Appendix 2 (*continued*)

Habitat–propagule pool size	Scientific name	Common name	Impact	Weediness	Biocontrol	% Weedy relatives	Combined score	CARA category
Moderate–moderate	*Senna bicapsularis*	Rambling cassia	5	0	10	1	62	3
	Senna pendula var. *glabrata*	Rambling cassia	5	2	10	1	68	3
	Sesbania bispinosa var. *bispinosa*	Spiny sesbania	0	0	10	4	45	
	Sophora japonica	Japanese pagoda tree	0	0	10	2	42	
	Syzygium cumini	Jambolan	5	1	10	0	66	3
	Syzygium jambos	Rose apple	5	1	10	0	66	3
	Tithonia diversifolia	Mexican sunflower	0	1	10	3	48	1
	Ulmus parvifolia	Chinese elm	0	0	10	5	46	
	Verbena brasiliensis	Slender wild verbena	0	1	10	2	45	
Riparian–large	*Canna indica*	Indian shot	5	2	10	10	79	1
	Canna x *generalis*	Garden canna	5	1	10	10	72	
	Casuarina cunninghamiana	Beefwood	5	1	10	4	69	2
	Cortaderia jubata	Purple Pampas	5	3	10	2	75	1
	Cortaderia selloana	Pampas grass	5	5	10	2	81	1
	Oenothera biennis	Evening primrose	5	1	10	4	67	
	Populus deltoides	Match poplar						Proposed
Riparian–moderate	*Eucalyptus microtheca*	Coolabah	0	0	10	2	42	
	Mimosa pigra	Giant sensitive plant	5	4	10	1	76	3
	Myriophyllum spicatum	Spiked water-milfoil	5	4	10	3	80	1
	Oenothera glazioviana	Evening primrose	5	2	10	4	72	
	Oenothera indecora	Evening primrose	5	1	10	4	68	
	Oenothera jamesii	Giant evening primrose	5	0	10	4	64	
	Oenothera laciniata	Cutleaf evening primrose	5	1	10	4	67	
	Oenothera tetraptera	White evening primrose	5	0	10	4	66	
	Parkinsonia aculeata	Jerusalem thorn	5	1	10	0	66	
Small–large	*Alpinia zerumbet*	Shell ginger	5	0	10	0	62	
	Grevillea robusta	Australian silky oak	5	2	10	0	67	3
	Quercus robur	English oak	5	1	10	1	67	

Targeting emerging weeds for biological control in South Africa: the benefits of halting the spread of alien plants at an early stage of their invasion

T. Olckers*

Biological control against incipient, or emerging, weeds (plants in an early stage of invasion) has not been widely practised in many countries, largely because limited budgets tend to be directed at invasions that have already reached detrimental levels. Because of restricted funds and few opportunities for exploration abroad in the past, South African practitioners of biological control have made the most of their survey trips by collecting as many potentially useful control agents, from as many target plants, as they could. Exploration for agents against high-priority weeds thus allowed simultaneous collection of natural enemies of low-priority weeds in the same region. These opportunistic programmes have been beneficial for South Africa in the management of invasive alien plants. In 2003, the Working for Water programme allocated funds for biological control programmes against five emerging weed species. This investment has, for the first time, given formal recognition to the rationale of targeting incipient weeds and bodes well for the future of biological weed control in South Africa. This paper reviews cases where emerging weeds were targeted for biological control in this country, the successes that were achieved, and the prospects for enhancing this approach in the future.

*Plant Protection Research Institute, Private Bag X6006, Hilton 3245, South Africa.
E-mail: ntto@natal1.agric.za

Introduction

Biological control of invasive alien plants was begun in South Africa some 90 years ago and has an impressive record.[1] In recent years, much of the progress achieved here has been facilitated by the Working for Water programme. This enterprise, together with other factors that have influenced the success of weed biological control in South Africa, are comprehensively reviewed elsewhere in this issue.[2]

One of the important features of the biological control of weeds in South Africa has been the realization that the targeting of incipient weeds (that is, plants in an early stage of invasion) considerably enhances the prospects for success.[3] However, the targeting of emerging weeds has generally not been widely practised internationally, largely because biological control is often used as a last resort, when conventional methods of

Table 1. Details of 25 biological control programmes launched against emerging weeds in South Africa.

