Biocontrol Science and Technology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/cbst20

Prioritisation of targets for weed biological control II: the South African Biological Control Target Selection system

Iain D. Paterson, Martin P. Hill, Kim Canavan & Paul O. Downey

To cite this article: Iain D. Paterson, Martin P. Hill, Kim Canavan & Paul O. Downey (2021) Prioritisation of targets for weed biological control II: the South African Biological Control Target Selection system, Biocontrol Science and Technology, 31:6, 566-583, DOI: 10.1080/09583157.2021.1918637

To link to this article: https://doi.org/10.1080/09583157.2021.1918637

Published online: 29 Apr 2021.

BIOCONTROL SCIENCE AND TECHNOLOGY
2021, VOL. 31, NO. 6, 566–583
https://doi.org/10.1080/09583157.2021.1918637

RESEARCH ARTICLE

Prioritisation of targets for weed biological control II: the South African Biological Control Target Selection system

Iain D. Paterson[a], Martin P. Hill[a], Kim Canavan[a] and Paul O. Downey[b]

[a]Centre for Biological Control, Department of Zoology and Entomology, Rhodes University, Makhanda, South Africa; [b]Institute for Applied Ecology, University of Canberra, Australia

ABSTRACT

Invasive alien plants (IAPs) are considered one of the greatest threats to biodiversity in South Africa and are often associated with negative socio-economic and human health consequences. Biocontrol is seen as an effective strategy for managing IAPs however it can realistically only be considered for a subset of such plants given the limited funding resources available. Some plants are also better targets for biocontrol than others. This paper develops a prioritisation system to create an objective, transparent and easily usable method in which to target IAPs plants that are most suited to biocontrol in South Africa. The Biological Control Target Selection (BCTS) system builds on twelve previously developed prioritisation systems. The system uses three sections encompassing thirteen attributes that are combined to present the highest predicative powers to rank potential target IAPs as biocontrol targets.

ARTICLE HISTORY
Received 28 September 2020
Accepted 14 April 2021

KEYWORDS
Invasive alien plants; prioritisation; biocontrol of weeds; target selection system

Introduction

Invasive alien plant (IAP) species are considered one of the greatest threats to biodiversity worldwide (Higgins et al., 2008) and are often associated with other negative socio-economic and human health consequences (Pejchar & Mooney, 2009; Pimentel et al., 2001). The control of IAPs is generally implemented at a national level through responsible government bodies (Paynter et al., 2009; van Wilgen et al., 2012). One control strategy that is increasingly being adopted by governments is biological control (hereafter referred to as biocontrol). To date, 85 countries have authorised releases of over 400 biocontrol agents worldwide (Winston et al., 2014). South Africa has been one of the most active countries conducting and implementing biocontrol, with 59 IAPs being targeted (Zachariades et al., 2017). Since 1995, there has been an increase of funding and resources allocated to this management strategy (Zimmermann et al., 2004), which has allowed for more IAPs to be targeted, resulting in an impressive number of successes (Zachariades et al., 2017). With the ever-increasing threat and impacts of IAPs in South Africa more resources are expected to be put towards targeting new IAPs in the future (Van Wilgen & De Lange, 2011).

CONTACT Iain D. Paterson l.paterson@ru.ac.za Centre for Biological Control, Department of Zoology and Entomology, Rhodes University, P.O. Box 94, Makhanda, 6140, South Africa

A growth in the adoption of this management strategy needs to coincide with the strengthening of biocontrol practices to ensure the greatest chances of achieving success. A prioritisation system could help determine which plants should be targeted in South Africa based on the need for control and the likelihood that biocontrol will be successful. At present, there is no strategic decision-making framework to assist in prioritisation of targets for biocontrol in South Africa. This paper provides such a tool through the establishment of the Biological Control Target Selection (BCTS) system. The system builds on previously developed prioritisation systems to factor in attributes that are likely to be best suited for this region and have the greatest predictive power (Downey et al., in press). The system has recently been applied to alien plants listed as regulated species under the South African Government Notice R. 598 National Environmental Management: Biodiversity Act (10/2004) (NEMBA): Alien and Invasive Species Regulations, 2014, to produce a list that ranked the regulated species according to their priority for implementation of biocontrol in South Africa (Canavan et al., in press).

The Biological Control Target Selection (BCTS) system

To construct the Biological Control Target Selection (BCTS) system for South Africa, all previous systems were reviewed to determine suitable assessment criteria and attributes (Downey et al., in press). Based on this review, 19 key attributes were identified and evaluated for the construction of the BCTS. The 19 attributes were consolidated into 13 attributes and were grouped into 3 sections: the impact/importance of the target plant for biocontrol, likelihood of achieving successful biocontrol and the investment required (Table 1).

Information for populating the BCTS system was acquired through a desktop study using available knowledge from peer-reviewed literature or other available resources. A quantitative scoring system was used to populate the system whereby a value was assigned to each attribute from a range of scores with the highest score implying the highest priority. To overcome the known drawbacks of a purely quantitative approach, each score was accompanied by a written rationale and references (Canavan et al., in press).

Table 1. The 13 attributes identified for construction of the Biological Control Target Selection system grouped into 3 sections.

Section	Attribute	Possible scores
1. Impact/importance of the target plant	1A. Threat or impact posed by the target plant	1, 2, 4, 6, 8, 10
	1B. Geographic distribution	1, 2.5, 5, 7.5, 10
	1C. Alternative control options	1, 5, 10
	1D. Conflicts of interest	1, 5, 10
2. Likelihood of achieving success	2A. Success elsewhere of biocontrol programmes on the target plant	1, 3, 6, 8, 10, 12, 14, 16, 18, 20
	2B. Ecosystem	5, 10
	2C. Reproduction	5, 10
	2D. Weed of cultivation	5, 10
	2E. Life cycle	5, 10
3. Investment required	3A. Uncertainty of plant origin or taxonomy	1, 10
	3B. Information on natural enemies	1, 5, 10
	3C. Sourcing agents	1, 3, 6, 10
	3D. Potential to find host specific agents	1, 10

Section 1: impact/importance of the target plant

Section 1 addresses the target plant's status in South Africa in terms of its impact, distribution, availability of alternative control measures and any conflicts of interest. A significant requirement for determining the potential for biocontrol of a plant target is based on the negative impact of the alien plant and the need to use biocontrol rather than other control measures.

Attribute 1A – threat or impact posed by the target plant

Attribute 1A addresses the negative consequences that may occur due to the target plant invasion, and includes economic, social and environmental impacts and threats. Here, we have adopted the definitions of threat and impact by Downey et al. (2010) where threat indicates a possible danger (or exposure to harm), combined with the likelihood of that harm occurring; and impact is the actual effects that the alien plant has.

