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Assessing the status of biological control as a management tool for suppression of invasive alien plants in South Africa

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Background: Biological control of invasive alien plants (IAPs) using introduced natural enemies contributes significantly to sustained, cost-effective management of natural resources in South Africa. The status of, and prospects for, biological control is therefore integral to National Status Reports (NSRs) on Biological Invasions, the first of which is due in 2017.

Objectives: Our aim was to evaluate the status of, and prospects for, biological control of IAPs in South Africa. We discuss expansion of biological control and suggest indicators to be used in the upcoming NSR to assess sufficient growth.

Method: We used published literature, unpublished work and personal communication to assess the status of biological control of IAPs. We propose indicators based on the targets for biological control that were proposed in the 2014 'National Strategy for dealing with biological invasions in South Africa'. To prioritise targets for future efforts, we used published lists of damaging IAPs and assessed the prospects for their biological control. Recommendations for using biological control as a management tool were made after discussion among the authors and with colleagues.

Results: Significant control of several Cactaceae, Australian *Acacia* species and floating aquatic plants, and many other IAPs has been achieved in South Africa since 1913. Recently, biological control has benefited from improved international collaboration, a streamlined application process for the release of new biological control agents (resulting in the approval of 19 agents against 13 IAP species since 2013), and increased funding and capacity. There is still a need to improve implementation and to better integrate biological control with other control methods. In order to maximise benefits from biological control, increased investment is required, particularly in implementation and post-release evaluation, and in targeting new IAPs. Proposed targets for growth between 2017 and 2020 include an increase in financial investment in research by 29%, implementation by 28% and mass-rearing by 68%. Research capacity should increase by 29%, implementation capacity by 63% and mass-rearing capacity by 61%. New research projects should be initiated on 12 new IAP targets, while post-release monitoring efforts should be expanded to another 31 IAPs.

Conclusion: Biological control of IAPs has contributed substantially to their management in South Africa, and continues to do so. Further investment in targeted aspects of IAP biological control will increase this contribution.

Introduction

Biological control of invasive alien plant (IAP) species is the use of introduced, highly selective natural enemies (usually herbivorous arthropods or pathogens) to control plants. It has been used in 130 countries as a valuable tool for the control of IAP species, with a total of over 550 biological control agents having been released (Winston et al. 2014). The benefits of biological control to natural ecosystems are significant (Van Driesch et al. 2010), with some specific examples of threatened indigenous species being protected by the action of biological control agents (Barton et al. 2007; Meyer, Fourdrigniez & Taputuarai 2011). Detailed analyses of programmes on biological control of IAPs have also clearly indicated that the risks of non-target effects from biological control agents are minimal (Fowler, Syrett & Hill 2000; Funasaki et al. 1988; Moran & Hoffmann 2015; Paynter et al. 2004; Pemberton 2000; Suckling & Sforza 2014). Less than 1% of all the agents released have a negative impact on non-target plant populations, and those that do could have been predicted to do so, and would not be released today (Suckling & Sforza 2014).

Note: This paper was initially delivered at the 43rd Annual Research Symposium on the Management of Biological Invasions in South Africa, Goudini Spa, Western Cape, South Africa on 18-20 May 2016.

Biological control of IAPs is therefore an environment-friendly and safe control method that can result in effective and permanent control of IAPs, leading to the alleviation of their economic and ecological impacts.

In 2013, South Africa marked its 100-year anniversary in biological control of IAPs (Moran, Hoffmann & Zimmermann 2013). During the first few decades (1913 to the 1930s), invasive Cactaceae were the targets of biological control introductions (Klein 2011). These were all 'transfer projects', using insects that had already been successfully introduced as biological control agents in other countries. In the 1950s and 1960s, transfer projects were initiated on *Lantana camara* L. (Verbenaceae) and *Hypericum perforatum* L. (Clusiaceae), but the 1960s also saw the first novel South African projects, on *Hakea* species (Proteaceae) and *Leptospermum laevigatum* (Gaertn.) (Myrtaceae), which had predominantly invaded natural rather than agricultural ecosystems. During the 1970s and 1980s, more groups of IAPs, in particular floating aquatic plants and Australian *Acacia* species (Mimosaceae), became the targets of biological control efforts (Klein 2011). This was facilitated by the formation of a dynamic group of young researchers by Dr David Annecke (Plant Protection Research Institute, then under the national Department of Agriculture) in the early 1970s. Challenges during these decades included a paucity of funding and political restrictions on collecting candidate agents in many of the regions of origin. These challenges have since been resolved. The advent of democracy in South Africa in 1994 led to normalised international relations, and the inclusion of biological control in the funding model of the Working for Water programme (WfW) [now one of the Natural Resource Management Programmes (NRMP) within the national Department of Environmental Affairs (DEA)] in 1997 has led to substantial increases in the funding available for biological control of IAPs over the past 20 years. To date, about 93 species of insects, mites and plant pathogens have been established on 59 IAP species in the country (41 as primary targets and 18 as alternative hosts). An additional 25 species of plants have been worked on, or are currently being investigated, but do not have biological control agents established on them (Klein 2011, updated 2016: http://www.arc.agric.za/arc-ppri/Documents/Target weed species in South Africa.pdf). For several decades, South Africa has been recognised as one of the top five countries globally with regard to research on the biological control of IAPs (Cock et al. 2010; Moran & Hoffmann 2015).

Activities on biological control of IAPs in South Africa have been well documented through the publication of three sets of reviews of the local programmes (Hoffmann 1991; Olckers & Hill 1999; Moran, Hoffmann & Hill 2011). These reviews have contributed towards the success of IAP biological control in South Africa as they have encouraged the biological control community to reflect on successes and challenges, and provided an account of progress for local and international benefit (Moran et al. 2013).

For almost two decades prior to 2013, one of the main constraints to effective IAP biological control was an inefficient system by which agents were cleared for release through the relevant governmental departments. However, a far more effective system has been implemented (see section 'A streamlined biological control agent release process') and approval for a total of 19 biological control agents for 13 IAP species (or species complexes) has been granted since 2013. Of these, two agents were pathogens and the remainder were insect agents. Most have already been released, and in some cases establishment has been confirmed (Table 1).

In this article, we review the status of IAP biological control in South Africa and the contribution of biological control towards the management of the most problematic and damaging IAPs. We also discuss successes and constraints, and prospects both for the control of the most damaging of South Africa's IAPs and for the pro-active management of IAPs that are a threat but are not yet damaging to natural resources. Indicators to assess the effectiveness of a substantial investment in biological control, with targets for future national status reports, are proposed.

Measures of success of IAP biological control in South Africa

Control levels

In South Africa, biological control contributes significantly to the control of 34 of the 59 IAP species on which biological control agents are established. Fourteen of these target species are considered to be under complete control, with no need for any other control intervention (Klein 2011, updated 2016; see Box 1). Many of the most obvious successes have been against Australian *Acacia* species, cacti and floating aquatics (Klein 2011), although successes have certainly not been limited to these groups (e.g. Gordon & Kluge 1991; Hoffmann & Moran 1991).

The first-ever release of a biological control agent in South Africa was the cochineal insect *Dactylopius ceylonicus* (Green) (Hemiptera: Dactylopiidae) for the control of drooping prickly pear, *Opuntia monacantha* Haw. (Cactaceae), in 1913 (Moran et al. 2013). This agent was highly effective, resulting in a permanent reduction of the once extensive infestations of this plant to the point that it is no longer considered problematic (Moran & Zimmermann 1991; Moran et al. 2013). Since this early success, biological control agents have been released on another twenty cactus species, eight of which are considered to be under substantial control and seven under complete control (Klein 2011, updated 2016; Table 2). These include major IAP species, such as the sweet prickly pear, *Opuntia ficus-indica* (L.) Miller, which was reduced from an area of about 900 000 ha to less than 100 000 ha, and the Australian pest pear, *Opuntia stricta* (Haw.) Haw., which has declined in biomass by 90% in the Kruger National Park as a result of the impact of biological control (Paterson et al. 2011).

Other notable successes involved the use of seed attacking agents for the control of ten species of Australian *Acacia* using five seed-feeding weevils and two flower-galling

TABLE 1: Weed biological control agents for which permission to release in South Africa has been granted since the 2011 reviews were published.

Target weed	Natural enemy	Feeding guild	Agent status
ASTERACEAE			
Campuloclinium macrocephalum	*Liothrips tractabilis* (Thysanoptera: Phlaeothripidae)	Stem- and leaf-deformer	Released 2013, established
	Cochylis campuloclinium (Lepidoptera: Tortricidae)	Flower feeder	Release permit issued
Chromolaena odorata	*Dichrorampha odorata* (Lepidoptera: Tortricidae)	Stem-tip galler	Released 2013, establishment unconfirmed
	Recchia parvula (Coleoptera: Cerambycidae)	Stem- and root crown-borer	Released 2016, establishment unconfirmed
Parthenium hysterophorus	*Listronotus setosipennis* (Coleoptera: Curculionidae)	Stem borer	Released 2013, established
	Smicronyx lutulentus (Curculionidae)	Seed feeder	Released 2015, established
	Zygogramma bicolorata (Coleoptera: Chrysomelidae)	Leaf feeder	Released 2013, established
Tithonia rotundifolia	*Zygogramma piceicollis* (Coleoptera: Chrysomelidae)	Leaf feeder	Released 2015, establishment unconfirmed
	Zygogramma signatipennis (Coleoptera: Chrysomelidae)	Leaf feeder	Released 2015, establishment unconfirmed
BASELLACEAE			
Anredera cordifolia	*Plectonycha correntina* (Coleoptera: Chrysomelidae)	Leaf feeder	Release permit issued
BIGNONIACEAE			
Tecoma stans (L.) var. *stans*	*Mada polluta* (Coleoptera: Coccinellidae)	Leaf feeder	Released 2013, established
	Pseudonapomyza sp. (Diptera: Agromyzidae)	Leaf miner	Released 2014, establishment unconfirmed
CACTACEAE			
Pereskia aculeata	*Catorhintha schaffneri* (Hemiptera: Coreidae)	Stem wilter	Released 2014, established
HYDROCHARITACEAE			
Hydrilla verticillata	*Hydrellia purcelli* (Diptera: Ephydridae)	Leaf miner	Release permit issued
MIMOSACEAE			
Acacia baileyana, *A. decurrens* [*A. dealbata, A. podalyriifolia*]	*Dasineura pilifera* (Diptera: Cecidomyiidae)	Flower galler	Release permit issued
Paraserianthes lophantha	*Uromycladium* sp. (Pucciniales: Pileolariaceae)	Gall former	Release permit issued
PONTEDERIACEAE			
Eichhornia crassipes	*Megamelus scutellaris* (Hemiptera: Delphacidae)	Leaf sucker	Released 2013, established
SAPINDACEAE			
Cardiospermum grandiflorum	*Cissoanthonomus tuberculipennis* (Coleoptera: Curculionidae)	Seed feeder	Released 2013, established
VERBENACEAE			
Lantana camara	*Puccinia lantanae* (Pucciniales: Pucciniaceae)	Leaf- and stem-rust pathogen	Release permit issued

Source: Modified from Klein 2011

BOX 1: Evaluating success in biological control of IAPs in South Africa.

Hoffmann (1995) first proposed the current system for evaluating success of biological control programmes. This system is now widely accepted and has been adapted and improved (Klein 2011). For each biological control programme, the level of success is estimated based on the reduction of alternative control methods owing to the impacts of biological control (Klein 2011). Each programme is assigned to one of the following categories:

Complete: No other control measures are needed to reduce the IAP to acceptable levels, at least in areas where the agents are established.

Substantial: Other methods are needed to reduce the IAP to acceptable levels, but less effort is required (e.g. less frequent herbicide applications or less herbicide needed per unit area).

Negligible: In spite of damage inflicted by the agents, control of the IAP remains entirely reliant on the implementation of other control measures.

Not determined: Either the release of the agents has been too recent for meaningful evaluation or the programme has not been evaluated.

These categories are useful for estimating success across a wide variety of biological control programmes, many of which do not have quantitative post-release evaluation data available. To quantify success more accurately, long-term studies which measure the changes in IAP density and the associated reduction in the negative impact of the IAP should be conducted (e.g. changes to native biodiversity, water resources, fire regimes or agricultural productivity). It is essential that measurable pre-defined goals are set in order to evaluate success because complete eradication is not an appropriate goal for biological control (Morin et al. 2009; Paterson et al. 2011). There are very few studies where a reduction in the negative impacts of the IAP is quantified after control (e.g. Barton et al. 2007), but these studies will hopefully become more common if post-release evaluations are given a higher priority in biological control programmes.

midges (Impson et al. 2011). These *Acacia* species are considered among the most problematic and damaging invasive alien species in South Africa (Henderson 2001, 2007; van Wilgen et al. 2008), and biological control has resulted in extensive damage to six of the species, with considerable or moderate damage to a further three species (Impson et al. 2011). As a result, six Australian *Acacia* species are under substantial control (Klein 2011, updated 2016; Table 2). Although the impact of seed-attacking agents is less obvious and visible than agents that damage the structural tissue or leaves, the reduction in reproductive output caused by these agents is significant, even for IAPs with long-lived seedbanks, and has made control using manual and chemical methods economically viable (van Wilgen & Wannenburgh 2016). The successful long-term impact of seed-attacking agents on populations of some woody invasive species has resulted in a call to stop manual removal of species that have effective agents in order to focus efforts on those without biological control (van Wilgen et al. 2016). The use of seed-attacking agents has led to a reduction in the reproductive output of a number of woody tree species while still allowing the species to be exploited commercially, thus avoiding conflicts of interest (Impson et al. 2011).