Weed species	Initial weed status (distribution in brackets)	Year of first releases	Number of biocontrol agents established	Current weed status (biocontrol success in brackets)
Water lettuce (*Pistia stratiotes*, Araceae)*	Increasing (widespread)	1985	1	Minor (complete)
Crofton weed (*Ageratina adenophora*, Asteraceae)*	Minor (localized)	1984	2	Increasing (negligible)
Creeping crofton weed (*Ageratina riparia*, Asteraceae)*	Minor (localized)	1989	1	Minor (negligible)
Spear thistle (*Cirsium vulgare*, Asteraceae)*	Minor (widespread)	1984	1	Minor (negligible)
Red water fern (*Azolla filiculoides*, Azollaceae)	Increasing (widespread)	1997	1	Minor (complete)
Cat's claw creeper (*Macfadyena unguis-cati*, Bignoniaceae)	Minor (localized)	1999	1	Increasing (negligible)
Queen of the night (*Cereus jamacaru*, Cactaceae)	Minor (localized)	1990	2 (from *H. martinii*)	Minor (substantial)
Moon cactus (*Harrisia martinii*, Cactaceae)*	Minor (localized)	1983	2	Minor (complete)
Long-spine cactus (*Opuntia exaltata*, Cactaceae)	Very minor (localized)	Extension†	1 (from *O. ficus-indica*)	Very minor (negligible)
Rosea cactus (*Opuntia fulgida*, Cactaceae)	Minor (localized)	1970	1 (from *O. imbricata*)	Increasing (negligible)
Imbricate cactus (*Opuntia imbricata*, Cactaceae)*	Minor (widespread)	1970	1	Minor (substantial)
Finger cactus (*Opuntia leptocaulis*, Cactaceae)	Very minor (localized)	1977	1 (from *O. imbricata*)	Very minor (complete)
Small round-leaved prickly pear (*Opuntia lindheimeri*, Cactaceae)	Minor (localized)	1938	2 (from *O. ficus-indica*)	Minor (substantial)
Cactus, no common name (*Opuntia salmiana*, Cactaceae)	Very minor (localized)	Extension	1 (from *O. ficus-indica*)	Very minor (substantial)
Saucepan cactus (*Opuntia spinulifera*, Cactaceae)	Very minor (localized)	Extension	1 (from *O. ficus-indica*)	Very minor (negligible)
Australian pest pear (*Opuntia stricta*, Cactaceae)*	Increasing (widespread)	1980s	2	Major but reduced (complete)
Barbados gooseberry (*Pereskia aculeata*, Cactaceae)	Increasing (widespread)	1991	1	Increasing (negligible)
St John's wort (*Hypericum perforatum*, Clusaceae)*	Increasing (localized)	1960	2	Minor (complete)
Parrot's feather (*Myriophyllum aquaticum*, Haloragaceae)	Increasing (widespread)	1994	1	Major but reduced (complete)
Leucaena (*Leucaena leucocephala*, Mimosaceae)	Increasing (localized)	1999	1	Increasing (unknown)
Australian myrtle (*Leptospermum laevigatum*, Myrtaceae)	Increasing (widespread)	1994	2	Increasing (negligible)
Red sesbania (*Sesbania punicea*, Papilionaceae)	Increasing (widespread)	1970s	3	Minor (complete)
Kariba weed (*Salvinia molesta*, Salviniaceae)*	Increasing (widespread)	1985	1	Minor (complete)
Silver-leaf bitter apple (*Solanum elaeagnifolium*, Solanaceae)	Increasing (localized)	1992	2	Major but reduced (substantial)
Dense-thorned bitter apple (*Solanum sisymbriifolium*, Solanaceae)	Minor (localized)	1994	1	Minor (substantial)