In addition, one of the 'best predictors' of an alien plant's invasive ability is its alien status elsewhere (Gordon et al., 2008) and as such we have included this component within the attribute. The scoring of attribute 1A is based on priority being given to an alien plant with a recorded impact over one where only a threat has been recorded. In using Downey et al.'s (2010) definitions the impact should be measurable, whilst the threat may be assumed, thus in selecting a score here, documented justification (if available) should be referenced (i.e. the impact or threat as recorded by a published study). The level of impact can then be assessed using the classification proposed by Blackburn et al. (2014). Blackburn et al. (2014) designate impacts based on 12 impact classes according to semi-quantitative scenarios. According to the scenarios, a species is assigned to one of five categories of impact; minimal (ML), minor (MI), moderate (MO), major (MR) and massive (MA) based on evidence of impact in any one of the 12 classes. Such a classification was aligned with the scoring of this attribute (Table 2). Impacts or threats recorded in South Africa were considered a higher priority than those recorded elsewhere in the world; with the 'elsewhere in the world' criteria providing an indication of the potential which may, or may not, be realised in South Africa in future.

Eleven of the previous systems developed to prioritise targets for biocontrol included impact and/or weed importance attributes, with the majority only considering certain types of impacts (e.g. economic, environmental or social) (Downey et al., in press).

Attribute 1B – geographic distribution

Attribute 1B addresses the geographic extent of the target plant in South Africa. Alien plant species with wider distributions are likely to have greater negative consequences (threats and impacts) than ones with narrower distributions. The number of locations

Table 2. Scoring categories for attribute 1A.

Score	Attribute 1A: Threat and impact posed by the target plant
1	No record of a threat or having an impact anywhere in the world.
2	Recorded as a threat in another country but the target plant is not yet naturalised.
4	Recorded impact in another country but the target plant is not yet naturalised.
6	The target plant poses a threat or has minimal/negligible impact.
8	The target plant has a minor or moderate level impact.
10	The target plant has a major or massive impact.

at which an alien plant has been recorded to have naturalised and the geographical pattern of these locations can therefore be used as a proxy to indicate the species extent and is a reasonable predictor of a negative impact and desirability to utilise biocontrol (Table 3).

Determining the geographic distribution of an alien plant will also give an indication of the appropriate control methods. There is a strong evidence that eradication of alien species is only possible when the number of localities and distribution in the introduced range are very limited (Genovesi, 2005; Rejmánek & Pitcairn, 2002; Renteria et al., 2017). The lowest score in this attribute is intended for species where the possibility of eradication exists. Ten recorded locations are seen as the absolute maximum number of sites where eradication could be possible. Rejmánek and Pitcairn (2002) found that one third of eradications were successful for species with distributions of less than 100 ha and that eradication was extremely unlikely for populations above 1000 ha. Importantly, the only species that had been successfully eradicated completely were those found at only one site of less than 1 ha (Rejmánek & Pitcairn, 2002) indicating that the number of sites chosen for the lowest score of this attribute is conservative and could be even lower. Another key component of eradication success is the number of distinct infestations (Panetta & Timmins, 2004). Thus the more 'clumped' the infestations of an alien plant the greater the likelihood of achieving eradication. Alien plants with dispersed infestations are not considered suitable eradication targets. Although there have been successful plant eradications from larger areas, such successes have often been due to exceptional circumstances that were favourable to eradication (see Dodd, 2004) or they occurred on islands (Mack & Lonsdale, 2002).

Expected spread is not explicitly dealt with as a separate attribute in the BCTS system because for most alien plants this data is not available, so the inclusion of this attribute would limit the number of plants that could be prioritised by the system. However, the system is intended to be updated as new information is made available and, therefore, species that experience an increase in distribution should have this information updated and thus be given a higher score as a result.

The scoring system uses the number of localities recorded for the alien plant in question. There are three categories, being (1) <10 localities – eradication may be possible with other methods (2) 10–50 localities – effective control with other techniques may still be achievable, and (3) >50 localities – biocontrol is required to play a significant role in reducing the invasiveness of the species because it is widely established. In addition, we have tried to encompass some assessment of the extent of these locations as a proxy of the spread and ability to achieve effective control (i.e. locations that are spatially clumped and more likely to be controlled using other control methods than those which are geographically dispersed). Target plants are considered to have

Table 3. Scoring categories for attribute 1B.

Score	Attribute 1B: Geographic distribution
1	Naturalised at 10 or less locations.
2.5	Naturalised at >10 and <50 locations, geographically clumped (within one municipal area)
5	Naturalised at >10 and <50 locations, geographically dispersed (across multiple municipal areas)
7.5	Naturalised at ≥50 locations, geographically clumped (within one biome and province)
10	Naturalised at ≥50 locations, geographically dispersed (across multiple biomes and provinces)

clumped distribution if their populations fall within one municipal area and thus management could take place under one administration. For targets found at more than 50 localities, those found in more than one of the eight major biomes (vegetation types) or provinces of the country were considered dispersed (Table 3). The extent or distribution of the alien plant in a region was considered in nine of the previous prioritisation systems in various forms (Downey et al., in press).

Attribute 1C – alternative control options

Attribute 1C assesses the availability of alternative control methods for the target plant which should assist in screening out species that have no viable options for herbicide or manual control. Alternative control methods can be ineffective or exorbitantly expensive for a number of reasons. This attribute gives priority (score of 10) to target plants with particular traits that make control difficult or even impossible (Table 4). The decision on control method is highly dependent on the species growth form (Weidlich et al., 2020), we recognise the following growth forms as those that would likely impede control efforts if mechanical/physical removal or herbicides were used: creeping and rooting stems (groundcover plants), epiphytes, deep-rooted rhizomes or tubers, submerged aquatic plants, trees with suckering roots and vines. Such growth forms can often not be sustainably controlled using manual or chemical control, for example, *Anredera cordifolia* (Ten.) Steenis (Basellaceae), produces prolific stem-tubers which are easily dislodged resulting in dense re-growth after clearing attempts (Van der Westhuizen, 2011) and the vines of *Pereskia aculeata* Mill. (Cactaceae) grow intertwined with native vegetation which makes it very difficult to remove or spray without damaging other plant species that are present (Paterson et al., 2011).

This attribute also prioritises target plants that grow in areas or habitats where alternative control methods are not possible or feasible. Certain habitats within South Africa may not be conducive to control operations due to inaccessibility, such as high altitude mountainous habitats. Similarly, if an area is ecologically sensitive whereby any non-targets effects to the native vegetation or landscape is deemed unacceptable, then alternative control options would largely be prohibited, and the plant is given a high score.

