.R. (ed.) (2000). *Proc. X International Symposium on Biological Control of Weeds,* 1999, Bozeman, Montana.
12. Dennill G.B. and Donnelly D. (1991). Biological control of *Acacia longifolia* and related weed species (Fabaceae) in South Africa. *Agric. Ecosyst. Environ.* **37**, 115–135.
13. Dennill G.B., Donnelly D., Stewart K. and Impson F.A.C. (1999). Insect agents used for the biological control of Australian *Acacia* species and *Paraserianthes lophanta* (Willd.) Nielsen (Fabaceae) in South Africa. *African Entomology Memoir* No. 1, 45–54.
14. Hoffmann J.H., Impson F.A.C., Moran V.C. and Donnelly D. (2002). Biological control of invasive golden wattle trees (*Acacia pycnantha*) by a gall wasp, *Trichilogaster* sp. (Hymenoptera: Pteromalidae), in South Africa. *Biol. Control* **25**, 64–73.
15. Morris M.J. (1999). The contribution of the gall-forming rust fungus *Uromycladium tepperianum* (Sacc.) McAlp. to the biological control of *Acacia saligna* (Labill.) Wendl. (Fabaceae) in South Africa. *African Entomology Memoir* No. 1, 125–128.
16. Moran V.C., Hoffmann J.H., Donnelly D., van Wilgen B.W. and Zimmermann H.G. (2000). Biological control of alien invasive pine trees (*Pinus* species) in South Africa. *Proc. X International Symposium on Biological Control of Weeds,* ed. N.R. Spencer, Bozeman, Montana, pp. 941–953.
17. Olckers T. (1999). Biological control of *Solanum mauritianum* Scopoli (Solanaceae) in South Africa: a review of candidate agents, progress and future prospects. *African Entomology Memoir* No. 1, 65–73.
18. Olckers T., Hoffmann J.H., Moran V.C., Impson F.A.C. and Hill M.P. (1999). The initiation of biological control programmes against *Solanum elaeagnifolium* Cavanilles and *S sisymbriifolium* Lamarck (Solanaceae) in South Africa. *African Entomology Memoir* No. 1, 55–63.
19. Baars J-R. and Neser S. (1999). Past and present intitatives on the biological control of *Lantana camara* (Verbenaceae) in South Africa. *African Entomology Memoir* No. 1, 21–33.
20. Hill M.P. and Cilliers C.J. (1999). A review of the arthropod natural enemies, and factors that influence their efficacy, in the biological control of water hyacinth, *Eichhornia crassipes* (Mart.) Solms-Laubach (Pontederiaceae), in South Africa. *African Entomology Memoir* No. 1, 103–112.
21. Zachariades C., Strathie-Korrûbel L.W. and Kluge R.L. (1999). The South African programme on the biological control of *Chromolaena odorata* (L.) King & Robinson (Asteraceae) using insects. *African Entomology Memoir* No. 1, 89–102.
22. Hill M. P. (1999). Biological control of red water fern, *Azolla filiculoides* Lamarck (Pteridophyta: Azollaceae), in South Africa. *African Entomology Memoir* No. 1, 119–124.
23. McConnachie A.J., de Wit M.P., Hill M.P. and Byrne M.J. (in press). Economic

evaluation on the biological control of *Azolla filiculoides* in South Africa. *Biological Control.*