Five floating aquatic species have had agents released against them in South Africa. Four of these [*Pistia stratiotes* L. (Araceae) (water lettuce), *Salvinia molesta* D.S. Mitch. (Salviniaceae) (salvinia), *Myriophyllum aquaticum* (Vell. Conc.) Verd. (Halogaraceae) (parrot's feather) and *Azolla filiculoides* Lam. (Azollaceae) (red water fern)] have each had a single

TABLE 2: Invasive alien plants in South Africa which are under complete or substantial biological control, indicating whether deliberate, human-mediated biological control actions are required, and whether a change in the legal status of the IAP is desirable.

Species	Continue deliberate biological control actions? †	Type of intervention‡	Suggested change to legislation
Complete control§			
Ageratina riparia	No	Integrated control	-
Azolla filiculoides	No	n/a	Remove from NEM:BA
Cereus jamacaru and *C. hildmannianus*	Yes	Biological control only	-
Cylindropuntia fulgida var. *fulgida*	Yes	Biological control only	-
Cylindropuntia fulgida var. *mamillata*	Yes	Biological control only	-
Cylindropuntia leptocaulis	Yes	Biological control only	-
Harrisia martini	Yes	Biological control only	-
Hypericum perforatum	Yes	Biological control only	-
Myriophyllum aquaticum	Yes	Biological control only	-
Opuntia humifusa	Yes	Biological control only	-
Opuntia monacantha	Yes	Biological control only	-
Pistia stratiotes	Yes	Biological control only	-
Salvinia molesta	Yes	Biological control only	-
Sesbania punicea	Yes	Biological control only	-
Substantial control§			
Acacia cyclops	Yes	Integrated control	-
Acacia longifolia	No	Integrated control	-
Acacia mearnsii	Yes	Integrated control	-
Acacia melanoxylon	No	Integrated control	-
Acacia pycnantha	No	Integrated control	-
Acacia saligna	Yes	Integrated control	-
Cylindropuntia imbricata	Yes	Biological control only	-
Eichhornia crassipes	Yes	Integrated control	-
Hakea sericea	Yes	Integrated control	-
Harrisia balansae	Yes	Integrated control	-
Harrisia pomanensis	Yes	Integrated control	-
Harrisia tortuosa	Yes	Integrated control	-
Lantana camara (some varieties)	Yes	Integrated control	-
Opuntia aurantiaca	Yes	Biological control only	-
Opuntia ficus-indica	No	n/a	Remove from NEM:BA
Opuntia salmiana	Yes	Integrated control	-
Opuntia stricta	Yes	Biological control only	-
Paraserianthes lophantha	No	Integrated control	-
Solanum elaeagnifolium	Yes	Biological control only	-
Solanum sisymbriifolium	Yes	Biological control only	-

†, Where 'yes', efforts may range from minor, for weeds with small, isolated populations, to major, for weeds with more widespread populations.

‡, Integrated control here incorporates biological control in all cases (whether human-mediated or self-sustained), with other control methods (chemical, mechanical or fire). Restoration may also be included.

§, From Klein (2011), updated 2016. See also Henderson (2016 – this volume).

agent released and are considered to be under complete control (Klein 2011), whereby, if the agents are implemented correctly these IAPs no longer pose a threat to aquatic ecosystems (Coetzee et al. 2011; Hill & Coetzee 2017). Indeed, the programme against red water fern using the weevil *Stenopelmus rufinasus* Gyllenhal (Coleoptera: Curculionidae) has been so successful that it has led to widespread extirpation of this plant from most of the infested sites (McConnachie, Hill & Byrne 2004) and it should be removed from the *National Environmental Management: Biodiversity Act* (2004) (NEM:BA) list of invasive species in South Africa to allow utilisation (see section 'Integration of biological control in IAP management programmes'; Table 2). The biological control programme against the fifth species, *Eichhornia crassipes* (Mart.) Solms-Laub. (Pontederiaceae) (water hyacinth), was initiated in 1974 with the release of the first agent, *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae) (Cilliers 1991). Since 1974, a further seven agents have been released against the species, of which six have been confirmed as established (Coetzee et al. 2011). Biological control contributes substantially to the reduction in the invasiveness of water hyacinth (Klein 2011), but there are some areas of South Africa where additional measures, mostly herbicide application, are required to bring the plant under complete control. These are usually areas where the system is polluted with nitrates and phosphates (Coetzee & Hill 2012) and where winter temperatures result in a number of frost days (Hill & Olckers 2001). In these areas, biological control has to be correctly integrated with other control options (Hill & Coetzee 2008).

Fungal pathogens have played an important role in the success of biological control in South Africa. Fungal pathogens are often highly host specific and under suitable environmental conditions (temperature and humidity) can be extremely damaging to host plants. Introduced pathogens have achieved significant levels of biological control on several invasive plants, for example, the rust fungus

Uromycladium tepperianum (Sacc.) McAlpine (Pucciniales: Pileolariaceae) on *Acacia saligna* (Labill.) H.L. Wendl. (Mimosaceae), which after almost 30 years in the field has reduced densities in monitored stands by between 70% and 98% between fires (Wood & Morris 2007; A.R. Wood [ARC-PPRI], pers. comm., 15 August 2016) (although because of the high soil-stored seed bank, plants currently still regenerate at high densities following fires). Some pathogens require deliberate inoculation into stands of IAP populations but many, once established in a small area, spread rapidly under suitable conditions without, or with limited, further need for human intervention [e.g. *Puccinia eupatorii* Dietel (Pucciniales: Pucciniaceae) on *Campuloclinium macrocephalum* (Less.) DC. (Asteraceae) and *P. xanthii* Schwein. var. *parthenii-hysterophorae* Seier, H.C. Evans and Á. Romero on *Parthenium hysterophorus* L. (Asteraceae)]. Some indigenous fungi have been formulated into mycoherbicides, for example, *Colletotrichum acutatum* J.H. Simmonds (Sordariomycetidae: Glomerellaceae) (trade name Hakatak®) causing gummosis on *Hakea sericea* Schrad. and J.C. Wendl. (Proteaceae), and the saprophytic *Cylindrobasidium laeve* (Pers.) Chamuris (Agaricales: Physalacriaceae) (trade name Stumpout®) as a cut-stump treatment of *A. mearnsii* De Wild. (Fabaceae: Mimosoideae) (Morris et al. 1999) which can be applied in the field by IAP management teams with little biological control expertise.

For many biological control programmes, including those utilising seed-attacking agents, the impacts of the agents on the IAP populations may happen over a number of years or decades and are not always obvious without detailed post-release evaluations. For example, insecticide exclusion experiments have shown that the reproductive output and growth parameters of *L. camara* have been significantly reduced owing to the action of the suite of biological control agents released against it, although control of *L. camara* is not considered a complete success (Urban et al. 2011). Although partial success in biological control may be perceived by some as incomplete or failure to control, it is important to consider to what level an IAP population may have expanded if biological control had not been implemented (van Wilgen et al. 2004). A biological control agent that has not resulted in an obvious, visible decrease in the IAP population may still be making a considerable contribution through reducing the density and rates of increase, growth and spread of the IAP, through reduced photosynthetic ability, altered plant physiology or reduced ability to produce propagules. This highlights the need for detailed, quantitative post-release evaluations, an aspect of biological control that has been somewhat neglected, primarily because of the lengthy and sometimes difficult process. However, the assessment of agent impact and level of control attained is essential so that success can be quantified (Morin et al. 2009), so that supplementary biological or other control measures can be implemented if required, and so that control methods can be integrated. Such evaluations are also necessary to determine, for example, the most susceptible target IAPs and optimal selection of effective agents in order to improve the efficacy, success rate and cost-effectiveness of biological control programmes in future.

Economic costs and benefits of IAP biological control in South Africa

Compared with other options available to control IAPs (i.e. manual or chemical control), biological control can be extremely efficient in economic terms. The development of herbicides requires a great deal of expensive research (Rüegg, Quadranti & Zoschke 2007) and repeated herbicide applications are usually required, frequently in conjunction with manual clearing, to achieve any measurable IAP population reductions, while manual control is labour-intensive and therefore also expensive. Restoration after clearing is also expensive (Holmes & Richardson 1999), especially if it has to be applied over a large area, as is often the case. Biological control, by comparison, is effective because the research produces solutions that are cheap to apply, and that are usually self-sustaining. Biological control can also be integrated with other control methods in order to reduce the costs of control (van Wilgen & Wannenburgh 2016). In some cases, such integration of various control methods is essential for optimal control of the IAP.

The initial stages of IAP biological control programmes are the most costly because they require studies to confirm the origin of the IAP (which may include the need for molecular and taxonomic studies), exploratory surveys for candidate biological control agents in the region of origin and assessment of the suitability of candidate agents in both the region of origin and in quarantine in South Africa. In cases in which the initial phases of the biological control programme have already been conducted in other countries, significant savings in time and money can be made. Mass-rearing and releases of the agents to establish permanent, self-sustaining field populations (essential for the success of such a programme) may also be relatively costly. Several biological control research programmes that face complexities such as unknown origins or hybridisation of target plants, or conflicts of interest owing to the utilisation and benefits of the target plant, have required several decades of research, some having been initiated in the 1960s (Moran et al. 2013). Importantly, however, once biological control agents have established self-sustaining populations in the field, there are few further input costs, while the benefits continue to accrue indefinitely. Using South African case studies (six terrestrial IAP species from several functional groups), van Wilgen et al. (2004) calculated the total historical cost for the research programme to be ZAR41.1 million, expressed in values in 2000 currently, 14 ZAR ~ 1 US$). The total cost of biological control research on four ‘functional groups’ of terrestrial IAPs in five South African biomes was ZAR102 million, expressed in 2008 values (de Lange & van Wilgen 2010); the cost for individual groups covered an approximate five-fold range, from ZAR10 million for fire-adapted trees to ZAR50 million for subtropical shrubs.

Several assessments have been made of the benefits accruing from IAP biological control in South Africa, both at the time of the study and projected into the future. Versfeld, Le Maitre and Chapman (1998) estimated that existing biological control programmes had already reduced management costs by 20% (ZAR1.38 billion), with the potential to further reduce costs by more than 40% (ZAR2.89 billion). For the six terrestrial IAPs considered by van Wilgen et al. (2004), estimated current benefits of biological control varied from ZAR22 million for *Sesbania punicea* (Cav.) Benth. (Fabaceae) to ZAR6.1 billion for *Opuntia aurantiaca* Lindl. (Cactaceae), and the benefit to cost ratios from 8:1 for *S. punicea* to 709:1 for *O. aurantiaca*. Further, they estimated the future value of biological control for these species by calculating the final realised invasive range, compared with the benefits accrued with biological control. Here the benefits ranged from ZAR152 million for *S. punicea* to ZAR10.3 billion for *A. aurantiaca*. De Lange and van Wilgen (2010) estimated that the annual flow of benefits from the biological control of the four 'functional groups' of IAPs totalled ZAR11.6 billion, but that this varied widely between the groups, with fire-adapted trees (e.g. *Hakea* species) at ZAR67 million and invasive Australian trees at ZAR8.3 billion (subtropical shrubs and invasive succulents were intermediate, at ZAR205 million and ZAR3.0 billion, respectively). They estimated net present values of ecosystem service benefits which were attributable to biological control, for these four groups in the five biomes, to total almost ZAR145 billion, again with wide variation. McConnachie et al. (2003) conducted a cost–benefit analysis on the *A. filiculoides* biological control project in South Africa and showed that in 2000 the benefit to cost ratio was 2.5:1, but that this increased over time to 13:1 by 2005 and 15:1 by 2010 as less input was required, but with benefits still accruing. Economic evaluations therefore clearly indicate that biological control is a high value-for-money investment that should be given priority within control programmes (van Wilgen & de Lange 2011; van Wilgen et al. 2012).

Recent enablers and constraints

International cooperation

In the past, many surveys for biological control agents undertaken in countries of origin of the target plant by South African research organisations were carried out on a multi-species, opportunistic basis with little formal engagement with institutions in those countries. This was the result of restrictions on international field work as a result of a lack of cooperative international legislation governing the transfer of biodiversity or management of invasive species, lack of material transfer agreements between countries, political and bureaucratic difficulties and a lack of funding. While numerous successes were achieved in this manner, such a *modus operandus* is no longer tenable.

