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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

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ABSTRACT

Biological control is an effective and sustainable method for management of invasive alien plants (IAPs), and has been implemented on 68 of the 367 plant species that are listed as legally requiring management strategies under South Africa's National Environmental Management: Biodiversity Act (10/2004): Alien and Invasive Species Regulations. With limited resources and funding available, it can realistically only be considered for a subset of the remaining alien plants for which biocontrol has not yet been implemented. Considerable funding has been allocated towards biocontrol in South African in the past, principally through the Working for Water Programme of the Nature Resource Management Programmes (Department of Environment, Forestry and Fisheries), and this support is expected to continue with the intention of increasing the number of IAPs under this management approach in the future. To ensure appropriate targets are selected, the Biological Control Target Selection (BCTS) system was applied to the alien plants on this list that are not under biocontrol (299 species). This paper presents the resultant list of top priority species that represent good investments for biocontrol when funds are available.

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Alien plants; biological control; NEMBA; prioritisation

Introduction

South Africa is a mega-diverse country and has a long history of documenting the significant number of alien plants present (Bennett & Van Sittert, 2019), and attempting to limit the ecological impacts of biological invasions (Van Wilgen & Wannenburgh, 2016). With an estimated 10 million hectares of South Africa already invaded to some degree (Le Maitre et al., 2000), the extent of the problem facing managers of invasive alien plants (IAPs) is huge. To address the problems of alien plant invasions, South Africa has developed legislation related to their management under the National Environmental Management Biodiversity Act (Act 10 of 2004) (hereafter referred to as NEMBA) (Bennett & Van Sittert, 2019; Department of Environmental Affairs, 2014). The regulations under this legislation list 379 alien plant species that require management in some form depending on their threat, 367 on mainland South Africa and a

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further 12 species which are restricted to the sub-Antarctic Island protectorates (NEMBA, 2014).

In addition to the legislation, South Africa initiated a large, nation-wide, alien plant control programme known as Working for Water (WfW) that began in 1995 (Bennett & Van Sittert, 2019) and continues within the Department of Environment, Forestry and Fisheries: Natural Resource Management Programme (DEFF: NRM, hereafter DEFF). Most government expenditure on the control of IAPs is now channelled through the WfW programme which operates on an annual budget in excess of R2 billion ($147,058,823 from 2017 conversion rate value) (Van Wilgen, Raghu, et al., 2020, Van Wilgen, Wilson, et al., 2020) . Part of this programme's strategy to address IAPs is to support and fund biological control (hereafter referred to as biocontrol) (Moran et al., 2013). Biocontrol agents have been released on 68 IAPs of which 34 are considered under significant control (Zachariades et al., 2017). The benefits of this approach are estimated to be saving South Africa several billion rands each year by reducing the negative impacts of IAPs on ecosystem services (De Lange & van Wilgen, 2010). Biocontrol will likely continue to play an important role going forward, with investment in this research increasing from 1% of the total annual budget of WfW in 2009/2010 financial year (Van Wilgen & De Lange, 2011), to 2.8% in the 2012/2013 financial year (Ntshotsho et al., 2015).

Despite the many successes of WfW, there are still many IAPs with no management interventions (Wilson et al., 2013). Historically, intuition, political expediency and logistical convenience have often been the common determinants of what, where and how an IAP is managed (Common Ground, 2003; Ntshotsho et al., 2015). Similarly, the selection of biocontrol targets has largely been determined by political and pragmatic considerations and based on the experience, knowledge and intuition of the senior and leading researchers (Zimmermann et al., 2004). Reviews of the WfW programme have raised concern for a lack of clear guidelines and strategy to guide its operations (Anonymous, 2007; Common Ground, 2003; Palmer Development Group, 2014; Van Wilgen & Wannenburgh, 2016). It was recommended that investment be made to develop strategies to prioritise the selection of projects and to invest 'a portion of funds into the prioritisation of control operations, planning, monitoring and evaluation' (Van Wilgen et al., 2012). There have been efforts to address this shortfall with a number of prioritisation initiatives that outline transparent and systematic approaches to guide the decision-making of which IAPs to manage, the type of control and which areas to target in South Africa (see Forsyth et al., 2009; Forsyth et al., 2012; Hoeneisen, 2013; Le Maitre & Forsyth, 2010; Macdonald & Jarman, 1985; Nel et al., 2004; Robertson et al., 2003; Roura-Pascual et al., 2009; Van Wilgen et al., 2007, 2008).

The development of a transparent and systematic approach for the choice of biocontrol projects in South Africa has not been developed. This paper aims to provide such an approach through the application of the Biological Control Target Selection (BCTS) system (Paterson et al., in press). This approach aligns with the needs of both the funding bodies and researchers involved in ensuring a scientifically developed strategy to set priorities and ensure the best use of resources. Here, we use the NEMBA list as it contains all alien plants that are considered as currently the greatest threat to South Africa and therefore warrant management.