The lowest score in this attribute (score of 1) is intended for plants that represent good targets for eradication and is only considered for plants that have low populations in South Africa (lowest score from attribute 1B). If eradication is a possibility then biocontrol should not be considered until all attempts at eradication have failed. The feasibility of eradication is assessed for each species based on current literature on their control and invaded habitat in South Africa and the plant's growth form (see above) as these are recognised as important factors to successful control (Renteria et al., 2017; Simberloff, 2003).

Table 4. Scoring categories for attribute 1C.

Score	Attribute 1C: Alternative control options
1	Substantial or complete control can be achieved without the need for biocontrol measures in a cost effective manner
5	Partial control can be achieved without the need for biocontrol measures in a cost effective manner
10	Limited or no control can be achieved in a cost effective manner without biocontrol

The scoring in this section should place the majority of the target plants in the middle criteria (score of 5) with only the targets with no other control options being given the highest score (10). Other available control methods were taken into consideration in five of the previous prioritisation systems (Downey et al., in press).

Attribute 1D – conflicts of interest

Attribute 1D evaluates the current cultural and economic value of the target plant to determine if there are any conflicts of interest that may occur if biocontrol were to be initiated. Conflicts of interest can occur if an alien plant is targeted for control but there are value disagreements including utilitarian, humanistic (cultural or spiritual value), and aesthetic values (Novoa et al., 2017). Such conflicts of interest have significantly delayed and even stopped some biocontrol programmes (Turner, 1985). For example, the *Echium plantagineum* L. biocontrol programme in Australia was halted between 1981 and 1988 due to a conflict with apiarists (Piggin & Sheppard, 1995). Thus, all potential conflicts need to be assessed and evaluated prior to the initiation of a biocontrol programme to avoid unnecessary costs and delays.

The complexity of determining conflicts of interest is acknowledged within this attribute and is reflected in the different scoring options (Table 5). In some cases, it is possible for commercially valuable plants to be targeted by biocontrol without any negative impacts to their value. There are a number of examples of biocontrol being initiated on IAPs despite their commercial value when releases can be made that will not affect the quality of the end product. For example, the control of *Acacia mearnsii* De Wild. (Mimosaceae) in South Africa which has two well-established agents that dramatically reduce seed set but do not result in any loss of quality or quantity of wood production for which *A. mearnsii* is commercially grown (Impson et al., 2008). However, reducing the number of seed produced can greatly limit the spread and establishment of this IAP outside of forestry operations. For other target plants, it may be unlikely that the conflict of interest could be resolved because any damage by the biocontrol agent to the plant is likely to result in a reduction of the plant's value to the industry. For example, plants that are grown commercially for seeds or fruit. For the purpose of scoring this attribute, commercially grown plants that are not used for flowers, fruits or seeds can generally be scored 5, while plants where the flowers, fruits, or seeds are harvested should be scored 1.

A score of 5 is also given for target plants that have recorded cultural/aesthetic value, legislated exemptions for cultivation under certain conditions or anticipated future commercial uses in South Africa. The invasive species regulations of South Africa contains exemptions for some alien plant species (mostly ornamentals) including the exception

Table 5. Scoring categories for attribute 1D.

Score	Attribute 1D: Conflicts of interest
1	The target plant is grown commercially or is highly valued and <u>all</u> options for biocontrol are likely to have a negative effect on its' production/use.
5	The IAP is grown commercially however biocontrol options are unlikely to result in negative effects on the production of such species <u>or</u> has been targeted for new uses <u>or</u> has cultural/aesthetic value <u>or</u> has exemptions to be traded or grown under NEMBA.
10	There are no known conflicts of interest (commercial or otherwise) associated with the target plant <u>or</u> it is not yet introduced to the country.

for the trade of 'sterile cultivars or hybrids' within some provinces; and the designation of National Heritage Trees (depending on area or size). Plants under these exemptions have commercial or other value under these specifications (Department of Environmental Affairs, 2014). Biocontrol would likely present some level of conflict for these species as it cannot be constrained to one area or one cultivar and thus might impact these exempt populations.

Some alien plants may hold little commercial value but have important social or cultural value (Zengeya et al., 2017). The cultural value of plants in South Africa can include those used for traditional medicine; in South Africa, an estimated 30,000 plant species are used for herbal medicine (Van Wyk et al., 1997) including many IAPs (Lewu & Afolayan, 2009). Another area of potential conflict lies in plants that are currently under consideration for future uses including biofuels and bioremediation. For example, globally many bamboo species are now seen as 'miracle crops' with the development of new processing techniques and applications, the use and therefore cultivation of these plants is expected to greatly increase (Canavan et al., 2017). Assessing these plants should take note of how biocontrol may impact their value and whether or not any damage to the plants would be considered unacceptable (score of 1 if biocontrol is likely to be unacceptable to a valued part of plant).

Non-commercial plants are generally less problematic conflict of interest species. This includes target plants that are restricted from commercial trade however may continue to be exchanged and planted. For example, *Lilium formosanum* Wallace (Liliaceae) is listed as a category 1b under NEMBA which restricts any cultivation of the species (NEMBA, 2014), however, the plants continue to be used as ornamentals in South Africa (Henderson, 2001). Although these species may have some value their restriction from being commercially traded with no exemptions likely indicates a reduced chance of conflict. Such species were assessed individually on whether or not this value would likely interfere with biocontrol efforts. Target plants that show no signs of conflicts of interest such as agricultural weeds and species not yet introduced into a country but listed as prohibited species were given the highest possible score (score of 10).

Conflicts of interest are taken into account in ten of the previous prioritisation systems (Downey et al., in press). If all other attributes suggest that a conflict of interest species is a high priority for biocontrol then it should still be considered a potential target. In this case, resolution of the conflict of interest should be the first priority of the biocontrol programme.

Section 2: likelihood of achieving success

Section 2 focuses on attributes that are considered good predicators of successful biocontrol programmes. The section includes an assessment of biocontrol of the target plant and congeners elsewhere in the world, and plant traits that are correlated with improved success rates.

Attribute 2A – success of biocontrol programmes elsewhere

This attribute examines whether or not any biocontrol programmes have been initiated for the target plant elsewhere in the world. One of the best predictors of whether a biocontrol agent might be successful in the country of interest, is assessing the outcome of any biocontrol programmes that may exist elsewhere (Crawley, 1989; Paynter et al., 2009). In addition, when biocontrol has been initiated elsewhere this will help reduce the cost of a potential programme as the prior work conducted will help with a number of aspects of a project such as reducing the number of host plants needed for testing (Paynter et al., 2009).