The international Convention on Biological Diversity (CBD) (https://www.cbd.int/convention/text/default.shtml), to which South Africa is party, was developed to provide a platform for a more structured approach to the transfer of biological diversity, such as potential IAP biological control agents, between countries. It has three primary objectives, namely to promote sustainable development through the conservation of biological diversity, the sustainable use of its components and sharing of the benefits arising from the utilisation of genetic resources. A supplementary agreement to the CBD came into force in 2014 (https://www.cbd.int/abs/). It was developed to advance the CBD objective on the fair and equitable sharing of benefits arising out of the utilisation of genetic resources, by providing a transparent legal framework. However, in reality, IAP biological control practice, which must be recognised as non-commercial and of benefit to all recipients, has been hindered by the implementation of additional complex regulations and bureaucratic procedures for collection and exportation of potential biocontrol agents. These processes have made the practice of biological control more difficult, time-consuming and costly. Cock et al. (2010) described how biological control does not fit well into an access and benefit sharing regime, and advocated that national regulations should build on the existing multi-lateral practice of free exchange of biocontrol agents, with fair and equitable sharing of the benefits globally. Access and benefit sharing based on non-financial benefit sharing, such as cooperative research programmes, capacity building and technology transfer, were recommended (Cock et al. 2010).

International cooperation is key to the success of every IAP biological control programme, as many countries require any foreign parties wishing to access their biodiversity to operate through a local institution. Consequently, South African institutions undertaking research on IAP biological control have developed formal links with similar institutions in, *inter alia*, Argentina, Australia, Brazil, Jamaica, Mexico, New Zealand, the USA and Venezuela. These links have taken the form of Memoranda of Agreement or purpose-specific contracted research or tasks. Institutions in these countries undertake contracted preliminary research on prospective agents, and facilitate the acquisition of appropriate collection and export permits, as well as assisting with logistics and the collection and export of candidate biological control agents. Exploratory surveys and export of collected organisms would not be possible or advisable nowadays without such formal agreements. The funding of studies by postgraduate students at these institutions, and joint publication of findings, is encouraged, and it constitutes an example of 'south–south' collaboration. Comprehensive, focused exploratory surveys on several IAP species in countries of origin have yielded an array of prospective agents, allowing for prioritisation of those with the greatest potential (e.g. Paterson et al. 2014). Intensive surveys and prioritisation processes should be further developed in future, for additional species of IAP.

Transfer projects continue to be important to the biological control of IAPs in South Africa, and also require cooperation with other countries. Recent examples include those on *P. hysterophorus*, where agents were imported from their introduced range in Australia, *Tradescantia fluminensis* Vell. (Commelinaceae) (spiderwort) (from New Zealand) and *Arundo donax* L. (Poaceae) (Spanish reed) (from the USA). Selection of the most suitable agents for South African conditions, from those that are already well-established on these IAPs in their primary country of introduction, has resulted in considerable savings. South African research programmes on novel IAP species have also benefited, or could potentially benefit, other countries in which these species are invasive. These include *Cardiospermum grandiflorum* Swartz (Sapindaceae); *Dolichandra unguis-cati* (L.) Lohman (Bignoniaceae); *L. camara; Solanum mauritianum* Scop. and *S. elaeagnifolium* (Cav.) (Solanaceae); *Tecoma stans* (L.) Juss ex Kunth (Bignoniaceae); and *Tithonia diversifolia* (Hemsl.) A. Gray (Asteraceae) (see Moran et al. 2011).

South Africa is a leader in IAP biological control on the African continent, and has collaborated with other countries on both aquatic (e.g. *E. crassipes*, *P. stratiotes*) and terrestrial [e.g. *O. ficus-indica*, *Chromolaena odorata* (L.) R.M. King and H. Rob. (Asteraceae), *P. hysterophorus*] IAPs [see Winston et al. (2014) for agents that have been released in other countries via South Africa]. The natural spread of some IAP biological control agents, for example, the leaf-mining fly *Ophiomyia camarae* Spencer (Diptera: Agromyzidae) on *L. camara* or *Pareuchaetes insulata* (Walker) (Lepidoptera: Erebidae) on *C. odorata,* which have dispersed from South Africa to neighbouring countries, or even further north on the continent and adjacent islands, must have benefited the management of these plant species, although such benefits have rarely been measured. This ability of some biological control agents to disperse over large distances also illustrates that the potential for non-target attack on plant species present in other countries in sub-Saharan Africa must be considered when evaluating the suitability of agents for release (Faulkner et al. 2017). For example, *Guizotia abyssinica* (L.f.) Cass. (Asteraceae), a crop native to Ethiopia, was, under laboratory conditions, susceptible to damage by *Epiblema strenuana* (Walker) (Lepidoptera: Tortricidae), a potential biological control agent for *P. hysterophorus* (McConnachie 2015). This, together with the known strong dispersal ability of the moth and its use of multiple host plant species in the field in Australia, raised concerns over its possible spread to Ethiopia if it were to be released in South Africa. Further research is needed to determine whether this insect poses a risk to *G. abyssinica*, before it can be considered for release.

A streamlined biological control agent release process

Klein et al. (2011) reviewed the legislation associated with importing and releasing IAP biological control agents in South Africa. Until 2010, DEA legislation had proved the main stumbling block to releasing agents for over a decade, with the other agency, the Directorate: Plant Health within the national Department of Agriculture, Forestry and Fisheries (DAFF-DPH), having generally approved release applications timeously, using an evaluation panel. After 2010, when biological control was removed as an activity requiring a Basic Assessment to be conducted under DEA legislation, this obstacle fell away (albeit temporarily). However, as indicated by Klein et al. (2011), by this stage the DAFF process had also stalled, not through the presence of any adverse legislation, but rather through the legislative confusion created by the *National Environmental Management: Biodiversity Act* (2004) (NEM:BA) (administered by DEA) and its potential overlap with the *Conservation of Agricultural Resources Act* (CARA), administered by DAFF. By late 2012 a substantial backlog (for 11 agents on 8 IAPs) of release applications had developed, dating back to 2009. The negative consequences of delayed processing of applications included (1) the inability to release biological control agents, while IAP populations continued to expand; (2) the utilisation of quarantine resources and capacity for the holding of agents, or the culling of cultures resulting in the need for recollection at a later stage, incurring additional costs, and (3) occupation of the limited quarantine space, preventing the importation of new potential biological control agents for assessment.

In 2012 and early 2013, the IAP biological control community, together with representatives from DEA: NRMP who were funding the research, thus engaged with DAFF-DPH to find a way forward. This resulted in the formation of the National Biological Control Release Application Review Committee (NBCRARC), chaired by the South African National Biodiversity Institute (SANBI), and with representatives from DAFF (both agriculture and forestry), DEA, private consultants (experts in IAP and insect biological control), and the Forestry and Agricultural Biotechnology Institute. Protocols were drawn up, including a standard application format and guidelines (which request the applicant to consider, *inter alia*, the need for biological control for the IAP; the identity, safety and potential efficacy of the candidate agent; a proposed release strategy: possible ecological effects its release would have; and plans for post-release mitigation, if needed) as well as a standard review format and guidelines. A list of potential expert external reviewers, at both national and international levels, was compiled (including IAP and insect biological control experts, entomologists, pathologists, botanists and others). The current process is as follows: applicants submit the application to DAFF-DPH which forwards it to the chair. After consultation with the committee, the chair distributes the application to the agreed reviewers. For each application, the chair solicits voluntary reviews from three experts (usually two national and one international reviewer for each application), with a timeline of four weeks. The reports from these experts are then read and discussed by the committee members, either over e-mail or more commonly at a meeting, and a recommendation is passed from the committee to DAFF-DPH. DAFF-DPH then either issues a release permit or passes on the committee's recommendation for further information, which may require either a desktop study/response, or further host range testing or other work. This process has enabled the release of a number of new agents in the past three years (Table 1).

Environmental legislation relevant to the importation of candidate biological control agents and their release falls under the ambit of NEM:BA. However, the Alien and Invasive Species Regulations for this Act were only published and put into effect in 2014 (Department of Environmental Affairs 2014a, 2014b;

http://www.invasives.org.za/legislation/invasive-species-legislation.html), at which time they supplanted the CARA legislation. Up to the present, this has not affected the process of import permits for biological control agents or candidate agents, which are still issued only by DAFF, or release permits, but this will certainly change in future, when Pest Risk Assessments will be evaluated by DEA. It is hoped, though, that the NBCRARC or a similar single, central channel ('one-stop shop') will continue to function. It is critical that a similar streamlined procedure is adopted and that this process is embedded in legislation soon.

The research versus implementation debate

Until the mid-1990s, South African researchers conducted or oversaw most work on IAP biological control, including the mass-rearing, release and post-release monitoring of agents. This often worked well with a relatively high rate of establishment of agents, but for some agents [e.g. *Pareuchaetes* species on *C. odorata* (Zachariades et al. 2011)] establishment could only be achieved by large scale mass-rearing which was beyond the capacity of research organisations. Furthermore, with an increase in the amount of work being conducted on control of IAPs owing to the launch of WfW in 1995, the demand for agents increased substantially, in order to achieve more widespread and faster biological control. An 'implementation' programme, embedded within WfW, was thus set up in the late 1990s and early 2000s (Gillespie, Klein & Hill 2004), with the aim of mass-rearing, field collection for redistribution, releases and basic monitoring of the establishment and spread of agents. Several mass-rearing centres were set up around the country, the existing insect-rearing facilities at the South African Sugarcane Research Institute (SASRI) were contracted and provincially based implementation officers employed. Interaction between researchers and implementers was encouraged, and facilitated by the annual 'Weed Biocontrol Workshops' that have been held since the 1970s (Wilson et al. 2017). Although this programme has facilitated thousands of releases of biological control agents throughout the country, there have been some limiting factors, such as several mass-rearing centres failing owing to funding issues; a lack of biological control expertise at the mass-rearing centres; implementation officers being co-opted into non-biological control activities; and a lack of structured cooperation and feedback loops between researchers and implementers (e.g. on which agents to mass-rear, numbers to be released or under what circumstances to make use of biological control). Often, inadequate distinction was made between agents which were still at an experimental phase (i.e. their establishment or efficacy was not yet proven) and agents which had already been shown to be effective but needed further redistribution as a management tool (see section 'Integration of biological control in IAP management programmes'). This also raised the question of where the dividing line between research and implementation lay, owing to the grey area along the continuum between these activities. Nevertheless, the implementation programme has substantially increased the number of biological control releases made in the country and the number of plants with active biological control implementation programmes in operation, increased capacity to some degree and has undoubtedly improved the level of control for many IAP species. Recently, quarterly meetings between researchers and implementers, and increased field interactions have closed the perceived gap between research and implementation further. Currently, there is a move back towards mass-rearing, field collection and releases being included within research programmes, but these will still need to be coordinated at a national level and should be structured so as not to distract researchers from their core functions.

Increases in funding and capacity

The growth in IAP biological control in South Africa in recent years can be largely attributed to the significant investment in the development of research and implementation by DEA: NRMP and its predecessor, WfW (which was based in the Department of Water Affairs), since 1997. Following economic analyses and recommendations by van Wilgen and de Lange (2011) and van Wilgen et al. (2012), a three-fold increase for 2014–2017 (3.4 years) from the previous funding contract has enabled the scaling up of research and implementation activities on terrestrial and aquatic IAPs. During 2014–2017, an investment of ZAR116.7 million was allocated to the development of IAP biological control research and implementation on 50 plant species, ZAR23.8 million in mass-rearing of selected biological control agents, and a further ZAR50.8 million in field implementation by DEA (officers whose mandate is the control of invasive alien species, including biological control of IAPs, in each province, with resources for biological control agent releases, redistribution and monitoring), a total of almost ZAR200 million (Table 3).

Capacity within South Africa has been built through various channels, including (1) expanded expertise through appointments at universities and national research organisations, (2) mass-rearing initiatives, (3) bursaries that have attracted increased numbers of postgraduate students, (4) internships, (5) an IAP biological control short course and (6) implementation officers stationed in each province to facilitate field activities. A Capacity Building Programme at the University of KwaZulu-Natal exposes university undergraduate students to experiential training periods of two months per annum at research institutions engaged in research and implementation activities on IAP biological control, stimulating knowledge of, and interest in, the practice (Downs 2010). A number of these students have gone on to work in this or related fields. Currently, IAP biological control in South Africa employs approximately 77 personnel in the field of research, at research organisations and universities, many of whom are also involved in mass-rearing of agents for releases (Table 3). An additional 32 personnel are involved in mass-rearing activities specifically, of whom seven have physical disabilities. Another 16 'biodiversity officers' (whose remit includes the implementation of IAP biological control) and managers, as well as 17 people in two field implementation

TABLE 3: Baseline indicators (between 2014 and 2017) and proposed targets (between 2017 and 2020) for a range of indicators that can be used to assess progress towards national strategic goals, and reported on at three-yearly intervals in the national status of biological invasions report.