A list of target plants ranked in order of priority to receive funding for research into and implementation of a biocontrol programme is the intended outcome. This list should help inform future investment in biocontrol and could potentially be incorporated into the current system of 'work and resource allocation' by the DEFF. Currently, agencies involved in biocontrol research outline their potential research priorities for a three-year period and the DEFF allocates available budget to these agencies, as long as the research proposal fits within the range of targeted species. With an agreed list of target plants ranked according to priorities, the research agencies can select high priority species to research and the DEFF can use the list to support budget allocation.

Methods

Invasive alien plants that have had biocontrol agents released in South Africa are not considered in this model as they have already been selected as appropriate targets. This included alien plants that are alternative hosts for biocontrol agents released on congeneric and closely related species such as, *Cereus hildmannianus* K. Schum. (Cactaceae) that is an alternative host for two biocontrol agents originally released on *Harrisia martinii* (Cactaceae) (Paterson et al., 2011). Plant targets that are alternative hosts were only excluded here if the damage caused by agents has resulted in complete control in South Africa. However, target plants that have had biocontrol programmes started but were subsequently shelved for various reasons were considered, for example, *Hakea drupacea* (C.F. Gaertn.) Roem. & Schult. (Proteaceae) and *Melia azedarach* L. (Meliaceae). These species were included in the analysis to account for any changes of information or data that may make biocontrol more favourable again such as increased geographic distribution or new potential biocontrol agents. Targets that have active biocontrol programmes but have not had agents released were included in the assessment because further investments are likely to be required in these projects and whether to continue supporting these project or reallocate funds to new projects should be considered. Of the 367 regulated alien plants for mainland South Africa, 68 species listed have had biocontrol agents released on them, so 299 species were potential targets for future biocontrol programmes. For details of how the system is constructed, the attributes that were included and scoring of attributes, see Paterson et al., (2021).

For each attribute contained within a section, a score was given for the particular target plant (Table 1 and Table S1: Supplementary Material, https://biocontrol-bcts.netlify.app/index.html). The rationale for the score is provided with an accompanying reference (Table S1: Supplementary Material). The type of reference was indicated in each case; high confidence was assigned for peer-reviewed literature including journals, books and reports, medium quality to academic grey literature and expert opinion and lower confidence to sources such as websites and unverified information indicated by green, orange or red font respectively. Commentary from the authors is written in black text. All literature searches included both the currently accepted taxonomic delimitations for each target plant and its synonyms to ensure all relevant information was accessed. Where target plants have been assigned new names due to taxonomic revisions, the current accepted name is listed and all previous synonyms are given.

Below is a detailed account of how the BCTS system was applied to the target plants listed in NEMBA in South Africa. For each attribute within the three sections, a

Table 1 . The thirteen attributes identified for construction of the Biological Control Target Selection grouped into three 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

description of how relevant information was gathered and how it was used to populate the model is given.

Section 1. Impact/importance of the target plant

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

The target plants listed under the NEMBA regulations have all gone through a selection process that determined these alien plants to be the most threatening to the country. In light of this, the lower scores available in the model (1 – no threat or impact, 2 – threat in another country) were not assigned for any of the target plants considered. The lower score of four was only given for the species that are listed as a precautionary measure and have not yet been found to have naturalised or are not present in the country but legislation is there to monitor any potential naturalisation or avoid any introduction. For example, *Bartlettina sordida* (Less.) RMKing & H.Rob (Asteraceae) is cultivated for horticulture however there are no records of naturalisation at present and it is listed in NEMBA due to its potential to become invasive (Henderson & Wilson, 2017). It was noted in the rationale whether these species are present in the country or not and in this way, any future changes to their status or records of introduction could be updated in the system. Information will then be readily available to inform management options should there be a need to control their populations. The remaining species were then classified as; score of 6 – threat in the country of interest or minimal/negligible impacts, 8 – minor or moderate impact, 10 – massive or major impact.

The scoring of this attribute is intended to be based on actually recorded impacts within South Africa from available literature (Paterson et al., in press). However, impacts have largely not been assessed in detail for most of the NEMBA list. Most research on alien plant impacts has been focused on small spatial scales and has largely been biased towards certain areas (particularly the fynbos biome), while impacts at a larger ecosystem-level have been inadequately studied (Richardson & Van Wilgen, 2004). As a result, most available evidence of impacts is based on undocumented observations and expert opinion (Richardson & Van Wilgen, 2004).

All target plants were first checked for any available literature on their impacts in South Africa using Google Scholar™ searches including the species name, 'South Africa', followed by relevant keywords including 'impact', 'biodiversity', 'threat', 'invasion'. Scoring was then applied based on whether there was evidence of any impacts according to Blackburn et al. (2014). Information on impacts was primarily obtained from two sources; the Southern African Plant Invaders Atlas (SAPIA) (Henderson, 2001), and the Status Report on Biological Invasions in South Africa (Van Wilgen, Raghu, et al., 2020, Van Wilgen, Wilson, et al., 2020).