Asterisks indicate species that were targeted because of successes in other countries (i.e. 'transfer projects'), while the remaining species involved 'secondary projects' that are unique to South Africa. Initial weed status and distribution reflects the situation at the time that biological control was begun. Further details on the species targeted and the agents implicated as well as definitions of the degrees of success are provided elsewhere in this issue.[2] †Extension indicates agents that were not released on that weed but were naturally recruited from a closely related species.

management have been deemed to be unsustainable, or have failed.[4] Limited funds tend to be directed at high-priority species that have already reached detrimental levels. South Africa has a history of launching opportunistic biological control programmes (see below), which has been characterized by the targeting of invasive species that, at the time, were of lesser priority but had the potential as a future problem. Indeed, of the 44 biological control programmes begun against weeds in South Africa,[2] some 25 were started opportunistically, as spin-offs from major projects aimed at top-priority weeds (Table 1). In 2003, these initiatives were given formal recognition when the Working for Water programme, the main sponsor of weed biological control in South Africa, inaugurated programmes against five emerging weeds.[2]

This paper reviews emerging weeds that have been targeted for biological control in South Africa, the successes that have been achieved, and the prospects for enhancing this approach in the future. The primary aim of this review is to promote support for the early targeting of weeds for biological control, which can provide a rationale for incorporation into alien-plant management strategies.

Opportunism and weed biological control in South Africa

Before 1996, opportunities for overseas exploration and the importation of novel biological control agents were severely limited by a lack of funding and by political and other difficulties. South African programmes relied, to a large extent, on two circumstances to sustain the momentum of weed biological control. The first was the exploitation of the successes achieved with agents used in other countries, notably Australia, against the same (or similar) weed species as those that were a problem in South Africa. These 'transfer projects' were initiated in the 1930s against cactaceous weeds in South Africa, such as sweet prickly pear (*Opuntia ficus-indica*)[5] and jointed cactus (*Opuntia aurantiaca*),[6] that had already reached catastrophic densities. Following the success of these initiatives, species that were starting to show signs of becoming a problem in South Africa were also targeted. Such transfer projects were directed against emerging weeds that included St John's wort (*Hypericum perforatum*),[7] crofton weed (*Ageratina adenophora*),[8] spear thistle (*Cirsium vulgare*),[9,10] Kariba weed (*Salvinia molesta*),[11] water lettuce (*Pistia stratiotes*)[12] and several *Opuntia* and other cactaceous species of lesser priority[13] (Table 1).

The second circumstance was pragmatic opportunism. It was, and still is, a usual practice to collect natural enemies of weeds of secondary importance during exploratory trips overseas that mainly focused on high-priority weeds. Although these opportunistic collections were relatively superficial, several useful natural enemies were introduced, tested and released against weeds that would otherwise never have been targeted. Examples of such 'secondary projects' include those launched against red sesbania (*Sesbania punicea*),[14,15] Barbados gooseberry (*Pereskia aculeata*),[16] parrot's feather (*Myriophyllum aquaticum*),[17] silver-leaf bitter apple (*Solanum elaeagnifolium*),[18] dense-thorned bitter apple (*Solanum sisymbriifolium*),[18] Australian myrtle (*Leptospermum laevigatum*),[19] red water fern (*Azolla filiculoides*),[20] cat's claw creeper (*Macfadyena unguis-cati*)[21] and leucaena (*Leucaena leucocephala*)[22] (Table 1).

Key successes achieved against emerging weeds in South Africa

Table 1 lists details of 25 biological control programmes that have targeted emerging weeds and the degrees of success[2] that have been achieved. These programmes have largely been effective, with 60% of the weeds being brought under complete (36%) or substantial (24%) biological control. Selected case histories are reviewed below.

The benefits of implementing biological control against a weed

in the early stages of invasion were demonstrated in South Africa during the 1960s by the programme against *H. perforatum*.[4,7] In 1945, only three years after its accidental introduction, infestations of *H. perforatum* were reported in the Western Cape province and fears of further spread led to an extensive chemical control campaign in 1948. However, this campaign, carried out at great expense and sustained for 26 years in order to contain the plant's expansion, failed to eradicate the weed.