Variable	Indicator	Baseline (2014–2017)	Proposed target (2017–2020) †
Funding (ZAR millions over 3 years)	Research‡	116.7	150 (29%)
	Implementation§	50.8	65 (28%)
	Mass-rearing§	23.8	40 (68%)
Human resources	Research capacity‡	39 researchers including consultants; 38 technical support personnel; 55 students (third year to postdoctorate)¶	50 researchers (28%); 50 technical support (32%); 70 students (mostly postgraduate) (27%)
	Implementation capacity§	16 implementation officers¶	26 implementation officers (63%)
	Mass-rearing capacity§	32 mass-rearing technicians¶	52 mass-rearing technicians (61%)
No. weed species targeted for biological control	Pre-release research (major species) ‡,††	34	41 (20%)
	Pre-release research (pro-active species) ‡,††	5	10 (100%)
	Post-release evaluations§	31	62 (100%)
	Mass-rearing§	30	37 (23%)

Monetary values are given as 2016 values.

†, Percentage increase over baseline indicated in brackets.

‡, Targets for 2017–2020 are based on the 100% growth over 10 years (2017–2027) for research recommended by the National Strategy for dealing with biological invasions in South Africa. This assumes that the growth over 10 years will be linear (i.e. 30% growth over 3 years). However, because, for example, infrastructure needs building, this may not be true.

§, Targets for 2017–2020 are based on the 100% growth over 5 years (2017–2022) for implementation recommended by the National Strategy. This assumes that the growth over 5 years will be linear (i.e. 60% growth over 3 years). However, because, for example, infrastructure needs building, this may not be true.

¶, Numbers for 2016.

††, Note that 'pre-release research' is distinct from 'pre-release monitoring' mentioned in the National Strategy. We include the former under research and the latter under implementation.

teams, are employed within the ranks of DEA and SA National Parks.

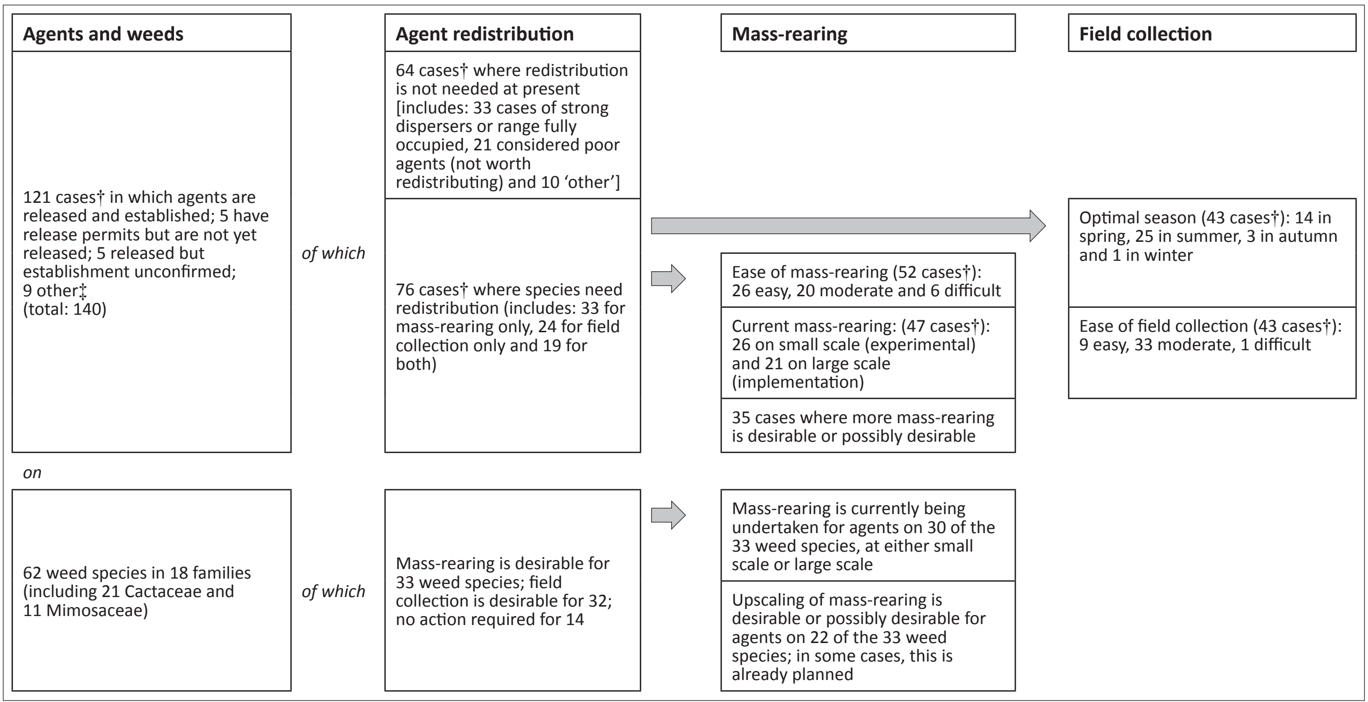
Increased investment has allowed for the expansion of infrastructure for research, through the development of new or extended quarantine facilities at national research and university institutions. There are currently six IAP biological control quarantine facilities around the country, four of which are run by ARC-PPRI [one in Pretoria, two in Stellenbosch (for insects and pathogens, respectively) and one in Cedara (near Pietermaritzburg)], with the others at Rhodes University in Grahamstown and the University of the Witwatersrand in Johannesburg. Such developments have facilitated research on new IAPs and additional agents on existing projects, and improved successes on existing projects.

Increased investment into mass-rearing of agents that have been approved for release has also been made by DEA, and is currently being undertaken at facilities in the provinces of KwaZulu-Natal (SASRI and ARC-PPRI), the Eastern Cape (Rhodes University, at both its Waainek and Uitenhage facilities), the Western Cape (City of Cape Town and ARC-PPRI), Gauteng (ARC-PPRI) and Limpopo (DEA: NRMP in collaboration with ARC-PPRI). Optimal mass-rearing can often not be conducted solely at research institutions because of a shortage of space, resources, capacity and in some cases, sub-optimal climatic conditions; mass-rearing techniques often differ substantially from methods used to rear small numbers of agents for research. In cases where mass-rearing has been conducted successfully at research institutions, it was because a separate mass-rearing unit was set up. Some of the 'mass-rearing' (a rather loose term) being carried out is currently on a small scale, for experimental releases of agents in order to try to establish them at sites with different climates or habitats, or to determine optimal release techniques, rather than large scale releases for distribution of established agents with known efficacy. Not all agents require intensive mass-rearing efforts but many benefit from such efforts, allowing more successful establishment and a greater degree of IAP control to be achieved more rapidly. For some situations, repeated augmentative releases are required to achieve ongoing control of an IAP, although this is less so for terrestrial than for aquatic species, for which flooding events and water eutrophication create conditions in which classical biological control is insufficient (Hill & Coetzee 2017). Mass-rearing and field implementation of developed biological control agents has not yet been used to its full potential in South Africa as the optimal model for such endeavours is still evolving.

Currently, pre-release studies on 34 species of IAP are being undertaken, with post-release research on 31 species (Table 3). Of the 140 cases where 111 biological control agents have been released, occur locally or for which release permits have been issued, human-mediated redistribution is desirable in 76 cases on 48 IAP species (Figure 1). Of these 76 cases, mass-rearing alone is needed for 33, field collection alone for 24 and both of these methods are appropriate for 19. Currently, mass-rearing is being undertaken for 47 of the 52 cases for which it is desirable, for 30 of the 33 IAP species. However, for more than half of these, the mass-rearing is on a relatively small scale, experimental basis, and there are 35 cases (22 IAP species) for which an increase in mass-rearing effort is desirable (Figure 1).

Integration of biological control in IAP management programmes

The integration of IAP biological control into a wider control programme is routinely advocated (e.g. Watson & Wymore 1989), but in practice, in South Africa at least, this is often not achieved. In some cases, it is not easy to incorporate biological control, for example, when the aim of a control programme is to dramatically reduce the density of an IAP species in a defined area over a short period of time. For most IAP species, the biological control agent cannot be 'applied' like a



Source: Klein (2001), updated 2016, and the IAP biological control research and implementation community in South Africa

†, The term 'case' indicates a unique combination of a species of biological control agent on a species of weed. In some cases, the same species of agent is used on multiple weed species. The number of agent species established is 93, and total number released and established, with permits to release, or occurring in field naturally, is 111.

‡, Most of these occurred locally, and some were used as mycoherbicides.

FIGURE 1: Current and recommended mass-rearing and field collection of available weed biological control agents in South Africa.

herbicide, and although the agent may already be widely present and a good disperser, it might not reduce IAP density to the desired levels within the desired time frame. The agent may also be difficult to establish on the desired infestation, which could be a function of its biology or the local climatic conditions, or its abundance and performance may not be uniform throughout the invaded range, which is often the case owing to the variety of habitats that an IAP species invades.

Two scenarios are applicable in this context. (1) For a few groups of IAPs, biological control can be used within a designated area as part of a clearing programme, with other areas subject to herbicide or mechanical control measures. For many of the Cactaceae, cochineal (*Dactylopius* species) and the mealybug *Hypogeococcus festerianus* (Lizer y Trelles) (Hemiptera: Pseudococcidae) can be introduced onto individual plants or infestations and severely damage or kill most of the plants in the area. In the case of *H. festerianus*, fruiting is almost completely eliminated. This is a clear case where current control methods (manual and chemical) could in many instances be replaced by the correct use of biological control, thereby reducing costs (Table 2). Chemical and manual control may in fact impact negatively on the overall level of control of these species (Zimmermann 1979), so integration needs to be carefully considered. Some invasive alien aquatic species, such as *S. molesta*, *P. stratiotes* and *M. aquaticum*, can be completely controlled with augmentative releases of biological control agents, but control is disrupted by the use of herbicide applications (Coetzee et al. 2011). (2) There are also IAPs which are under such effective biological control at a regional or national level (e.g. *A. filiculoides, O. ficus-indica*) that no human intervention is required, either with respect to manual or chemical clearing, or the redistribution of biological control agents. Under NEM:BA, it is permissible to use biological control alone to manage a category 1b species, and therefore it would not be necessary to change the categorisation of species described under (1) above (Table 2). However, it should become policy that only biological control is used for managing these species as no other control method is required. On the contrary, we recommend that *A. filiculoides* and *O. ficus-indica* [described under (2) above] be removed from the A&IS regulatory list so that they can be used as crops (both species have beneficial attributes), and so that resources are not wasted on their control (Table 2). Utilisation of *A. filiculoides* and *O. ficus-indica* could result in dispersal to new sites but the agents will disperse, or alternatively could be actively released to prevent the IAPs from becoming problematic. Biological control of *A. filiculoides* and *O. ficus-indica* has reduced the negative impacts of the plants to the point that the benefits of the plant now outweigh the negative impact to the environment and society. Species such as *S. punicea* and *H. perforatum* may require occasional, very limited redistribution of agents, and *Ageratina riparia* (Regel) R.M. King & H. Rob. (Asteraceae) may require manual or chemical control outside of areas in which its biological control agent [*Entyloma ageratinae* R.W. Barreto & H.C. Evans (Entylomatales: Entylomataceae)] provides complete control.

Calls by DEA: NRMP and other agencies for fuller integration of biological control into South African clearing programmes have been made for several years (e.g. A. Khan 2011, presentation to 39th Weed Biocontrol Workshop). DEA: NRMP has invested substantially in biological control of IAPs in South Africa, with the aim not only of developing new agents but also of more effective use of existing ones, in order to improve the control of IAPs and reduce the unnecessary use of resources. Integration of biological control into clearing operations [for appropriate agents, as described in (2) above] has occurred to some extent, but there is considerable room for improvement. Improved research-implementation feedback loops would facilitate management efforts. Management guidelines could be compiled for each IAP species, particularly those under complete or substantial control, with an indication of the areas in which biological control is likely to be effective and the areas in which the IAP should be prioritised for clearing using other methods. For example, *L. camara* is under more effective biological control along the South Coast of KwaZulu-Natal province than in higher-altitude regions and regions with different varieties of the plant. The coastal region should therefore be prioritised for biological control, whereas manual removal and chemical control could be used more intensively in high-altitude areas. Definitive guidelines may however not be practical to compile in all cases because of the multitude of environments and situations which a plant invades, interacting with variable performance of biological control agents under different environmental conditions. Such guidelines would be more easily compiled in later stage programmes once agents have had several years to be distributed and establish widely, and once the agents' field requirements and limitations are understood.