Included within this attribute is an assessment of whether or not congeners have also had biocontrol programmes initiated on them. Successful biocontrol of a closely related weed species is a strong predictor that the target weed will be susceptible to biocontrol (Crawley, 1989; Paynter et al., 2009). Phylogenetically related plants are likely to have analogous plant traits and thus have similar plant–herbivore interactions and host-range patterns (Pearse & Hipp, 2009: Zachariades et al., 2017). There are certain groups of related plants that have shown to be good targets for biocontrol, such as *Opuntia* spp. (Cactaceae) and *Acacia* spp. (Fabaceae) (Klein, 2011). As such, in identifying congeneric plants that have had biocontrol, it will be possible to get a better indication of how susceptible a target plant may be. Congeners are only considered here if they have had recorded impacts elsewhere.

The highest score for this attribute is given to target plants that have had successful control using biocontrol agents elsewhere (recorded as having a heavy impact) and also have congeners that have been successfully controlled. The lowest score is assigned to target plants where the agents have failed to establish or provide any level of control elsewhere and also have had failed programmes on congeners (Table 6).

Novel alien plant targets are given the same score as biocontrol targets that have not had any recorded impacts (score of 6), given they may or may not be successful and in turn this will ensure novel targets are not underestimated compared to IAPs with existing programmes elsewhere. Most of this information can be sourced from the comprehensive review of biocontrol projects globally (Winston et al., 2014), which is frequently updated and available online (www.ibiocontrol.org/catalog/). As such the scoring is a reflection of the categories of impact given to each programme in this resource.

Success with biocontrol elsewhere in the world was used in eleven of the previous prioritisation systems (Downey et al., in press). Evaluating precedent in biocontrol programmes is considered the best predictor of successful biocontrol (Paynter et al., 2009)

Table 6. Scoring categories for attribute 2A.

Score	Attribute 2A: Successful biocontrol programmes elsewhere
1	Target plant was a target without success and has had congeners targeted without success.
3	Target plant was a target without success and has had congeners targeted with success.
6	Novel target or biocontrol target elsewhere and has had no impacts, too early to evaluate, or programme was compromised.
8	Novel target or biocontrol target elsewhere and has had no impacts, too early to evaluate, compromised and has had congeners with success.
10	Target plant has had a biocontrol programme initiated with slight or variable impacts.
12	Target plant has had a biocontrol programme initiated with slight or variable impacts and has had congeners with success.
14	Target plant has had a biocontrol programme initiated with medium impacts.
16	Target plant has had a biocontrol programme initiated with medium impacts and has had congeners with success.
18	Target plant has had a biocontrol programme initiated with high impacts.
20	Target plant has had a biocontrol programme initiated with high impacts and has had congeners with success.

and therefore a higher total score of 20 was given to ensure a high weighting in the calculation of the BCTS score (see Section 3.4 below).

Attribute 2B – ecosystem

Attribute 2B assesses the ecosystem in which the target plants are invading in South Africa and classifies them according to whether they are aquatic (emergent, floating, or submerged) and wetland plants (plants that are in areas that subject to regular seasonal flooding, for example, *Mimosa pigra* L. (Paynter & Flanagan, 2004)) or terrestrial plants (Table 7). Many of the world's most successful biocontrol programmes have been against aquatic and wetland weeds (Winston et al., 2014). This was further confirmed by Paynter et al. (2012), where aquatic plants were found to have a statistically significant higher probability of successful biocontrol. Consideration of the target plant's invaded ecosystem was included in five of the previous prioritisation systems (Downey et al., in press).

Attribute 2C – plant reproduction

The reproductive mode of an alien plant has been found to be related to the success of a biocontrol programme (Burdon & Marshall, 1981; Paynter et al., 2012). Plants that can only reproduce asexually and are, therefore, clonal have been found to have a greater chance of being controlled using biocontrol agents (Paynter et al., 2012). Two levels of reproduction were considered here, according to the methods used in Paynter et al. (2012) (Table 8). Asexual was assigned to target plants that can only reproduce by vegetative means or by apomixis. Sexual (score of 10) was assigned to target plants that can reproduce sexually (including those that can also use vegetative reproduction). The reproductive mode within South Africa was assessed, so plants that were limited to asexual reproduction in South Africa but could reproduce both sexually and asexually in the native distribution were given the higher score. This attribute was included in five previous systems (Downey et al., in press).

Attribute 2D – habitat stability

The stability of the habitat in which a target plant invades is an important consideration in the likelihood of success for a programme. For a biocontrol agent to be successful, it needs to establish and persist on the IAPs. Target plants that occupy areas that are frequently disturbed such as cultivated land and improved pastures are less likely to sustain adequate biocontrol agent populations (McClay, 1989). Assessments of the relationship between habitat stability and biocontrol success have indicated that this attribute can improve biocontrol target selection (Paynter et al., 2012) and an evaluation of South African biocontrol programmes has supported these conclusions (Downey et al., in press). For this attribute, target plants that predominantly occupy relatively undisturbed habitats in South Africa are given a higher score (Table 9). Habitat stability was considered in seven of the previous prioritisation systems (Downey et al., in press).

Table 7. Scoring categories for attribute 2B

Score	Attribute 2B: Ecosystem
5	Terrestrial
10	Aquatic/wetland

Table 8. Scoring categories for attribute 2C.

Score	Attribute 2C: Plant reproduction
5	Sexual reproduction: target plants are capable of sexual reproduction, including those that can also reproduce vegetatively.
10	Asexual reproduction: target plants can only reproduce by vegetative means or apomixis

Attribute 2E – life cycle

Attribute 2E assesses the target plant's life cycle whereby plants that are annual have been found to be more difficult to control compared to biennial and perennial plants (Chaboudez & Sheppard, 1995; McClay, 1989; Paynter et al., 2012). Biocontrol on annuals can only be successful if biocontrol agents are able to impact seed production within a single growing season (McClay, 1989). In South Africa, almost all biocontrol programmes have been focused on biennial or perennial plants. Only one annual IAP has been targeted for biocontrol, *Silybum marianum* (L.) Gaertn. (Asteraceae), and the biocontrol agent failed to establish (Winston et al., 2014). A lower score is, therefore, given to annuals than to biennials and perennials in this attribute (Table 10). This attribute was included in seven previous systems (Downey et al., in press).

Section 3: investment required

Section 3 aims to account for the research effort required in a biocontrol programme that will ultimately influence the costs, and hence investment and feasibility of the programme. If costs are too high then it is possible that programmes may run out of funding and fail (Paynter et al., 2009). Less expensive programmes should, therefore, be given preference over more expensive programmes but the potential benefits (i.e. the chances of success combined with the negative impacts of the alien plant) must be taken into account. The attributes outline steps within a biocontrol programme that are seen as limiting factors in developing a successful programme.