24. Syrett P., Briese D.T., and Hoffmann J.H. (2000). Success in biological control of terrestrial weeds by arthropods. In *Biological Control: Measures of success,* eds G. Gurr and S. Wratten, pp. 189–230. Kluwer, Dordrecht.
25. Hoffmann J.H (1991). Introduction. Special issue: Biological control of weeds in South Africa. *Agric. Ecosyst. Environ.* **37**, 1–3.
26. Hoffmann J.H. (1995). Biological control of weeds: The way forward, a South African perspective. *Proc. British Crop Protection Council Symposium: Weeds in a Changing World, BCPC* **64**, 77–89.
27. McFadyen R.E. (1998). Biological control of weeds. *Annu. Rev. Ent.* **43**,–369-393.
28. Fowler S.V. (2000). Trivial and political reasons for the failure of classical biological control of weeds: a personal view. *Proc. X International Symposium on Biological Control of Weeds,* ed. N.R. Spencer, Bozeman, Montana, pp. 169–172..
29. Fowler S.V., Syrett P. and Hill R.L. (2000) Success and safety in the biological control of environmental weeds in New Zealand. *Aust. Ecol.* **25**, 553–562.
30. Van Wilgen B.W., Richardson D.C., Le Maitre D.C., Marais C. and Magadlela D. (2001). The economic consequences of alien plant invasions: examples of impacts and approaches to sustainable management in South Africa. *Environment, Development and Sustainability* **3**, 145–168
31. Le Maitre D.C., Versfeld D.B. and Chapman R.A. (2000). The impact of invading alien plants on surface water resources in South Africa: a preliminary assessment. *Water SA* **26**, 397–408.
32. Zimmermann H.G. and Neser S. (1999). Trends and prospects for biological control of weeds in South Africa. *African Entomology Memoir* No. 1, 165–173.
33. Van Wilgen B.W., Le Maitre D.C. and Cowling R.M. (1998). Ecosystem services, efficiency, sustainability and equity: South Africa's Working for Water programme. *Trends Ecol. Evol.* **13**, 378.
34. Higgins S.I., Turpie J.K., Costanza R., Cowling R.M., Le Maitre D.C., Marais C. and Midgley G.F. (1997). An ecological economic simulation model of mountain fynbos ecosystems. Dynamics, valuation and management. *Ecol. Econ.* **22**, 155–169.
35. Preston G., Brown G. and van Wyk E. (eds) (2000). *Best management practices for preventing and controlling invasive alien species.* Symposium proceedings. Working for Water Programme, Cape Town.
36. Cilliers C.J., Hill M.P., Ogwang J.A. and Ajuonu O. (in press) Aquatic weeds in Africa and their control. In *Biological Control in IPM systems in Africa,* eds P. Neuenschwander, C. Borgemeister and J. Langerwald. CABI Publishing, Wallingford, Oxon.
37. Van der Heyden F. (2000). Proceedings: Biocontrol of alien invading plants in South Africa — strategy workshop, Stellenbosch, 1999. CSIR Report no. ENV-S-C 2000-015.Pretoria
38. Van Wilgen B. W., van der Heyden F., Zimmermann H.G., Magadlela D. and Willems T. (2000). Big returns from small organisms: developing a strategy for the biological control of invasive alien plants in South Africa. *S. Afr. J. Sci.* **96**, 148–152.
39. Le Maitre D.C. van Wilgen B.W., Gelderblom C.M., Bailey C., Chapman R.A. and Nel J.A. (2001). Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *For. Ecol. Mngmnt* **160,** 143–150.
40. Van Wilgen B.W., de Wit M.P., Anderson H.J., Le Maitre D.C., Kotze I.M. Ndala S., Brown B. and Rapholo M.B. (2004). Costs and benefits of biological control of invasive alien plants: case studies from South Africa. *S. Afr. J. Sci.*, **100,** 113–122.

Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response

Peter Dye[a*] **and Caren Jarmain**[b]

Black wattle (*Acacia mearnsii*) is one of the most widespread and significant invasive alien trees in South Africa, and great concern is frequently expressed over its potential effect on reducing catchment water yields. The species often forms dense stands, maintains a high green leaf area throughout the year, and frequently replaces seasonally dormant grasslands and fynbos. It is widely accepted that removal of such stands of trees in these circumstances leads to improved catchment water yields. Quantifying this benefit would be useful for analyses of the full economic benefit of alien tree clearing programmes, but relevant information is scarce and scattered in different publications. Streamflow response information is also required to assist in prioritizing areas for alien tree removal. This paper reviews relevant available information on rates of total evaporation from black wattle and from grasslands and fynbos shrublands. These data provide an indication of the likely change in catchment water yield following invasion or clearing of black wattle. The assumption is made that over the long term, reductions in total evaporation equate to water yield increases. Soil water storage and leakage from catchments are therefore considered to be small and constant under the different vegetation covers. Our review shows that very high rates of total evaporation are possible from dense infestations of black wattle occurring in riparian zones, where there are no soil water deficits through the year. Annual total evaporation from such sites may exceed 1500 mm, a figure that is comparable to many evergreen tropical lowland forests. Annual total evaporation from dense stands of black wattle established over entire catchments is likely to be lower than that from trees in riparian zones, since some degree of dry season drought stress is common on non-riparian sites. Annual total evaporation at such sites may exceed the current year's rainfall for a time, if prior accumulation of soil water has occurred. In general, however, low rainfall and low soil water storage capacity will both increase the frequency and severity of drought stress, and restrict annual total evaporation. Annual total evaporation from indigenous grasslands and fynbos shrublands commonly varies over a relatively narrow range of 600 to 850 mm. Differences in total evaporation following invasion or removal of black wattle in such vegetation are potentially large, up to as much as 600 mm. Some indigenous riparian plant communities may, however, demonstrate high year-round rates of total evaporation comparable to those recorded in dense stands of black wattle. The significant feature of such vegetation is the year-round high green leaf area that permits continuously high rates of total evaporation. Streamflow increases following removal of invading black wattles will be greatest in areas of high evaporative demand, where dense stands of trees experiencing low levels of drought stress through the year are replaced by seasonally dormant indigenous vegetation.

[a]CSIR Division of Water, Environment and Forest Technology, c/o Agrometeorology, School of Applied Environmental Sciences, University of Natal, Private Bag X01, Scottsville 3209, South Africa.
[b]CSIR Division of Water, Environment and Forest Technology, P.O. Box 320, Stellenbosch 7599.
*Author for correspondence. E-mail: pdye@csir.co.za

Introduction

This paper presents a synthesis of information on the water use by invasive black wattle (*Acacia mearnsii*) trees in South Africa. Our study provides important additional support for the