There are also other issues, including the inadvertent destruction of important biological control sites (e.g. release sites and well-established sites from which agents could be redistributed) by DEA: NRMP clearing teams and other agencies. A live, updatable centralised national database containing such data, which is available to all organisations involved in clearing operations and that could be integrated into their GIS-based IAP management planning systems, is recommended. Currently, although some release information is stored within the national DEA: NRMP database, it is not readily available to other organisations or to the general public and is not always used to full effect within DEA: NRMP's own clearing operations. Biological control needs to be better embedded as a management tool within the operational planning of DEA: NRMP and other organisations involved in clearing programmes.

The status of IAP biological control in South Africa, in the context of the National Strategy and National Status Reports

A 'National Strategy for dealing with biological invasions in South Africa' was commissioned by DEA in 2014 (https://sites.google.com/site/wfwplanning/strategy). This document was designed to provide a baseline for invasions in South Africa and to set targets for the future. The success of the strategy, and progress in combatting IAPs, will be assessed every three years starting in 2017 in the form of National Status Reports on Biological Invasions in South Africa (Wilson et al. 2017).

The National Strategy recommends the following with regard to IAP biological control:

- Double the biological control research capacity in South Africa over the next decade.
- Expand the biological control programme to include species for which eradication from South Africa has been ruled out but for which widespread impacts are predicted but have not yet been demonstrated.
- Expand the capacity of the biological control implementation programme (100% growth over the next 5 years), with explicit targets and ring-fenced funding for pre- and post-release monitoring; mass-rearing; and agent distribution.

From the National Strategy targets, it is clear that significant growth in biological control would be required in both research and implementation for these goals to be met. While research capacity is recommended to increase by 100% in 10 years, implementation is required to increase by the same degree in half of this time. Implicit in the recommendations is that new targets for biological control should be worked on and that these targets should include species that are not yet widespread or damaging (i.e. pro-active targets; see Text Box 2). If the recommendations of the National Strategy are to be achieved, it is essential that (1) the most appropriate IAP species be targeted for biological control and (2) that development of capacity is facilitated. Capacity growth would need to incorporate expanded numbers of personnel at all relevant levels, as well as infrastructure.

In the following sections, we examine whether the species that have been targeted for biological control are aligned with priorities by determining how many of South Africa's worst IAPs are either under biological control or are targets for biological control. We report on prospects for control of recently targeted species and provide recommendations on future programmes, targeting both plants which are currently considered the worst of South Africa's invasive species as well as pro-active targets (see Box 2) which could become problematic in future. Finally, we discuss how growth in biological control capacity could be facilitated and provide specific 'indicators' that can be used to determine whether biological control is growing at a suitable rate to achieve the recommendations in the National Strategy (Table 3).

Prioritisation of targets for biological control

The recently revised Alien and Invasive Species Regulations under NEM:BA list 379 plant species that are considered problematic IAPs or plants that could become problematic in the country in future (Department of Environmental Affairs 2016). This large number of species highlights the

BOX 2: Prioritisation of targets for biological control.

A number of factors should be taken into consideration when selecting new targets for biological control programmes. A combination of these factors must be taken into account and not all factors should be evenly weighted. Although IAPs that are damaging to the natural resources of the country should be selected as targets, the threat of IAPs that are not yet damaging should also be taken into account. IAPs that are targeted using biological control before they have become very widespread and damaging are referred to as pro-active targets.

Factors that suggest that biological control is appropriate and likely to succeed:

1. Transfer programmes, where progress towards the development of a biological control programme of the target IAP made in other countries can reduce the costs of the biological control programme. Cases where biological control of the target IAP elsewhere in the world has already succeeded are best.
2. Successful control of congeners (or close relatives) of the target IAP.
3. Other control methods (e.g. herbicides; manual clearing) are ineffective, making biological control the most feasible option.
4. IAPs are very hard to reach or in inaccessible areas.

Factors that suggest that biological control may be inappropriate and unlikely to succeed, or that are likely to make a programme more difficult or lengthy:

1. Failed attempts at using biological control for the target IAP elsewhere in the world.
2. A high diversity of indigenous and commercially important plant species that are closely related to the target weed are present in the region where biological control is desired. This increases the number of plant species that must be included in host-specificity testing, and thus the costs of the biological control programme, and may prolong the process of finding a suitably specific biological control agent.
3. The origin of the target IAP is unknown or disputed, or the taxonomy of the plant and its close relatives is unresolved. This makes sourcing suitable agents difficult and increases the complexity of host-specificity testing, resulting in the programme becoming more expensive and reducing the chances of rapid success.
4. The target IAP is a beneficial plant that is utilised commercially or non-commercially, causing a conflict of interest (Zengeya et al. 2017). Biocontrol options become more limited and restricted to certain plant parts.

scale of the IAP problem in South Africa and raises the question of how to select and prioritise species for biological control. There are too many IAPs for all of them to be targeted for biological control, some species are better suited for biological control than others, and others cannot be targeted because of conflicts of interest (Box 2); therefore, a prioritisation process is essential. In the past, selection of candidate target species has been done by the biological control community on an *ad hoc* basis in collaboration with funding bodies such as DEA: NRMP, and through discussions and consensus at the annual Weed Biocontrol Workshops. Although selecting targets in this way has been largely successful because of the considerable cumulative expertise of the group, a more formal system that could rank the IAPs listed in the NEM:BA regulations in order of appropriateness as targets for biological control would be beneficial. It would reduce subjectivity and therefore provide stronger evidence to funders for the need to work on the most appropriate targets. Plants that are not appropriate for biological control could then be prioritised for manual removal and/or chemical control.

A number of systems have been developed for the prioritisation of target plants for biological control (Hansen & Bloem 2006; McClay 1989; Paynter et al. 2009; Peschken & McClay 1995; Syrett 2002; van Klinken, Morin & Sheppard 2016), which could be modified to form a system to prioritise species for biological control in South Africa. The most recent prioritisation framework was developed for IAPs impacting the livestock industry in Australia and drew on the expert opinions of biological control researchers during a two-day workshop (van Klinken et al. 2016). A similar method could be adopted by the South African biological control community in order to better structure and justify prioritisation decisions. Although van Klinken et al. (2016) warned against the use of quantitative scoring systems to the exclusion of expert knowledge, they suggest that the more qualitative methods used in their study could be combined with a quantitative scoring system. The development of a prioritisation system for South Africa, which could rank species according to their suitability as candidate targets for biological control based on both quantitative assessments and expert opinion, should be considered.

Current and future targets for biological control of IAPs in South Africa

Van Wilgen et al. (2008, 2012) present the most recent and well supported lists of the most important IAPs in the country, and we used them in the absence of any other objective list, in full recognition that not all of the species should be considered as transformers. The list presented by van Wilgen et al. (2012) was compiled based on previous studies which estimated the area that each species occupied (Kotzé et al. 2010; Le Maitre, Versfeld & Chapman 2000) and the prominence value as defined by Henderson (2007). The list included 18 taxa of the worst IAPs in the country, combining all *Eucalyptus* spp., *Pinus* spp., *Populus* spp., *Prosopis* spp. and, importantly, all Cactaceae, into a single taxon (van Wilgen et al. 2012). Van Wilgen et al. (2008) list the worst IAPs in terms of the negative impact to ecosystem services. These species were selected based on the impact to surface water, grazing potential and biodiversity. Fifty-six taxa were included in that list, all as individual species rather than taxonomically related groups of species.

Here we categorise each of the worst IAPs from the work of van Wilgen et al. (2008) in terms of the contribution that biological control has, or will likely have, towards the management of the species. Each species was allocated to one of the following categories in terms of the current effectiveness of biological control: (1) under complete control, (2) under substantial control, (3) control effectiveness is currently negligible and (4) not determined (see Box 1). These four categories are widely used for evaluating success of biological control since they were first used in the 1999 biological control reviews (Hoffmann 1995; Klein 2011). We include two additional categories: (5) active research programme (for programmes with no agents released but where research to develop new agents is being undertaken) and (6) no research programme (for taxa that have no research programme at present) (Table 4). Information for each biological control programme was sourced from Klein (2011) as well as the biological control community for more recent developments.

For species that are not considered to be under complete control, we evaluated the prospects for improving control by reporting on any new potential agents, recently released agents or other ways that control could be improved, such as better integration with other control methods and increased implementation efforts (Table 4). For those species that have no active biological control research programme in the country, we first report whether the programme would be a novel programme in South Africa or whether it would be a repeat programme from elsewhere in the world. Biological control programmes require a substantial initial investment of funds (although these costs are miniscule compared to either the damage that the IAPs inflict or the cost of alternative control methods); therefore, transfer programmes are significantly less expensive and good value-for-money (Paynter et al. 2009). We then suggest which species are poor, possible, good or excellent candidates for biological control. Factors that were considered in allocating each species to the various categories are also given (Table 4). Poor candidates are those that should not be considered for biological control. Possible candidates include species that could be appropriate for biological control, but there is little evidence to support whether the programme would be successful or not. Good candidates are those with some evidence to support that biological control is possible and may be successful, and excellent candidates are those where potential agents are readily available and the chances of success are high (Table 4).

Thirteen (72%) of the 18 worst taxa from the work of van Wilgen et al. (2012) have biological control agents released on them already, and seven (39%) of these are under either complete or substantial biological control. When considering the more extensive list of species presented in van Wilgen et al. (2008), a list of 56 most damaging species to ecosystem functioning, 19 (34%) have active biological control and 13% are considered to be under substantial control. The higher percentage of taxa with biological control in van Wilgen et al. (2012) is probably because of the fact that the worst invaders have been targeted for biological control and only the worst 18 species were included in van Wilgen et al. (2012) while many other less damaging species were included in van Wilgen et al. (2008). Furthermore, of the 60 species in South Africa on which biological control is established, 21 are Cactaceae, which appear in van Wilgen et al. (2012) but not in van Wilgen et al. (2008). In our opinion, of the 37 species

TABLE 4: The status of and prospects for biological control of the 56 most damaging invasive alien plant species in South Africa. The list of target weed species is from van Wilgen et al. (2008).

Species	Degree of control achieved by biological control	Biological control has reached full potential	Prospects for biological control					Comments/reference
			New agent	Excellent candidate	Good candidate	Possible candidate	Poor candidate	
Acacia baileyana	Negligible	-	X	X	-	-	-	New agent released but too soon to evaluate impact; [+] successful biological control of other Australian *Acacia* species
Acacia cyclops	Substantial	X	-	-	-	-	-	Impson et al. (2011)
Acacia dealbata	Negligible	-	X	X	-	-	-	New agent released but too soon to evaluate impact; [+] successful biological control of other Australian *Acacia* species
Acacia decurrens	Negligible	-	X	X	-	-	-	New agent released but too soon to evaluate impact; [+] successful biological control of other Australian *Acacia* species
Acacia longifolia	Substantial	X	-	-	-	-	-	Impson et al. (2011)
Acacia mearnsii	Substantial	-	X	X	-	-	-	New agent spreading and damaging (J.H. Hoffmann [UCT] pers. comm., 2 September 2015); [+] successful biological control of other Australian *Acacia* species
Acacia melanoxylon	Substantial	X	-	-	-	-	-	Redistribution could improve control further (Impson et al. 2011)
Acacia saligna	Substantial	X	-	-	-	-	-	Impson et al. (2011)
Achyranthes aspera	No research programme	-	-	-	-	X	-	Novel programme; [-] uncertainties regarding native distribution of the target weed reduce the potential for biological control
Agave americana	No research programme	-	-	-	-	X	-	Novel programme; [-] possible conflict of interest as close relatives are grown commercially
Arundo donax	Active research programme, no agents released yet	-	-	X	-	-	-	Transfer programme; [+] agents have been released in USA
Atriplex lindleyi	No research programme	-	-	-	-	X	-	Novel programme; [-] plant has native congeners which would limit the potential for finding a host specific agent
Atriplex nummularia	No research programme	-	-	-	-	X	-	Novel programme; [-] plant has native congeners which would limit the potential for finding a host specific agent
Cortaderia selloana	No research programme	-	-	-	-	X	-	[+] Preliminary investigations into natural enemies have been conducted; [-] manual and herbicidal control is effective on a congener (DiTomaso, Drewitz & Kyser 2008)
Caesalpinia decapetala	Negligible	-	-	-	X	-	-	[+] Natural enemies known (Byrne, Witkowski & Kalibbala 2011)
Cestrum laevigatum	Research programme shelved	-	-	-	X	-	-	[+] Natural enemies known (D.O. Simelane [ARC-PPRI] pers. comm., 26 April 2016)

Table 4 continues on the next page →

TABLE 4 (continues…): The status of and prospects for biological control of the 56 most damaging invasive alien plant species in South Africa. The list of target weed species is from van Wilgen et al. (2008).