Attribute 3A – uncertainty of plant origin or taxonomy

Attribute 3A addresses the importance of information regarding the native distribution and taxonomic status of a target plant in biocontrol efforts. These factors can significantly increase the cost and time required to implement a biocontrol programme given the research required to overcome any data deficiencies or taxonomic uncertainties.

Plants are regarded as having taxonomic uncertainty when they have had known hybridisation events with congeners in South Africa, artificial selection to create hybrid cultivars that do not naturally occur in wild populations and are naturalising in South Africa, or there is uncertainty in their taxonomic delimitation that would have

Table 9. Scoring categories for attribute 2D.

Score	Attribute 2D: Habitat stability
5	Target plant is found predominantly in cultivated lands or improved pastures.
10	Target plant is not found in cultivated land or improved pastures.

Table 10. Scoring categories for attribute 2E.

Score	Attribute 2E: Plant life cycle
5	Target plant is an annual.
10	Target plant is a biennial or perennial.

biological significance to finding biocontrol agents. Plants selected for horticulture can be artificially selected for resulting in complexes of taxonomic units that do not exist naturally (Urban et al., 2011). Sourcing suitable agents for these species can be problematic because natural enemy populations adapted to the horticultural varieties may not exist. For example, *Lantana camara* L. (Verbanaceae) and its cultivars have had a complex horticultural history of breeding within and between cultivars and wild species that has created a cryptic systematic complex (Sanders, 2006). This has negatively impacted biocontrol against invasive *L. camara* cultivars; in South Africa, 26 agents have been released, however, most are specific to one or two varieties of the plant and thus managing the invasive potential of all populations has been challenging (Urban et al., 2011). The solution is usually to conduct a genetic study to gain an understanding of the history of the varieties and origins of the alien plants in question (Gaskin et al., 2011; Ward et al., 2008). These studies, while commendable, increase the cost and time required to implement biocontrol and there are some cases that do not result in clear answers or solutions to the problem.

An essential step in the development of a biocontrol programme is to conduct surveys for natural enemies in the native range of the target plant. Knowledge of the correct region of origin is therefore required for a successful biocontrol programme. Yet for some target plants, the origin and native distribution may be unknown, such as in cosmopolitan or widespread species like *Myriophyllum spicatum* L. (Haloragaceae), for which the status as either an indigenous or alien species in Africa is disputed due to its almost global distribution (Weyl & Coetzee, 2014). Genetic studies to determine the origin of IAP populations are now standard practice for most new biological control programmes but locating the region of origin of very widespread alien species can be more difficult and this is compounded when the species has been present in a country for so long that it may be considered native. Uncertainty in an IAP's native range would require genetic studies to determine the source area however, again this will add both time and cost to a biocontrol project. Furthermore, such genetic studies do not always result in definitive answers on the source of alien plant populations (Weyl et al., 2016).

Seven previous systems addressed the problems of taxonomic uncertainty and lack of knowledge of the native range in some form (Downey et al., in press). For example, Paynter et al. (2009) assessed this under the attribute 'Difficulty of targeting multiple forms of the weed' (Table 11).

Table 11. Scoring categories for attribute 3A.

Score	Attribute 3A: Uncertainties relating to the alien plant
1	Taxonomic status of the target plant is uncertain and/or in debate, and/or the origin (or native distribution) of the target is uncertain and/or in debate
10	The origin (or native distribution) and taxonomic status of the target plant are known

Attribute 3B – information on natural enemies

Attribute 3B addresses the advantage of having prior knowledge and research on the natural enemies of a target plant as it influences the initial development costs of a biocontrol programme. Target plants with the available literature on natural enemies are likely to require less research and thus incur fewer costs compared to targets with no prior knowledge of herbivores or other natural enemies such as pathogens. This attribute accounts for varying levels of intensity of research into the natural enemies of the target plant (Table 12). Literature containing information on prospective biocontrol agents including research into their life-cycle, distribution and behaviour of natural enemies, would add great value to a prospective programme. If this information is available then much of the preliminary work in biocontrol has been conducted and thus there is a better chance of successfully importing, rearing and conducting host-specificity on agents. As such, target plants that have undergone research that will be useful for biocontrol (e.g. knowledge of host-specific agents) are prioritised here. For some target plants, studies exist on the herbivores associated with the plant due to academic interests that are not directly relevant to biocontrol. Such research may not contain specific information on prospective biocontrol agents, however, the availability of information on natural enemies will still add some value to a project, particularly for providing baseline information for surveys for potential agents in the native range. For target plants that have records of natural enemies, an intermediate score of 5 is given. This attribute has been included in some way in ten previous prioritisation systems (Downey et al., in press).

Attribute 3C – Sourcing agents

Attribute 3C assesses the effort required to conduct surveys for potential biocontrol agents in the indigenous distribution of the target weed. Exploration within native ranges is a critical initial component of classical biocontrol of weeds and difficulties encountered here can often limit the ability to conduct a programme (Goolsby et al., 2006; Sheppard et al., 2006). This stage of a biocontrol programme is often limiting because it can be restrictively expensive, logistically difficult and is sometimes constrained by administrative problems, such as acquiring permits (Silvestri et al., 2020).

The levels of safety, infrastructure and the presence of biocontrol research organisations in the region of origin are used in this attribute to determine the level of effort, to source potential biocontrol agent populations (Table 13). The highest score is given when a biocontrol agent is already available in a biocontrol laboratory and can thus be directly sourced and this takes away the need for a collection trip or surveys. A high score (score of 6) is also given if there is an active biocontrol laboratory or research institute with the capacity to assist in survey efforts in the country of origin. These facilities can help in terms of safety and logistics of the collection trip but can also help with the procurement of permits to collect and export live organisms. Procurement of permits is

Table 12. Scoring categories for attribute 3B.

Score	Attribute 3B: Information on natural enemies
1	There is no literature or information regarding natural enemies of the target plant.
5	There has been some research on the natural enemies of the target plant.
10	There is substantial literature or information regarding natural enemies of the target plant that would assist in biocontrol efforts.

Table 13. Scoring categories for attribute 3C.

Score	Attribute 3C: Sourcing agents
1	The native distribution spans 'unsafe' country/ies and/or the native distribution encompasses country/ies with very limited infrastructure (specifically relating to biocontrol research facilities/units), and/or the native distribution is unknown.
3	The native distribution is safe and reasonably developed but there is no biocontrol research facility/unit in the country.
6	The native distribution is safe and reasonably developed and there is an active biocontrol lab or research facility in the country.
10	Surveys/collection trips to the native distribution are not required because a biocontrol research facility/unit has a culture/source of the potential agent/agents.

more and more regarded as a limiting factor for biocontrol programmes (Silvestri et al., 2020). The relatively large difference in score for when a biocontrol laboratory is present or not present (3 points) reflects the significant advantages that such a laboratory in the native distribution brings to a biocontrol programme.