In Henderson (2001), invasive status categories were assigned for each listed alien plant with the intention of giving an indication of their impact. These categories were aligned with the impact categories for this attribute. Van Wilgen, Raghu, et al., 2020, Van Wilgen, Wilson, et al., 2020 also categorised the alien plants on the NEMBA list and included an impact status for most of the species. The classes were aligned with Blackburn et al. (2014) impact categories and were assigned largely based on a study by Zengeya et al. (2017) that used taxon-specific experts to assess and score impacts for the target plants. Impact status categories were aligned with this model (negligible impacts (EICAT: minimal concern) = score of 6, a few or some impacts (EICAT: minor or moderate) = 8 and major or severe (EICAT: major or massive) = 10). If no literature was available from any of the above resources and the species are known to have naturalised in the country then a score of 6 is given to indicate that they present a threat.

Attribute 1B – geographic distribution

Attribute 1B assessed the extent of the geographic distribution of each target plant in terms of the number of recorded localities in South Africa. Distributional data was gathered from the SAPIA and iNaturalist databases. For the iNaturalist database, records were downloaded using the R package 'rinat' (Barve & Hart, 2014) [accessed 4–9 July 2020]. The records were filtered to only keep those that were assigned 'Research Grade' status (data quality assessments in iNaturalist have indicated that the record is verifiable and the community agrees on the species-level ID), and plants that are not in cultivation (records were indicated to be growing in the wild). In addition, any localities recorded on iNaturalist that were within the same quarter degree square as those recorded in SAPIA were excluded as new records to account for any potential duplication.

The lowest score given was intended to reflect species that have the potential for eradication (less than ten localities recorded). The number of known localities is considered a crucial factor in assessing eradication feasibility (Renteria et al., 2017). The remaining scores were based on whether the target plant was widely dispersed (>50 localities) or had limited distribution (<50 localities). For target plants that had wider distribution, it was assessed whether or not these populations were distributed across the nine biomes (Finch & Meadows, 2019) and provinces in South Africa. The nine biomes are geographical areas that share a similar community of naturally occurring flora and fauna (Mucina, 2019). From Henderson (2007), the number of study area records were indicated for each biome, if a species is found across more than one biome and province it was scored as having a dispersed distribution.

For species with limited distribution (<50 localities) the differentiation between clumped and dispersed distribution was based on the management area. For South

Africa, this is addressed as a municipal unit (see Van der Waldt (2007) for information on municipal structure) whereby if a plant occurs within one municipal region then it is considered clumped as management could take place under one administration. The lower score given to species with limited distributions (score of 2.5 if >10 and <50 locations and clumped) is intended to reflect populations that can have effective control without biocontrol. As such these populations must be within manageable areas to initiate alternative control options. For example, *Acacia stricta* (Andrews) Willd. (Fabaceae) is currently noted to only have naturalised in the Knysna area where small populations exist in several localities in this district (Kaplan, 2012). Due to this clumped distribution and involvement from local land managers, *A. stricta* is currently considered a suitable target for eradication (Kaplan, 2012). The number of localities noted for aquatic plants was based on the number of river systems or dams in which they were recorded in (i.e. one locality per river system). However, where river systems extend beyond provinces, localities were recorded per province.

Attribute 1C – alternative control measures

Attribute 1C assessed the availability of alternative control methods for the target plants. Target plants were only considered to have no control options (score of 10) if they have a growth form that would likely restrict the use of herbicide or manual control, or were evaluated to have invaded an area in which other control options are not possible (Paterson et al., in press). For example, *Sagittaria platyphylla* (Engelm.) J.G. Sm. (Alismataceae) is an aquatic macrophyte that can take on a submerged form, furthermore the plants can reproduce asexually via vegetative propagules such as underground stem fragments, daughter plants, stolons and tubers; these features allow the plants to largely survive both chemical and mechanical management in South Africa (Ndlovu et al., 2020). The determination of whether the invaded area is not conducive to control options was determined on a case by case basis. Only if the evidence is available outlining how control could not go ahead were target plants given a higher ranking in this regard.

In scoring a target plant as being likely to have complete control using methods other than biocontrol (score of 1), only target plants with less than 10 localities recorded (score of 1 from attribute 1B) were considered. A decision was then made on the feasibility of eradication based on factors that are known to impact success including growth form and habitat (see Paterson et al., in press). Literature was also searched for any current management strategies employed. For example, the South African National Biodiversity Institute's Invasive Species Programme (SANBI ISP) was reviewed to determine if an eradication plan had been implemented or is being investigated for the target plants with restricted distribution (<10 localities) (Wilson et al., 2013). Renteria et al. (2017) prioritised the management towards eradication of new potential invasive plant species and these feasibility levels were noted for these target plants.