Species	Degree of control achieved by biological control	Biological control has reached full potential	Prospects for biological control					Comments/reference
			New agent	Excellent candidate	Good candidate	Possible candidate	Poor candidate	
Chromolaena odorata	Not determined	-	X	-	X	-	-	Two new agents released and more under consideration; [+] biological control has been successful elsewhere
Cuscuta campestris	No research programme	-	-	-	-	X	-	[+] Natural enemies known; [-] failed attempts at biological control elsewhere; [-] plant has native congeners which would limit the potential for finding a host specific agent
Datura stramonium	No research programme	-	-	-	X	-	-	[+] Fungal biological control agents known
Dolichandra (Macfadyena) unguis-cati	Negligible	-	-	-	X	-	-	Agents have been released too recently to determine impact; [+] other control methods are ineffective
Echinopsis spachiana	No research programme	-	-	-	X	-	-	[+] Success on other Cactaceae
Eucalyptus camaldulensis	No research programme	-	-	-	-	-	X	Novel programme; [-] conflict of interest with bee-keeping industry; [-] biological control investigated and no suitable candidates are available (all possible agents stop flowering and therefore conflict with bee-keeping industry). Seed feeder already present (Klein et al. 2015)
Eucalyptus grandis	No research programme	-	-	-	-	-	X	Novel programme; [-] conflict of interest with commercial forestry;
Eucalyptus conferruminata	No research programme	-	-	-	-	-	X	Novel programme; [-] conflict of interest with bee-keeping industry; [-] biological control investigated and no suitable candidates are available (all possible agents stop flowering and therefore conflict with bee-keeping industry)
Hakea drupacea	Research programme shelved	-	-	-	X	-	-	[+] Natural enemies known; [+] successful biological control of congeners
Hakea gibbosa	Negligible	X But see comments		-	-	-	-	Better integration with other control methods could improve success, agents have been released too recently to determine impact (Gordon & Fourie 2011)
Hakea sericea	Substantial	X But see comments		-	-	-	-	Better integration with other control methods could improve success, agents have been released too recently to determine impact (Gordon & Fourie 2011)
Ipomoea indica	No research programme	-	-	-	-	-	X	Novel programme; [-] uncertainties regarding native distribution of the target weed reduce the potential for biological control, indigenous and commercially valuable relatives (including congeners) which would limit the potential for finding a host specific agent; [+] other control methods ineffective
Jacaranda mimosifolia	No research programme	-	-	-	-	X	-	Novel programme; potential conflict of interest but seeds could be targeted; [-] seed attacking surveys were conducted and no suitable agents were discovered
Lantana camara	Negligible - substantial	-	X	-	-	X	-	One new agent and others have also been released too recently to determine impact (Urban et al. 2011)
Leptospermum laevigatum	Negligible	-	-	-	-	-	X	[-] Known natural enemies are considered unpromising (Gordon 2011)
Melia azedarach	Research programme shelved	-	-	-	-	X	-	Novel programme; [-] uncertainties regarding native distribution; [-] preliminary surveys failed to find promising candidates
Nicotiana glauca	No research programme	-	-	-	X	-	-	Transfer programme; [+] biological control successful elsewhere; [-] potential conflict with tobacco growers
Paraserianthes lophantha	Substantial	-	X	-	X	-	-	New agent released but too soon to evaluate impact; [+] successful biological control with close relatives (Australian *Acacia*)
Pennisetum clandestinum	No research programme	-	-	-	-	X	-	Novel programme; [-] little past success with grasses; [-] conflict of interest as plant is grown commercially
Pinus elliottii	No research programme	-	-	-	-	-	X	Novel programme; [-] biological control of pines investigated and no suitably specific candidates were available; [-] conflict of interest
Pinus halepensis	No research programme	-	-	-	-	-	X	Novel programme; [-] biological control of pines investigated and no suitably specific candidates were available; [-] conflict of interest

Table 4 continues on the next page →

TABLE 4 (continues…): The status of and prospects for biological control of the 56 most damaging invasive alien plant species in South Africa. The list of target weed species is from van Wilgen et al. (2008).

Species	Degree of control achieved by biological control	Biological control has reached full potential	Prospects for biological control					Comments/reference
			New agent	Excellent candidate	Good candidate	Possible candidate	Poor candidate	
Pinus patula	No research programme	-	-	-	-	-	X	Novel programme; [-] biological control of pines investigated and no suitably specific candidates were available; [-] conflict of interest
Pinus pinaster	Research programme shelved	-	-	-	-	-	X	Novel programme; [-] biological control of pines investigated and no suitably specific candidates were available; [-] conflict of interest
Pinus radiata	No research programme	-	-	-	-	-	X	Novel programme; [-] biological control of pines investigated and no suitably specific candidates were available; [-] conflict of interest
Populus alba	No research programme	-	-	-	-	X	-	Novel programme
Populus canescens	No research programme	-	-	-	-	X	-	Novel programme
Prosopis glandulosa	Negligible	-	X	-	-	X	-	Conditional release permit for new agent granted
Prunus persica	No research programme	-	-	-	-	-	X	Novel programme; [-] conflict of interest with commercial growers
Psidium guajava	No research programme	-	-	-	-	-	X	Novel programme; [-] conflict of interest with commercial growers
Pyracantha angustifolia	No research programme	-	-	-	X	-	-	Novel programme; [+] no close relatives in South Africa; [+] known native distribution
Robinia pseudoacacia	No research programme	-	-	X	-	-	-	Novel programme; [+] extensive knowledge of effective agents
Rubus cuneifolius	Research programme shelved	-	-	-	-	-	X	Novel programme; [-] closely related plants are valuable; [-] taxonomic uncertainties
Rubus fruticosus	Research programme shelved	-	-	-	-	-	X	Novel programme; [-] closely related plants are valuable; [-] taxonomic uncertainties; [-] conflict of interest
Salix babylonica	No research programme	-	-	-	-	X	-	Novel programme
Senna didymobotrya	No research programme	-	-	-	-	X	-	Novel programme; [-] manual and herbicidal control effective
Senna occidentalis	No research programme	-	-	-	-	X	-	Novel programme; [-] manual and herbicidal control effective
Solanum mauritianum	Negligible	-	-	-	X	-	-	Impact of recently released agents not determined; [+] success with two congeners (Hoffmann, Moran & Impson 1998; Klein 2011); [-] congeners of economic importance
Solanum seaforthianum	No research programme	-	-	-	X	-	-	Novel programme; [+] success with two congeners (Hoffmann et al. 1998; Klein 2011); [-] congeners of economic importance
Solanum sisymbriifolium	Substantial	X	-	-	-	-	-	
Xanthium strumarium	No research programme	-	-	-	X	-	-	Repeat programme; [+] successful agent available
TOTAL		**7**	**8**	**6**	**13**	**16**	**14**	-

The degree of control for each species was taken from Klein (2011) updated in 2016 (http://www.arc.agric.za/arc-ppri/Documents/Target weed species in South Africa.pdf). Species where biological control has not reached full potential were classified as either poor, possible, good or excellent candidates for biological control (see section 'Current and future targets for biological control of IAPs in South Africa' for definitions). The factors that were considered in allocating each species to one of these categories are included under comments. In the comments column, a minus sign indicates that the factor suggests that biological control is inappropriate or unlikely to succeed. A plus sign indicates that the factor suggests that biological control is appropriate and likely to succeed. A novel programme refers to one that has not been developed in any other country before while an active research programme is one that is active in South Africa specifically.

in the list of worst invaders from van Wilgen et al. (2008) that do not have biological control agents released, there are 2 excellent candidates [*A. donax* and *Robinia pseudoacacia* L. (Fabaceae)] for biological control, 8 good candidates, 14 possible candidates and 13 poor candidates (Table 4). If the species that have new agents or biological control programmes that have not yet reached full potential are included, then there are 6 excellent candidates for biological control, 13 good candidates, 16 possible candidates and 14 poor candidates (Table 4). Of the species that are considered under negligible control, there is one good candidate for future biological control research, one poor candidate and six species with recently released agents (Table 4). We recommend that biological control should be considered for all but the poor candidates. Research into biological control of excellent and good candidates should be supported and possible candidates should be considered depending on the availability of capacity and funds.

While biological control has contributed significantly towards the control of several major IAPs in South Africa, there are many more species that have also been targeted for biological control in the past. Excluding the species with active biological control programmes that coincide with van Wilgen et al. (2008) leaves 37 species with biological control agents established in South Africa. Some of these (such as *O. ficus-indica* and *E. crassipes*) should certainly be considered major IAPs, but many are currently rather minor. This does not necessarily indicate that these target species for biological control were poorly selected because pro-actively targeting

IAPs for biological control before they become widespread invaders can be even more beneficial than targeting well-established species. The contribution of biological control to pro-active management of IAPs in South Africa should not be overlooked (Olckers 2004) but is more difficult to quantify than impacts to abundant species, as it is difficult to predict how much of a problem they would have become if biological control had been implemented against them only at a later date. It is probable that some species (e.g. *H. perforatum* and *A. riparia*) would be far more problematic today if they had not been the targets of earlier biological control programmes. Transfer projects are ideal for IAP species that have not yet become problematic in the country but are likely to cause problems in future, because the costs of these projects are dramatically reduced compared to novel targets, and the project can be implemented rapidly before the IAP increases extensively in abundance and distribution. Biological control should however only be considered an option once it is clear that eradication of the IAP is no longer possible, as eradication is often more cost-effective (see Wilson et al. 2013 for a review of eradication attempts in South Africa to date).

The initiation of biological control programmes on new target species should be carefully considered beforehand, as each constitutes a potentially major commitment of research time and funding. Most IAP biological control programmes require a minimum intensive commitment of about 10 years, with an average of approximately 4 years to develop each agent (Moran, Hoffmann & Zimmermann 2005). Some transfer projects may have shorter timeframes [an average of 2.8 years per agent, as opposed to novel projects which have an average of 5.0 years (Moran et al. 2005)]. Several of the older, successful programmes have taken decades to realise their full potential, generally owing to varying complexities particular to each target species, as well as owing to the inherent slow process of biological control and natural systems. In some of the previous contracts with DEA: NRMP (e.g. the early to mid-2000s), the biological control community may have been overambitious in their delivery targets. A better approach for certain IAPs may be to obtain funding for feasibility studies first, and thorough molecular studies in some cases [e.g. *Melia azedarach* L. (Meliaceae)] to determine origin or genetic diversity of populations of the target species, as well as thorough systematic surveys for potential agents, with preliminary screening of host range. It should be emphasised to the funder from the outset that by funding a project (particularly on a novel IAP species), they should consider that a long-term funding commitment may be needed to deliver good results (see Scott, Yeoh & Michael 2016). Furthermore, as many habitats are susceptible to secondary invasion following the biological control of the primary invader (e.g. cacti in arid areas, invasive aquatics and disturbed habitats), in some instances habitats (i.e. groups of IAPs) rather than individual IAPs should be prioritised. It should be understood that the initial development phase of every IAP biological control programme offers low returns on value for money, but that benefits increase incrementally and indefinitely once the initial stages of the implementation phase are passed. It should also be understood that not all programmes result in the release of biological control agents, nor are agent releases guaranteed to succeed.

Finally, we have recommended target numbers of IAPs to work on for the second status report due in 2020 (Table 3). The average increase for pre-release studies across both major and pro-active targets is 28%, which is in line with the level of growth suggested in the National Strategy. A higher percentage of growth to pro-active targets is indicated because many of these are small studies and because few pro-active species have been targeted in the past. Similarly, the suggested overall increase in the number of species for post-release evaluation and mass-rearing is 64% (Table 3). Sixty-two IAP species were recommended for post-release evaluation because this is the total number with biological control agents released on them.

Building IAP biological control capacity and creating job opportunities

Three main aspects need to be addressed for the expansion of capacity. Firstly, long-term training through expanded growth at universities, in both undergraduate and particularly postgraduate programmes, will be required to produce numerous qualified candidates who could be employed as researchers and skilled technicians in IAP biological control research programmes at universities and research organisations. Qualified expertise will also be required for mass-rearing facilities and implementation. As many opportunities for employment will exist in such structures, capacity growth aligns with the job creation priorities of national government and the Expanded Public Works Programme. People with disabilities can also be trained and employed within the field of biological control.

Secondly, short-term training in aspects of IAP biological control is required. At present, several such initiatives are in operation, which include an annual five-day short course, a short course on Cactaceae, eight-week undergraduate experiential training from one university, 12-months in-service training of final year University of Technology Diploma students at a research institution, public exhibitions and Farmers' Day events. Considerably greater scope is possible. New short courses at several levels are required to train research and technical support personnel, managers, implementers (mass-rearing, releases and field teams) and unskilled workers. A national IAP biological control internship programme after graduation from universities, within research and mass-rearing institutions, would be beneficial. National and international exchange programmes as well as exposure to top international researchers would broaden expertise. The retention of skilled expertise is essential to maintain consistency and development of the practice because of the long-term nature of IAP biological control.