When no biocontrol facilities exist in the native range, a review of the infrastructure and safety of the native range is conducted. Scoring is then given according to whether or not the country is safe to conduct research and has sufficient infrastructure (score of 3) or has limited infrastructure and poor safety that would hamper efforts to perform surveys (score of 1).

In cases where the native distribution of the target plant is unknown, the lowest possible score is given. Plants with unknown native distributions will, therefore, receive low scores from this attribute as well as in attribute 3A. The compounding effect on target weeds with unknown distributions is not a flaw in the system because very few target plants will fit into this category and because not knowing the native distribution of a target plant is a major problem in a biocontrol programme that is very difficult to overcome, so a high weighting is justified. This attribute was included in seven of the previous systems (Downey et al., in press). Syrett (2002) and Paynter et al. (2009) used this attribute in a very similar way to how it is used here.

Attribute 3D – potential to find host-specific agents

Attribute 3D aims to prioritise target plants that are likely to have natural enemies that will be suitably host specific for release in South Africa. Native plants in the same genus as target weeds are much more likely to be suitable hosts for natural enemies than more distantly-related plant species (Pemberton, 2000). The most common reason that potential biocontrol agents are rejected is that the agent is not suitably host specific and in most cases can feed on congeneric species (Suckling et al., 2014). In South Africa, 24% of agents imported into quarantine were rejected based on the results of host specificity studies (Klein, 2011). Identifying if there are closely related plant species to the target alien plant in South Africa is therefore seen as a good predictor of the chances of finding a suitably specific biocontrol agent (Table 14).

Table 14. Scoring categories for attribute 3D.

Score	Attribute 3D: The potential to find a suitably specific agent
1	There are native or commercially valuable congeners of the target plant in South Africa.s
10	There are no native or commercially valuable congeners of the target plant in South Africa.

It is important to acknowledge that the presence of congeners has been found to have little effect over the success of biocontrol programmes but rather a factor in pre-release efforts (extending host specificity and getting approval from risk-averse authorities) (Paynter et al., 2012). For example, two chrysomelid species, *Leptinotarsa texana* Schaeffer and *L. defecta* Stel were released on *Solanum elaeagnifolium* Cavanilles (Solanaceae) despite the presence of native congeners including important crops in South Africa (Olckers et al., 1999). In light of this, this attribute is not weighted heavily in the BCTS so as not to discount target plants with native congeners completely. This attribute was the only one to be included in all previous prioritisation systems in some form (Downey et al., in press).

The system

The BCTS system for ranking the suitability of alien plants as potential targets for biocontrol is presented below:

$$\text{BCTS index} = \underbrace{(1A+1B+1C+1D)}_{\text{Section 1}} \times ((\underbrace{2A+2B+2C+2D+2E}_{\text{Section 2}}) + (\underbrace{3A+3B+3C+3D}_{\text{Section 3}}))$$

Section 1 of the BCTS assesses the need for biocontrol and will result in IAPs that are not problematic or can be effectively controlled using other management techniques being given lower priority. Targets that do not require biocontrol should not be targeted even if there is a high chance of success and little investment required. In contrast, targets that have significant negative impacts and require biocontrol should be targeted even if the chances of success are relatively low and significant investments are required. The score obtained in Section 1 is, therefore, multiplied by the sum of the scores for the two other sections, thereby effectively weighting it and increasing the importance of Section 1 in calculating the BCTS index value.

- Sections 2 and 3 are not weighted in the BCTS system as they are considered of less importance than Section 1. Section 2, which assesses the likelihood of success, is considered relatively more important than Section 3, which assesses the investment required, so the maximum score for Section 2 is 60, while the maximum score for Section 3 is 40. Greater investment is therefore acceptable if the chances of controlling the target weed are high.
- The possible scores for each attribute and section are provided in Table 1. The minimum total score that is possible is 24 and the maximum total score is 4000.

Conclusion

The BCTS system is intended as a tool for the selection of biocontrol targets for South Africa, but it also contributes towards a growing body of literature that aims to improve how biocontrol targets are selected more generally. In a South African context, this system should help bridge gaps between funding bodies and the scientific community, and should help justify the use of funding on selected targets and explain why some problematic IAPs are not, and should not, target for biocontrol. The goal of this work was to develop a model that is easily applicable, transparent and adaptable to change. This model has all of these properties.

The BCTS system has been validated through its application to all the regulated plant species listed in the South African invasive species legislation (Canavan et al., in press). When applying the system, all attributes could be scored based on available data which shows that it is possible to answer all the questions for most IAPs with reasonable certainty (Canavan et al., in press). The inclusion of each of the attributes in the system, as well as the exclusion of others, are justified in this paper and in Downey et al. (in press), which presented a review of previous prioritisation systems used for similar purposes. We are, therefore, confident in the predictive power of the system to rank targets for biocontrol in South Africa.

The BCTS is not definitive and there will be inherent uncertainty in many of the attributes assessed due to lack of information. We have attempted to be as transparent as possible in presenting the system, showing the logic and justification behind decisions to include or exclude various attributes as well as for the weighting of each attribute and the BCTS index equation. In addition, it is intended that this prioritisation work evolves and incorporates new information as it becomes available.

Acknowledgments

This work was undertaken as part an Outside Study Program (OSP) in which POD was relieved from teaching responsibilities at the University of Canberra. POD undertook part of this programme at Rhodes University. The authors thank Guy Sutton, Philip Weyl, Grant Martin, Steve Compton for their valuable feedback. Any opinion, finding, conclusion or recommendation expressed in this material is that of the authors and the NRF does not accept any liability in this regard. We thank three anonymous reviewers for helpful comments and suggestions that improved this paper.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work is supported by funding from the South African Working for Water (WfW) programme of the Department of Environment, Forestry and Fisheries: National Resource Management (DEFF: NRM) programmes. Funding was also provided by the South African Research Chairs Initiative of the Department of Science and Technology and the National Research Foundation of South Africa.