By this time, *H. perforatum* was already a renowned weed in Australia and California, where remarkable success with biological control had been achieved. Following several importations from Australia, the leaf-feeding beetle *Chrysolina quadrigemina* was released in South Africa in 1960, causing spectacular damage and the near destruction of dense stands of the weed within 2–3 years. This agent, together with the bud-galling midge *Zeuxidiplosis giardi,* imported from Australia in 1974, has since contained and controlled the weed in the Western Cape, where it remains as an insignificant invader in a few localized areas. Chemical control measures were suspended in 1974, in favour of biological control, a trend which continues today and has undoubtedly resulted in considerable economic savings. Initiatives undertaken elsewhere in the world thus facilitated the start of successful biological control in South Africa, only 18 years after the weed's introduction.

There are other examples of weeds that were halted at a very early stage, some even before they were recognized as potential threats. These involved cactus weeds for which successful programmes in Australia were extended to South Africa or where the oligophagous biological control agents (that is, those that feed on several closely related species of host plants) were either released on, or naturally colonized, closely related weeds (Table 1). Plants in the former category include moon cactus (*Harrisia martinii*) and imbricate prickly pear (*Opuntia imbricata*).[13,16] Today, the agents responsible for the control of these two species continue to be propagated and redistributed to landowners by implementing agencies[23] (in this case the Working for Water programme acting in partnership with the Department of Agriculture). In addition, other cactus species (such as *Opuntia leptocaulis, O. lindheimeri,* and *O. salmiana*), that formed limited and localized infestations, were also controlled by natural enemies (for instance, cochineal bugs of the genus *Dactylopius* and the moth *Cactoblastis cactorum*) that were originally imported against other *Opuntia* species.[13] These successful programmes cost very little and the resultant benefits are largely underestimated because the weeds were halted before infestations reached economically threatening levels.

In recent times, one of South Africa's most acclaimed programmes has been that launched against red sesbania. Originally imported for ornamental purposes, this toxic tree proved to be highly invasive, particularly along watercourses and in wetlands. Its potential as a serious threat became apparent in the 1970s,[24] with predictions that its environmental importance would increase. At the same time, surveys by South African entomologists in South America, largely for agents of cactaceous weeds, also permitted the opportunity to source enemies of this plant. During the 1980s, three weevil species were imported for testing and later released in South Africa (although one of these was later found to have become established on its own, presumably having been accidentally introduced by South American tourists in the 1970s). The impact of these agents, acting in combination, has been dramatic in that both the spread and density of *S. punicea* populations were reduced to the extent that the weed's status has been reduced considerably.[14,15] The economic benefits of this project, begun opportunistically and at relatively little cost, have thus been substantial.[25]

The programme against Australian pest pear (*Opuntia stricta*) revealed that feeding by the cactus-boring moth *Cactoblastis cactorum,* which was considered to be ineffective in controlling the weed, reduced the intensity and costs of chemical control.[26,27] This is because larval damage continually stunts the growth and survival of immature plants, which now take far longer to mature and produce fruit, thus allowing herbicidal operations more time to focus on the large fruiting plants which are mostly unaffected by the larvae and aggravate infestations. The release of a host-specific biotype of the cochineal insect *Dactylopius opuntiae* in 1997 has reduced the need for chemical control even further. These events have ensured that rapid increases in the distribution of the Australian pest pear, observed during the 1990s, have been halted and further management will ensure that the weed is brought under biological control.[28]