Thirdly, expansion of infrastructure is required to build IAP biological control capacity. While this is a costly exercise, if the desired levels of IAP biological control are to be achieved, additional facilities will be required. Existing facilities are constrained in terms of space or operational mandates. Expansion of existing infrastructures, as well as erection of new, appropriate facilities (quarantine facilities, greenhouses, laboratories, offices, etc.), would be required. To achieve a 100% increase in implementation activities over the 5-year period indicated by the National Strategy, a significant investment (several million ZAR) would be required for infrastructure expansion within a short time frame. Involvement of organs of state, private companies and nongovernmental organisations (NGOs) operating in the environmental and agricultural sectors may be beneficial in mass-rearing operations. However, qualified, skilled and experienced entomologists and pathologists are critical to achieve the desired levels of success as well as to foster a strong link with research programmes. Regardless of the parties involved, a long-term funding commitment through multiple 3-year funding cycles will be necessary.

Our recommendations for targets in increasing capacity by 2020, in line with the National Strategy, are provided in Table 3. While the recommended increase in funding for research is in line with the National Strategy, that for implementation funding is lower (40% instead of 60% overall, for implementation and mass-rearing combined). In our opinion, a 60% increase over 3 years is too great, given that considerable additional facilities for mass-rearing will have to be developed. The higher relative budget for mass-rearing is designed with the development of infrastructure in mind. With regard to human resources, our recommended increases both in research and implementation capacity (Table 3) are consistent with the National Strategy. Most of the 10 additional implementation officers would be employed under existing research institutes. Most of the 20 additional mass-rearing technicians envisaged would only be employed once infrastructure is in place.

Currently, most provinces have one or two ‘biodiversity officers’ employed by DEA for field implementation of IAP biological control. However, additional duties within their portfolio include managing aquatic clearing teams and dealing with invasive fauna. During peak season in particular, there is a need for greater capacity on IAP biological control field implementation, including site selection, releases and monitoring of release sites. Furthermore, it is important to break down provincialism in the context of the implementation of IAP biological control, as virtually all IAPs with biological control agents released invade more than one province; therefore a national, coordinated outlook is required (e.g. through a national mass-rearing strategy which assigns each biological control agent to one or a few mass-rearing centres, for national or regional distribution).

The nature of funding (Expanded Public Works Programme) prescribes that the maximum number of people be employed in manual and chemical clearing operations, a principle that is often thought to be contradictory to the aims of biological control. However, despite the large investment in manual and chemical clearing programmes since 1995, the scale of plant invasions in South Africa remains so great that large scale employment, using these clearing methods, continues to be guaranteed for the foreseeable future. Furthermore, mass-rearing and redistribution of biological control agents have the potential to employ a substantial number of people, sometimes in higher-skilled, higher-paid positions than manual and chemical IAP clearing operations. The new NEMBA legislation requires the development of national management programmes for every IAP species that is categorised as 1b, which may also assist in promoting biological control to an appropriate status within clearing programmes.

A potential pitfall of the current *status quo* of IAP biological control in South Africa is the largely single funding source, which relies on the current priorities of government. Diversification of funding sources would protect against future radical priority shifts to retain capacity and infrastructure investments in IAP biological control, but may not be feasible. Another issue is the short-term allocation of funding because of national objectives for 3-year funding cycles. Longer-term allocation of funds would be preferable, particularly in cases where infrastructure and capacity expertise for IAP biological control research and implementation activities need to be expanded.

Conclusions

South Africa has a long and successful history of IAP biological control and has made considerable progress in cost-effectively protecting the country’s natural resources from IAPs. We are currently in a very favourable position, both in terms of funding and policy. South Africa has already increased capacity for IAP biological control and can do so to a greater extent, in line with the National Strategy recommendations. A relatively large proportion of this growth should be invested in implementation and post-release evaluations so that existing biological control agents are utilised to their full potential and the contribution of biological control can be better quantified. Research on selected new pro-active targets should also be undertaken to address the large number of NEM:BA-listed species. This will also provide a substantial number of higher-skilled, higher-paid employment opportunities in line with government policies. South Africa has already benefited substantially from previous investments into biological control of IAPs, but the full potential has most certainly not been reached. Continued and increased investment into biological control will result in greater protection of the country’s natural resources and benefit the people who depend on them.

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Competing interests

The authors declare that they have no financial or personal relationship(s) that may have inappropriately influenced them in writing this article.

Authors' contributions

C.Z. initiated the review paper and solicited co-authors, as well as wrote and edited sections of the paper, and obtained data on mass-rearing and field-distribution. I.D.P. suggested the structure of the paper, analysed data on prospects for new biological control programmes, wrote sections of the paper and contributed to the entire paper. L.W.S. obtained data on personnel numbers, wrote sections of the paper and contributed to the entire paper. M.P.H. wrote the sections on aquatic plants and commented on the paper as a whole. B.W.V.W. provided valuable insight into the National Strategy and status report, and commented on the paper as a whole.

References

Barton, J., Fowler, S.V., Gianotti, A.F., Winks, C.J., de Beurs, M., Arnold, G.C. et al., 2007, 'Successful biological control of mist flower (*Ageratina riparia*) in New Zealand: Agent establishment, impact and benefits to the native flora', *Biological Control* 40, 370–385. https://doi.org/10.1016/j.biocontrol.2006.09.010

Byrne, M.J., Witkowski, E.T.F. & Kalibbala, F.N., 2011, 'A review of recent efforts at biological control of *Caesalpinia decapetala* (Roth) Alston (Fabaceae) in South Africa', *African Entomology* 19, 247–257. https://doi.org/10.4001/003.019.0201

Cilliers, C.J., 1991, 'Biological control of water hyacinth, *Eichhornia crassipes* (Pontederiaceae), in South Africa', *Agriculture, Ecosystems and Environment* 37, 207–217. https://doi.org/10.1016/0167-8809(91)90149-R

Cock, M.J.W., van Lenteren, J.C., Brodeur, J., Barratt, B.I.P., Bigler, F., Bolckmans, K. et al., 2010, 'Do new access and benefit sharing procedures under the convention on biological diversity threaten the future of biological control?', *BioControl* 55, 199–218. https://doi.org/10.1007/s10526-009-9234-9

Coetzee, J.A. & Hill, M.P., 2012, 'The role of eutrophication in the biological control of water hyacinth, *Eichhornia crassipes*, in South Africa', *BioControl* 57, 247–261. https://doi.org/10.1007/s10526-011-9426-y

Coetzee, J.A., Hill, M.P., Byrne, M.J. & Bownes, A., 2011, 'A review of the biological control programmes on *Eichhornia crassipes* (C. Mart.) Solms (Pontederiaceae), *Salvinia molesta* D.S. Mitch. (Salviniaceae), *Pistia stratiotes* L. (Araceae), *Myriophyllum aquaticum* (Vell.) Verdc. (Haloragaceae) and *Azolla filiculoides* Lam. (Azollaceae) in South Africa', *African Entomology* 19, 451–468. https://doi.org/10.4001/003.019.0202

De Lange, W.J. & van Wilgen, B.W., 2010, 'An economic assessment of the contribution of biological control to the management of invasive alien plants and to the protection of ecosystem services in South Africa', *Biological Invasions* 12, 4113–4124. https://doi.org/10.1007/s10530-010-9811-y

Department of Environmental Affairs, 2014a, *Notice No. R. 598. National Environmental Management: Biodiversity Act (10/2004): Alien and Invasive Species Regulations, 2014*, Government Gazette 37885, Pretoria, 1 August 2014. (Regulation Gazette No. 10244).

Department of Environmental Affairs, 2014b, *Notice No. 599. National Environmental Management: Biodiversity Act (10/2004): Alien and Invasive Species List, 2014*, Government Gazette 37886, Pretoria, 1 August 2014.

Department of Environmental Affairs, 2016, *Notice No. 864. National Environmental Management: Biodiversity Act, 2004 (Act No. 10 Of 2004). Alien and invasive species lists, 2016*, Government Gazette 40166, pp. 31–104.

DiTomaso, J.M., Drewitz, J.J. & Kyser, G.B., 2008, 'Jubata grass (*Cordateria jubata*) control using chemical and mechanical methods', *Invasive Plant Science and Management* 1, 82–90. https://doi.org/10.1614/IPSM-07-028

Downs, C.T., 2010, 'Is vacation apprenticeship of undergraduate life science students a model for human capacity development in the life sciences?', *International Journal of Science Education* 32, 687–704. https://doi.org/10.1080/0950069 0903075004

Faulkner, K.T., Hurley, B.P., Robertson, M.P., Rouget, M. & Wilson, J.R.U., 2017, 'The balance of trade in alien species between South Africa and the rest of Africa', *Bothalia* 47(2), a2157. https://doi.org/10.4102/abc.v47i2.2157

Fowler, S.V., Syrett, P. & Hill, R.L., 2000, 'Success and safety in the biological control of environmental weeds in New Zealand', *Austral Ecology* 25, 553–562. https://doi.org/10.1046/j.1442-9993.2000.01075.x

Funasaki, G.Y., Lai, P.Y., Nakahara, L.M., Beardsley, J.W. & Ota, A.K., 1988, 'A review of biological control introductions in Hawaii: 1980 to 1985', *Proceedings of the Hawaii Entomological Society* 28, 105–160.

Gillespie, P., Klein, H. & Hill, M.P., 2004, 'Establishment of a weed biocontrol implementation programme in South Africa', in J.M. Cullen, D.T. Briese, D.J. Kriticos, W.M. Lonsdale, L. Morin & J.K. Scott (eds.), *Proceedings of the XIth International Symposium on Biological control of Weeds*, CSIRO Entomology, Canberra, Australia, pp. 400–406.

Gordon, A.J., 2011, 'Biological control endeavours against Australian myrtle, *Leptospermum laevigatum* (Gaertn.) F. Muell. (Myrtaceae), in South Africa', *African Entomology* 19, 349–355. https://doi.org/10.4001/003.019.0206

Gordon, A.J. & Fourie, A., 2011, 'Biological control of *Hakea sericea* Schrad. & J.C. Wendl. and *Hakea gibbosa* (Sm.) Cav. (Proteaceae) in South Africa', *African Entomology* 19, 303–314. https://doi.org/10.4001/003.019.0205

Gordon, A.J. & Kluge, R.L., 1991, 'Biological control of St. John's Wort, *Hypericum perforatum* (Clusiaceae), in South Africa', *Agriculture, Ecosystems and Environment* 37, 77–90. https://doi.org/10.1016/0167-8809(91)90140-S

Hansen, R. & Bloem, K., 2006, *USDA-APHIS_PPQ Biological targets for pest canvassing and evaluation 2005–2006, Final Report*, viewed 6 May 2016, from www.aphis.usda.gov/plant_health/plant_pest_info/biocontrol/download/pest-canvassing.pdf

Henderson, L., 2001, *Alien weeds and invasive plants*. Plant Protection Research Institute Handbook No. 12, Agricultural Research Council, Pretoria, South Africa.

Henderson, L., 2007, 'Invasive, naturalised and casual alien plants in southern Africa: A summary based on the Southern African Plant Invaders Atlas (SAPIA)', *Bothalia* 37, 215–248. https://doi.org/10.4102/abc.v37i2.322

Hill, M.P. & Coetzee, J.A., 2008, 'Integrated control of water hyacinth (*Eichhornia crassipes*) in Africa', *EPPO Bulletin/Bulletin OEPP* 38, 452–457. https://doi.org/10.1111/j.1365-2338.2008.01263.x

Hill, M.P. & Olckers, T., 2001, 'Biological control initiatives against water hyacinth in South Africa: Constraining factors, success and new courses of action', in M.H. Julien, M.P. Hill, T.D. Center & D. Jianqing (eds.), *Biological and integrated control of water hyacinth, Eichhornia crassipes. Proceedings of the Second Global Working Group Meeting for the Biological and Integrated Control of Water Hyacinth*, ACIAR Proceedings No. 102, Beijing, China, October 9–12, 2000, pp. 33–38.

Hill, M.P. & Coetzee, J.A., 2017, 'The biological control of aquatic weeds in South Africa: Current status and future challenges', *Bothalia* 47(2), a2152. https://doi.org/10.4102/abc.v47i2.2152

Hoffmann, J.H. (ed.), 1991, 'Biological control of weeds in South Africa', *Agriculture, Ecosystems and Environment* 37, 1–255.

Hoffmann, J.H., 1995, 'Biological control of weeds: The way forward, a South African perspective', *BCPC Symposium Proceedings* 64, 77–89.