ORCID

Martin P. Hil http://orcid.org/0000-0003-0579-5298

References

Blackburn, T. M., Essl, F., Evans, T., Hulme, P. E., Jeschke, J. M., Kühn, I., Kumschick, S., Marková, Z., Mrugała, A., Nentwig, W., Pergl, J., Pyšek, P., Rabitsch, W., Ricciardi, A., Richardson, D. M., Sendek, A., Vilà, M., Wilson, J. R. U., Winter, M., … Bacher, S. (2014). A unified classification of alien species based on the magnitude of their environmental impacts. *PLoS Biology*, *12*(5), e1001850. https://doi.org/10.1371/journal.pbio.1001850

Burdon, J., & Marshall, D. (1981). Biological control and the reproductive mode of weeds. *The Journal of Applied Ecology*, *18*(2), 649–658. https://doi.org/10.2307/2402423

Canavan, K., Paterson, I. D., Ivey, P., Sutton, G. F., & Hill, M. P. (in press). Prioritisation of targets for weed biological control III: A tool to identify the next targets for biological control in South Africa and set priorities for resource allocation. *Biocontrol Science and Technology*.

Canavan, S., Richardson, D. M., Visser, V., Le Roux, J. J., Vorontsova, M. S., & Wilson, J. R. (2017). The global distribution of bamboos: Assessing correlates of introduction and invasion. *AoB Plants*, *9*(1), plw078.

Chaboudez, P., & Sheppard, A. (1995). *Are particular weeds more amenable to biological control? A reanalysis of mode of reproduction and life history*: *Proceedings of the Eighth International Symposium on Biological Control* (pp. 95–102). DSIR/CSIRO, Montpellier, France.

Crawley, M. (1989). The successes and failures of weed biocontrol using insects. *Biocontrol News and Information*, *10*(3), 213–223.

Department of Environmental Affairs. (2014). *The National Environmental Management: Biodiversity Act (10/2004): draft alien and invasive species list*. Government Gazette.

Dodd, J. (2004). *Kochia (Bassia scoparia (L.) AJ Scott) eradication in Western Australia: a review*: *Proceedings of the 14th Australian Weeds Conference* (pp. 496–499), Department of Agriculture Western Australia, Australia.

Downey, P. O., Paterson, I. D., Canavan, K., & Hill, M. P. (in press). Prioritisation of targets for weed biological control I: A review of existing prioritisation schemes and development of a system for South Africa. *Biocontrol Science and Technology*.

Downey, P. O., Scanlon, T. J., & Hosking, J. R. (2010). Prioritizing weed species based on their threat and ability to impact on biodiversity: A case study from New South wales. *Plant Protection Quarterly*, *25*(3), 111–126.

Gaskin, J. F., Bon, M. C., Cock, M. J. W., Cristofaro, M., De Biase, A., De Clerck-Floate, R., Ellison, C. A., Hinz, H. L., Hufbauer, R. A., Julien, M. H., & Sforza, R. (2011). Applying molecular-based approaches to classical biological control of weeds. *Biological Control*, *58*(1), 1–21. https://doi.org/10.1016/j.biocontrol.2011.03.015

Genovesi, P. (2005). Eradications of invasive alien species in Europe: A review. *Biological Invasions*, *7*(1), 127–133. https://doi.org/10.1007/s10530-004-9642-9

Goolsby, J. A., De Barro, P. J., Makinson, J. R., Pemberton, R. W., Hartley, D. M., & Frohlich, D. R. (2006). Matching the origin of an invasive weed for selection of a herbivore haplotype for a biological control programme. *Molecular Ecology*, *15*(1), 287–297. https://doi.org/10.1111/j.1365-294X.2005.02788.x

Gordon, D. R., Onderdonk, D. A., Fox, A. M., Stocker, R. K., & Gantz, C. (2008). Predicting invasive plants in Florida using the Australian weed risk assessment. *Invasive Plant Science and Management*, *1*(2), 178–195. https://doi.org/10.1614/IPSM-07-037.1

Henderson, L. (2001). *Alien Weeds and Invasive Plants*. Plant Protection Research Institute, Agricultural Research Council, Cape Town, South Africa.

Higgins, A. J., Hajkowicz, S., & Bui, E. (2008). A multi-objective model for environmental investment decision making. *Computers & Operations Research*, *35*(1), 253–266. https://doi.org/10.1016/j.cor.2006.02.027

Impson, F., Kleinjan, C., Hoffmann, J., & Post, J. (2008). *Dasineura rubiformis* (diptera: Cecidomyiidae), a new biological control agent for *Acacia mearnsii* in South Africa. *South African Journal of Science*, *104*(7–8), 247–249.

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*(2), 515–549. https://doi.org/10.4001/003.019.0214

Lewu, F., & Afolayan, A. (2009). Ethnomedicine in South Africa: The role of weedy species. *African Journal of Biotechnology*, *8*(6), 929–934.

Mack, R., & Lonsdale, W. (2002). Eradicating invasive plants: Hard-won lessons for islands. In C. R. Veitch & M. N. Clout (Eds.), *Turning the tide: The eradication of invasive species* (pp. 164–172). IUCN SSC Invasive Species Specialist Groups.

McClay, A. (1989). Selection of suitable target weeds for classical biological control in Alberta. *Selection of Suitable Target Weeds for Classical Biological Control in Alberta. AECV89-R1*.

NEMBA. (2014). *National Environmental Management: Biodiversity Act (10/2004): Alien and Invasive Species Regulations (Government Notice R. 598)*. Department of Environmental Affairs and Tourism.

Novoa, A., Dehnen-Schmutz, K., Fried, J., & Vimercati, G. (2017). Does public awareness increase support for invasive species management? Promising evidence across taxa and landscape types. *Biological Invasions*, *19*(12), 3691–3705. https://doi.org/10.1007/s10530-017-1592-0

Olckers, T., Hoffmann, J., Moran, V., Impson, F., & Hill, M. (1999). The initiation of biological control programmes against *Solanum elaeagnifolium* Cavanilles and *S. Sisymbriifolium* lamarck (Solanaceae) in South Africa. *African Entomology Memoir*, *1*, 55–63.

Panetta, F., & Timmins, S. M. (2004). Evaluating the feasibility of eradication for terrestrial weed incursions. *Plant Protection Quarterly*, *19*(1), 5–11.