Several projects against aquatic weeds, that had not fully reached their invasive potential in South Africa, were conducted with considerable success. Although biological control initiatives in the 1970s and 1980s were mostly focused on water hyacinth (*Eichhornia crassipes*), lower priority species like Kariba weed and water lettuce were successfully controlled because highly effective agents were easily obtained as transfer agents from Australia at little cost.[11,12] The programme against parrot's feather followed because of fears that this weed would expand its range by invading habitats where *S. molesta* and *P. stratiotes* had declined, as a result of biological control. A leaf-feeding beetle in the genus *Lysathia* was released in 1994, and has since become numerous and widespread. The weed's growth is severely retarded by the beetle's feeding and local infestations of the plant, particularly in coastal and less temperate areas, have been reduced.[17] The most dramatically successful of these programmes was achieved against red water fern. Despite its phenomenal rate of increase during the 1990s, the fern was completely controlled in 1–2 years, following the release, in 1997, of the leaf-chewing weevil *Stenopelmus rufinasus.*[20] This agent had already been collected opportunistically for identification several years previously, thus facilitating rapid progress with this project when the decision was finally made, in 1995, to proceed.

Other programmes launched against emerging weeds in South Africa

In some instances (Table 1), biological control against emerging weeds has proved less successful in that the control agents are deemed to have had a negligible impact on their targets (for instance, crofton weed[8] and spear thistle[9,10]). However, these natural enemies may be having subtle effects (such as reduced flowering, stunted growth) that have remained undetected because lack of funding has limited comprehensive field evaluations. Indeed, the example of Australian pest pear (see above) clearly illustrated the importance of comprehensive post-release evaluations in quantifying the substantial benefits of an agent that was otherwise believed to have been of limited value.

Programmes that are showing signs of success include those against silver-leaf bitter apple and dense-thorned bitter apple. Success achieved so far against silver-leaf bitter apple is notable as this weed of croplands and rangelands has been difficult to control chemically, because its extensive root system is impervious to systemic herbicides and facilitates rapid re-growth after mechanical clearing. The release of two defoliating beetles, *Leptinotarsa texana* and *L. defecta,* in 1992 has reduced the vigour of the weed by simulating a chemical 'knock down' effect that allows broad-leafed crop and pasture species to proliferate and

Table 2. Details on five species of emerging weeds that were recently targeted for biological control by the Working for Water programme.

Weed species	Growth form	Current weed status (distribution in brackets)	Biocontrol agents sought
Pompom weed (*Campuloclinium macrocephalum*, Asteraceae)	Herb	Increasing (localized)	Rust fungi; defoliating, stem-boring and seed-reducing insects
Parthenium weed (*Parthenium hysterophorus*, Asteraceae)	Herb	Increasing (localized)	Rust fungi; defoliating, stem-boring and seed-reducing insects
Yellow bells (*Tecoma stans*, Bignoniaceae)	Tree	Increasing (widespread)	Gall-forming fungi; seed-reducing insects
American bramble (*Rubus cuneifolius*, Rosaceae)	Shrub	Increasing (widespread)	Rust fungi
Balloon vine (*Cardiospermum grandiflorum*, Sapindaceae)	Creeper	Increasing (widespread)	Rust fungi; defoliating, stem-boring and seed-reducing insects

further suppress the weed.[4,18] Despite earlier indications that populations of the defoliating beetle *Gratiana spadicea* were having little effect on dense-thorned bitter apple infestations, because of adverse climatic conditions and disruptive land management practices,[18] recent observations suggest that localized outbreaks of the beetle are suppressing weed populations.[29]

Despite a lack of demonstrable success so far, recent programmes against leucaena and cat's claw creeper are notable for different reasons. The release of the seed-feeding beetle *Acanthoscelides macrophthalmus* against the agroforestry tree leucaena in 1999 was remarkable because it heralded the first time that a beneficial plant species was targeted in the early stages of its being perceived as a potential invasive species in South Africa. Further releases and redistribution of this beetle, which has the potential to check further invasion by leucaena, without negating its useful attributes, may pre-empt the problems that have arisen with this plant elsewhere in the world.[22]

Biological control is also expected to play a crucial role in the management of the invasive cat's claw creeper, which smothers indigenous forests and degrades other sensitive habitats. Although current infestations are localized, further invasion is inevitable because of the plant's high capacity for seed and vegetative dispersal and the futility of both mechanical and chemical control efforts. Although only one agent has been released, with limited effect so far,[21] a further four agents are currently in quarantine and are awaiting permission for release.