Hoffmann, J.H. & Moran, V.C., 1991, 'Biological control of *Sesbania punicea* (Fabaceae) in South Africa', *Agriculture, Ecosystems and Environment* 37, 157–173. https://doi.org/10.1016/0167-8809(91)90144-M

Hoffmann, J.H., Moran, V.C. & Impson, F.A.C., 1998, 'Promising results from the first biological control programme against a solanaceous weed (*Solanum elaeagnifolium*)', *Agriculture, Ecosystems and Environment* 70, 145–150. https://doi.org/10.1016/S0167-8809(98)00120-0

Holmes, P.M. & Richardson, D.M., 1999, 'Protocols for restoration based on recruitment dynamics, community structure, and ecosystem function: Perspectives from South African fynbos', *Restoration Ecology* 7, 215-230. https://doi.org/10.1046/j.1526-100X.1999.72015.x

Impson, F.A.C., Kleinjan, C.A., Hoffmann, J.H., Post, J.A. & Wood, A.R., 2011, 'Biological control of Australian *Acacia* species and *Paraserianthes lophantha* (Willd.) Nielsen (Mimosaceae) in South Africa', *African Entomology* 19, 186–207. https://doi.org/10.4001/003.019.0210

Klein, H., 2011, 'A catalogue of the insects, mites and pathogens that have been used or rejected, or are under consideration, for the biological control of invasive alien plants in South Africa', *African Entomology* 19, 515–549. https://doi.org/10.4001/003.019.0214

Klein, H., Hill, M.P., Zachariades, C. & Zimmermann, H.G., 2011, 'Regulation and risk assessment for importations and releases of biological control agents against invasive alien plants in South Africa', *African Entomology* 19, 488–497. https://doi.org/10.4001/003.019.0215

Klein, H., Hoffmann, J.H., Neser, S. & Dittrich-Schröder, G., 2015, 'Evidence that *Quadrastichodella nova* (Hymenoptera: Eulophidae) is the only gall inducer among four hymenopteran species associated with seed capsules of *Eucalyptus camaldulensis* (Myrtaceae) in South Africa', *African Entomology* 23, 207–223. https://doi.org/10.4001/003.023.0117

Kotzé, J.D.F., Beukes, B.H., Van Den Berg, E.C. & Newby, T.S., 2010, *National invasive alien plant survey*, Report No. GW/A/2010/21, Agricultural Research Council: Institute for Soil, Climate and Water, Pretoria, South Africa.

Le Maitre, D.C., Versfeld, D.B. & 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.

McClay, A.S., 1989, *Selection of suitable targets of weeds for classical biological control in Alberta*, AECV89-RI, Alberta Environmental Central, Vegreville, AB, Canada.

McConnachie, A.J., 2015, 'Host range tests cast doubt on the suitability of *Epiblema strenuana* as a biological control agent for *Parthenium hysterophorus* in Africa', *BioControl* 60, 1–9. https://doi.org/10.1007/s10526-015-9675-2

McConnachie, A.J., de Wit, M.P., Hill, M.P. & Byrne, M.J., 2003, 'Economic evaluation of the successful biological control of *Azolla filiculoides* in South Africa', *Biological Control* 28, 25–32. https://doi.org/10.1016/S1049-9644(03)00056-2

McConnachie, A.J., Hill, M.P. & Byrne, M.J., 2004, 'Field assessment of a frond-feeding weevil, a successful biological control agent of red water fern, *Azolla filiculoides*, in southern Africa', *Biological Control* 29, 326–331. https://doi.org/10.1016/j.biocontrol.2003.08.010

Meyer, J.Y., Fourdrigniez, M. & Taputuarai, R., 2011, 'Restoring habitat for native and endemic plants through the introduction of a fungal pathogen to control the alien invasive tree *Miconia calvescens* in the island of Tahiti', *Biological Control* 57, 191–198.

Moran, V.C. & Hoffmann, J.H., 2015, 'The Fourteenth International Symposium on Biological Control of Weeds, 1969–2014: Delegates, demographics and inferences from the debate on non-target effects', *Biological Control* 87, 23–31. https://doi.org/10.1016/j.biocontrol.2015.04.008

Moran, V.C., Hoffmann, J.H. & Hill, M.P. (eds.), 2011, 'Biological control of invasive alien plants in South Africa (1999–2010)', *African Entomology* 19, 177–549. https://doi.org/10.4001/003.019.0218

Moran, V.C., Hoffmann, J.H. & Zimmermann, H.G., 2005, 'Biological control of invasive alien plants in South Africa: Necessity, circumspection, and success', *Frontiers in Ecology and the Environment* 3, 77–83. https://doi.org/10.2307/3868513

Moran, V.C., Hoffmann, J.H. & Zimmermann, H.G., 2013, '100 years of biological control of invasive alien plants in South Africa: History, practice and achievements', *South African Journal of Science* 109(9/10), Art. #a0022, 1–6. https://doi.org/10.1590/sajs.2013/a0022

Moran, V.C. & Zimmermann, H.G., 1991, 'Biological control of cactus weeds of minor importance in South Africa', *African Entomology* 19, 37–55. https://doi.org/10.1016/0167-8809(91)90138-n

Morin, L., Reid, A.M., Sims-Chilton, N.M., Buckley, Y.M., Dhileepan, K., Hastwell, G.T. et al., 2009, 'Review of approaches to evaluate the effectiveness of weed biological control agents', *Biological Control* 51, 1–15. https://doi.org/10.1016/j.biocontrol.2009.05.017

Morris, M.J., Wood, A.R. & den Breeÿen, A, 1999, 'Plant pathogens and biological control of weeds in South Africa: A review of projects and progress during the last decade', *African Entomology Memoir* 1, 129–137.

Olckers, T., 2004, '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', *South African Journal of Science* 100, 64–68.

Olckers, T. & Hill, M.P. (eds.), 1999, 'Biological control of weeds in South Africa (1990–1998)', *African Entomology Memoir* 1, 1–182.

Paterson, I.D., Hoffmann, J.H., Klein, H., Mathenge, C.W., Neser, S. & Zimmermann, H.G., 2011, 'Biological control of Cactaceae in South Africa', *African Entomology* 19, 230–246. https://doi.org/10.4001/003.019.0221

Paterson, I.D., Vitorino, M.D., de Cristo, S.C., Martin, G.D. & Hill, M.P., 2014, 'Prioritisation of potential agents for the biological control of the invasive alien weed, *Pereskia aculeata* (Cactaceae), in South Africa', *Biocontrol Science and Technology* 24, 407–425. https://doi.org/10.1080/09583157.2013.864382

Paynter, Q.E., Fowler, S.V., Gourlay, A.H., Haines, M.L., Harman, H.M., Hona, S.R. et al., 2004, 'Safety in New Zealand weed biocontrol: A nationwide survey for impacts on non-target plants', *NZ Plant Protection* 57, 102–107.

Paynter, Q., Hill, R., Bellgard, S. & Dawson, M., 2009, *Improving targeting of weed biological control projects in Australia*', Land and Water Australia, Canberra.

Pemberton, R.W., 2000, 'Predictable risk to native plants in weed biological control', *Oecologia* 125, 489–494. https://doi.org/10.1007/s004420000477

Peschken, D.P. & McClay, A.S., 1995, 'Picking the target – A revision of McClay's scoring system to determine the suitability of weeds for classical biological control', in E.S. Delfosse & R.R. Scott (eds.), *Proceedings of the Eighth International Symposium on Biological Control of Weeds*, Canterbury, New Zealand, February 2–7, 1992, CSIRO, Melbourne, pp. 137–143.

Rüegg, W.T., Quadranti, M. & Zoschke, A., 2007, 'Herbicide research and development: Challenges and opportunities', *Weed Research* 47, 271–275. https://doi.org/10.1111/j.1365-3180.2007.00572.x

Scott, J.K., Yeoh, P.B. & Michael, P.J., 2016, 'Methods to select areas to survey for biological control agents: An example based on growth in relation to temperature and distribution of the weed *Conyza bonariensis*', *Biological Control* 97, 21–30. https://doi.org/10.1016/j.biocontrol.2016.02.014

Suckling, D.M. & Sforza, R.F.H., 2014, 'What magnitude are observed non-target impacts from weed biocontrol?', *PLoS One* 9, e84847. https://doi.org/10.1371/journal.pone.0084847

Syrett, P., 2002, *Biological control of weeds on conservation land: Priorities for the Department of Conservation*, Internal series no. 82, Department of Conservation, Wellington, New Zealand.

Urban, A.J., Simelane, D.O., Retief, E., Heystek, F., Williams, H.E. & Madire, L.G., 2011, 'The invasive '*Lantana camara* L.' hybrid complex (Verbenaceae): A review of research into its identity and biological control in South Africa', *African Entomology* 19, 315–348. https://doi.org/10.4001/003.019.0225

Van Driesche, R.G., Carruthers, R.I., Center, T., Hoddle, M.S., Hough-Goldstein, J., Morin, L. et al., 2010, 'Classical biological control for the protection of natural ecosystems', *Biological Control* 54, S2–S33. https://doi.org/10.1016/j.biocontrol.2010.03.003

Van Klinken, R.D., Morin, L. & Sheppard, A., 2016, 'Experts know more than just facts: Eliciting functional understanding to help prioritise weed biological control targets', *Biological Invasions.* https://doi.org/10.1007/s10530-016-1175-5

Van Wilgen, B.W. & de Lange, W.J., 2011, 'The costs and benefits of biological control of invasive alien plants in South Africa', *African Entomology* 19, 504–514. https://doi.org/10.4001/003.019.0228

Van Wilgen, B.W., De Wit, M.P., Anderson, H.J., Le Maitre, D.C., Kotze, I.M., Ndala, S., Brown, B. & Rapholo, M.B., 2004, 'Costs and benefits of biological control of invasive alien plants: Case studies from South Africa', *South African Journal of Science* 100, 113–122.

Van Wilgen, B.W., Fill, J.M., Baard, J., Cheney, C., Forsyth, A.T. & Kraaij, T., 2016, 'Historical costs and projected future scenarios for the management of invasive alien plants in protected areas in the Cape Floristic Region', *Biological Conservation* 200, 168–177. https://doi.org/10.1016/j.biocon.2016.06.008

Van Wilgen, B.W., Forsyth, G.G., Le Maitre, D.C., Wannenburgh, A., Kotzé. J.D.F., van den Berg, E. et al., 2012, 'An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa', *Biological Conservation* 148, 28–38. https://doi.org/10.1016/j.biocon.2011.12.035

Van Wilgen, B.W., Reyers, B., Le Maitre, D.C., Richardson, D.M. & Schonegevel, L., 2008, 'A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa', *Journal of Environmental Management* 89, 336–349. https://doi.org/10.1016/j.jenvman.2007.06.015

Van Wilgen, B.W & Wannenburgh, A., 2016, 'Co-facilitating invasive species control, water conservation and poverty relief: Achievements and challenges in South Africa's *Working for Water* programme', *Current Opinion in Environmental Sustainability* 19, 7–17. https://doi.org/10.1016/j.cosust.2015.08.012

Versfeld, D.B., Le Maitre, D.C. & Chapman, R.A., 1998, *Alien invading plants and water resources in South African: A preliminary assessment*, WRC Report No. TT 99/98, Water Research Commission, Pretoria, South Africa.

Watson, A.K. & Wymore, L.A., 1989, 'Biological control, a component of integrated weed management', in E.S. Delfosse (ed.), *Proceedings of the VII International Symposium for Biological Control of Weeds*, Istituto Sperimentale per la Patologia Vegetale, Ministero dell'Agricoltura e delle Foreste, Rome, Italy, March 6-11, 1988, pp. 101–106.

Wilson, J.R.U., Gaertner, M., Richardson, D.M. & van Wilgen, B.W., 2017, 'Contributions to the National Status Report on Biological Invasions in South Africa', *Bothalia* 47(2), a2207. https://doi.org/10.4102/abc.v47i2.2207

Wilson, J.R.U., Ivey, P., Manyama, P. & Nänni, I., 2013, 'A new national unit for invasive species detection, assessment and eradication planning', *South African Journal of Science* 109(5/6), Art. #0111. https://doi.org/10.1590/sajs.2013/20120111

Winston, R.L., Schwarzländer, M., Hinz, H.L., Day, M.D., Cock, M.J.W. & Julien, M.H. (eds.), 2014, *Biological control of weeds: A world catalogue of agents and their target weeds*, 5th edition, FHTET-2014-04, USDA Forest Service, Forest Health Technology Enterprise Team, Morgantown, West Virginia.

Wood, A.R. & Morris, M.J., 2007, 'Impact of the gall-forming rust fungus *Uromycladium tepperianum* on the invasive tree *Acacia saligna* in South Africa: 15 years of monitoring', *Biological Control* 41, 68–77. https://doi.org/10.1016/j.biocontrol.2006.12.018

Zachariades, C., Strathie, L.W., Retief, E. & Dube, N., 2011, 'Progress towards the biological control of *Chromolaena odorata* (L.) R.M. King & H. Rob (Asteraceae) in South Africa', *African Entomology* 19, 282–302. https://doi.org/10.4001/003.019.0229

Zengeya, T., Ivey, P., Woodford, D.J., Weyl, O., Novoa, A., Shackleton, R. et al., 2017, 'Managing conflict-generating invasive species in South Africa: Challenges and trade-offs', *Bothalia* 47(2), a2160. https://doi.org/10.4102/abc.v47i2.2160

Zimmermann, H.G., 1979, 'Herbicidal control in relation to distribution of *Opuntia aurantiaca* Lindley and effect on cochineal populations', *Weed Research* 19, 89–93. https://doi.org/10.1111/j.1365-3180.1979.tb01580.x