Paterson, I. D., Coetzee, J. A., Hill, M. P., & Downie, D. D. (2011). A pre-release assessment of the relationship between the invasive alien plant, *Pereskia aculeata* miller (cactaceae), and native plant biodiversity in South Africa. *Biological Control*, *57*(1), 59–65. https://doi.org/10.1016/j.biocontrol.2010.12.002

Paynter, Q., & Flanagan, G. J. (2004). Integrating herbicide and mechanical control treatments with fire and biological control to manage an invasive wetland shrub, *Mimosa pigra*. *Journal of Applied Ecology*, *41*(4), 615–629. https://doi.org/10.1111/j.0021-8901.2004.00931.x

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

Paynter, Q., Overton, J. M., Hill, R. L., Bellgard, S. E., Dawson, M. I., & Cadotte, M. (2012). Plant traits predict the success of weed biocontrol. *Journal of Applied Ecology*, *49*(5), 1140–1148. https://doi.org/10.1111/j.1365-2664.2012.02178.x

Pearse, I. S., & Hipp, A. L. (2009). Phylogenetic and trait similarity to a native species predict herbivory on non-native oaks. *Proceedings of the National Academy of Sciences*, *106*(43), 18097–18102. https://doi.org/10.1073/pnas.0904867106

Pejchar, L., & Mooney, H. A. (2009). Invasive species, ecosystem services and human well-being. *Trends in Ecology & Evolution*, *24*(9), 497–504. https://doi.org/10.1016/j.tree.2009.03.016

Pemberton, R. W. (2000). Predictable risk to native plants in weed biological control. *Oecologia*, *125*(4), 489–494. https://doi.org/10.1007/s004420000477

Piggin, C., & Sheppard, A. (1995). *Echium plantagineum* L. *The Biology of Australian Weeds*, *1*, 87–110.

Pimentel, D., McNair, S., Janecka, J., Wightman, J., Simmonds, C., O'Connell, C., Wong, E., Russel, L., Zern, J., Aquino, T., & Tsomondo, T. (2001). Economic and environmental threats of alien plant, animal, and microbe invasions. *Agriculture, Ecosystems & Environment*, *84*(1), 1–20. https://doi.org/10.1016/S0167-8809(00)00178-X

Rejmánek, M., & Pitcairn, M. (2002). When is eradication of exotic pest plants a realistic goal. In C. R. Veitch & M. N. Clout (Eds.), *Turning the tide: The eradication of invasive species* (pp. 249–253). IUCN SSC Invasive Species Specialist Groups.

Renteria, J. L., Rouget, M., & Visser, V. (2017). Rapid prioritization of alien plants for eradication based on climatic suitability and eradication feasibility. *Austral Ecology*, *42*(8), 995–1005. https://doi.org/10.1111/aec.12528

Sanders, R. W. (2006). Taxonomy of Lantana sect. Lantana (Verbenaceae): I. correct application of *Lantana camara* and associated names. *Sida, Contributions to Botany*, 381–421.

Sheppard, A., Shaw, R., & Sforza, R. (2006). Top 20 environmental weeds for classical biological control in Europe: A review of opportunities, regulations and other barriers to adoption. *Weed Research*, *46*(2), 93–117. https://doi.org/10.1111/j.1365-3180.2006.00497.x

Silvestri, L., Sosa, A., Mc Kay, F., Vitorino, M. D., Hill, M., Zachariades, C., Hight, S., Weyl, P., Smith, D., & Djeddour, D. & Mason, P.G. (2020). Implementation of access and benefit-

sharing measures has consequences for classical biological control of weeds. *BioControl*, *65*, 125–141.
Simberloff, D. (2003). Eradication – preventing invasions at the outset. *Weed Science*, *51*(2), 247–253. https://doi.org/10.1614/0043-1745(2003)051[0247:EPIATO]2.0.CO;2
Suckling, D. M., Sforza, R. F. H., & Marion-Poll, F. (2014). What magnitude are observed non-target impacts from weed biocontrol? *PloS One*, *9*(1), 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.
Turner, C. (1985). *Conflicting interests and biological control of weeds*: *Proceedings of the Vth International Symposium on Biological Control of Weeds* (pp. 203–225), Canada Agriculture, Vancouver, Canada.
Urban, A., Simelane, D., Retief, E., Heystek, F., Williams, H., & Madire, L. (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*(2), 315–348.
Van der Westhuizen, L. (2011). Initiation of a biological control programme against Madeira vine, *Anredera cordifolia* (Ten.) Steenis (Basellaceae), in South Africa. *African Entomology*, *19*(2), 217–222. https://doi.org/10.4001/003.019.0227
Van Wilgen, B., & De Lange, W. J. (2011). The costs and benefits of biological control of invasive alien plants in South Africa. *African Entomology*, *19*(2), 504–514. https://doi.org/10.4001/003.019.0228
van Wilgen, B. W., Forsyth, G. G., Le Maitre, D. C., Wannenburgh, A., Kotzé, J. D. F., van den Berg, E., & Henderson, L. (2012). An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. *Biological Conservation*, *148*(1), 28–38. https://doi.org/10.1016/j.biocon.2011.12.035
Van Wyk, B., Oudshoorn, V., & Gericke, N. (1997). *Medicinal plants of South Africa (first)*. Briza Publications, Pretoria.
Ward, S. M., Gaskin, J. F., & Wilson, L. M. (2008). Ecological genetics of plant invasion: What do we know? *Invasive Plant Science and Management*, *1*(1), 98–109. https://doi.org/10.1614/IPSM-07-022.1
Weidlich, E. W., Flórido, F. G., Sorrini, T. B., & Brancalion, P. H. (2020). Controlling invasive plant species in ecological restoration: A global review. *Journal of Applied Ecology*. https://doi.org/10.1111/1365-2664.13656
Weyl, P. S., & Coetzee, J. A. (2014). The invasion status of *Myriophyllum spicatum* L. In Southern Africa. *Management of Biological Invasions*, *5*(1), 31–37. https://doi.org/10.3391/mbi.2014.5.1.03
Weyl, P., Thum, R. A., Moody, M., Newman, R., & Coetzee, J. (2016). Was *Myriophyllum spicatum* L.(Haloragaceae) recently introduced to South Africa from Eurasia? *Aquatic Botany*, *128*, 7–12. https://doi.org/10.1016/j.aquabot.2015.09.003
Winston, R., Schwarzländer, M., Hinz, H. L., Day, M. D., Cock, M. J., & Julien, M. (2014). *Biological control of weeds: A world catalogue of agents and their target weeds*. USDA Forest Service, Forest Health Technology Enterprise Team.
Zachariades, C., Paterson, I. D., Strathie, L. W., Hill, M. P., & Van Wilgen, B. W. (2017). Assessing the status of biological control as a management tool for suppression of invasive alien plants in South Africa. *Bothalia-African Biodiversity & Conservation*, *47*(2), 1–19. https://doi.org/10.4102/abc.v47i2.2142
Zengeya, T., Ivey, P., Woodford, D. J., Weyl, O., Novoa, A., Shackleton, R., Richardson, D., & Van Wilgen, B. (2017). Managing conflict-generating invasive species in South Africa: Challenges and trade-offs. *Bothalia-African Biodiversity & Conservation*, *47*(2), 1–11. https://doi.org/10.4102/abc.v47i2.2160
Zimmermann, H., Hoffmann, J., & Moran, V. (2004). Biological control in the management of invasive alien plants in South Africa, and the role of the Working for Water programme: Working for water. *South African Journal of Science*, *100*(1), 34–40.