Emerging weeds and the Working for Water programme

The principle of formally recognizing and funding research on biological control of emerging weeds was established in 2003 when the Working for Water programme decided to support studies on five species of incipient weeds.[2] These species were selected, from a long list of possible targets, because of their perceived threat and the notion that they may be vulnerable to biological control. The five species are: pompom weed (*Campuloclinium macrocephalum*), American bramble (*Rubus cuneifolius*), balloon vine (*Cardiospermum grandiflorum*), parthenium weed (*Parthenium hysterophorus*) and yellow bells (*Tecoma stans*) (Table 2). Except for American bramble, which was previously, but unsuccessfully, targeted with plant pathogens,[30] these represent new projects where potential biological control agents still need to be sourced by exploration abroad. However, earlier observations in their countries of origin have already provided sufficient evidence to suggest that there are several promising natural enemies for each of these five weeds.

Parthenium weed has already been subjected to biological control in Australia, where seven insect agents and two rust fungi have been successfully established,[31] and it is envisaged that cooperation with Australian research organizations will 'fast track' the project in South Africa. By contrast, neither American bramble, pompom weed, balloon vine nor yellow bells have been targeted elsewhere in the world and the projects are thus unique to this country.

Although the Working for Water programme has recognized the principle of targeting weeds at an early stage of invasion, formally through the five new projects, there remains a strong need to develop this rationale further. In particular, the prioritization of both 'major' and 'emerging' weeds for biological control needs to be an ongoing process so as to optimize the allocation of limited resources. Such setting of priorities is based on the potential impact of the weeds (as in a recent CSIR study that models the rate of spread of major and emerging weeds)[32] as well as factors which influence the possibility of success with biological control.

The way forward with emerging weeds in South Africa

The successful targeting of weeds at an early stage of invasion for biological control can be facilitated in various ways, which include:

1. Predicting future invasions by alien plant species naturalized in South Africa and thereby identifying and prioritizing emerging weeds.[32,33] In this regard, the Southern African Plant Invaders Atlas (SAPIA) programme, a mapping project established, in 1994, to collate information on the distribution, abundance and habitat types of alien invasive plants on the subcontinent, has already played a significant role.[34] This and more recent prioritization initiatives[32] will provide a useful starting point for identifying emerging weeds for biological control as a priority .
2. Sustaining cooperation with other countries in the sharing of biological control technology, an activity that has already contributed substantially to South Africa's record of biological control successes. In particular, progress achieved with the biological control of parthenium weed in Australia will facilitate new initiatives planned for this weed in South Africa, while the planning undertaken against cat's claw creeper in South Africa can similarly benefit Australia, where this species has also become invasive.
3. Initiating or sustaining cooperative research agreements and projects with organizations abroad in the countries of origin of these new weeds. These organizations can be commissioned to undertake surveys of natural enemies or specific collections of plant material (such as seed samples) to determine the feasibility of initiating new projects. Cooperative agreements currently under consideration include Argentina and Brazil (for pompom ween and balloon vine), Mexico (for yellow bells) and the United States (for American bramble).
4. Keeping a record of apparently promising natural enemies that are observed or collected on plant species known to have invasive tendencies, in chance encounters during exploration abroad. The setting up of new biological control programmes can be effectively motivated if the existence of potential agents is known from the outset. Indeed, the recent targeting of species like pompom weed, balloon vine and yellow bells was influenced by the knowledge that potential biological control candidates have already been recorded during surveys in South and Central America.
5. Introducing agents (for instance seed-feeders) that reduce

the spread, but not the useful properties, of beneficial plants known to have invasive tendencies, at the outset of their introduction.[35] Adoption of the strategy used against leucaena in South Africa can avoid future problems caused by the introduction of this and other agro-forestry species, sometimes via well-meant development aid projects, into developing countries.[36]

It is imperative that the rationale of targeting emerging weeds becomes firmly entrenched in South Africa's biological campaigns against alien invasive weeds. Formal recognition of this principle by the Working for Water programme has made a substantial contribution in this regard and bodes well for the future of weed biological control in this country.

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