The majority of target plants were scored as 'partial control can be achieved' (score of 5). This is appropriate because the attribute is designed to prioritise those plants that can only be successfully controlled using biocontrol, as well as to exclude those that should not be targeted by biocontrol. Most alien plants in South Africa are possible targets for biocontrol, as well as other interventions, so it is appropriate that the majority of the target was given a score of 5 and we would expect that only a few species fall outside of this score.

Attribute 1D – conflicts of interest

Attribute 1D evaluated the current economic, environmental or social value of the target plants in South Africa to determine if there are any conflicts of interest that may occur if biocontrol were to be initiated. All target plants were first evaluated for whether or not they are being grown for commercial purposes in any area of the country. If the plants were under cultivation then these were further evaluated as to whether or not the product would likely be impacted by biocontrol. Plants that are not cultivated for their seeds or fruits were regarded as having potential for biocontrol because reproductive parts could be targeted without damaging the produce (given a score of 5). For example, *Casuarina cunninghamiana* Miq. (Casuarinaceae) is an economically important tree in some areas of South Africa as it is used for shelterbelts, windbreaks and amenity purposes (Poynton, 1979). However, given the threat of invasive populations, the potential for biocontrol has been recognised whereby agents that would reduce the reproductive output of the trees could reduce the risk of spread from plantings (Potgieter et al., 2014). If the produce will likely be negatively impacted by biocontrol then there is a high likelihood of conflict of interest that would be deemed unacceptable to initiate biocontrol (score of 1).

Included within a higher score for conflicts of interest (score of 5) were target plants that hold significant cultural value, are anticipated for future commercial use or have an exemption to trade or protection under certain conditions. Google Scholar™ searches were conducted for each target plant including the words ‘conflict’, ‘value’ and ‘South Africa’. In addition, the following resources were used that have conducted assessments of uses and potential conflicts of interest for alien plants in South Africa, including medicinal plants (Lewu & Afolayan, 2009), cacti (Novoa et al., 2017), NEMBA list species (Zengeya et al., 2017), and listing of exemptions in the NEMBA regulations (Department of Environmental Affairs, 2014). Assigning scores based on non-commercial values is complex and often evaluations were done based on expert opinion (e.g. Novoa et al., 2017 and Zengeya et al., 2017) and therefore could be subjective or not reflect the entire costs and benefits of the species as a whole. As such, the NEMBA category was also considered within this and if a species was listed as a category 1 and prohibited from all trade, then despite potential for some conflict due to social or other non-commercial values this is likely to be overridden by the legislation in place to control the species (score of 10 given).

All remaining target plants that are not cultivated and were not found to have other uses or values that would result in any conflicts of interest were given the highest score of 10. Within this, there were many plants that are still likely to be traded as ornamentals however, depending on their category under NEMBA such trade was not considered to carry a commercial value and therefore potential for conflict is low.

Section 2. Likelihood of achieving success

Attribute 2A – success of biocontrol programmes elsewhere

This attribute assessed whether or not any of the target plants have had biocontrol programmes initiated elsewhere in the world. Scores were assigned based on the success of these programmes from post-release monitoring of the impacts of biocontrol (i.e. higher scoring for higher impacts). When there have been multiple programmes on a target plant elsewhere, the highest recorded impact in any of these areas is assigned to the scoring. Included within this scoring is an assessment of whether or not congeners have also been targeted for biocontrol. Target plant congeners were only reflected in the scoring if they have had a recorded impact, including slight, variable, medium and high impacts. The highest scoring for this attribute is given to target plants with heavy impacts elsewhere and having congeners with biocontrol implemented (score of 20). The main resource available for this section comes from Winston et al.'s (2014) world catalogue which reviewed all known biocontrol programmes to date. The catalogue is regularly updated and available online (www.ibiocontrol.org/catalog/).

Attribute 2B – ecosystem

Attribute 2B assessed the ecosystem in which the target plants are invading in South Africa. Plants that are aquatic have been found to be more likely to have successful biocontrol programmes compared to those growing in terrestrial ecosystems (Paynter et al., 2012). The target plants were classified as either aquatic including wetland plants (plants that are in areas that subject to regular seasonal flooding, for example, *Mimosa pigra* L. (Fabaceae) (Paynter & Flanagan, 2004)) or terrestrial plants.

Attribute 2C – reproduction

The reproductive mode of each target plant was considered in Attribute 2C. Two levels of reproduction were considered here, according to the methods used in Paynter et al. (2012). Asexual reproduction was assigned to target plants that can only reproduce by vegetative means or are apomictic and can be considered clonal. For these targets plants a higher score (10) was given as clonal plants have been found to have a greater likelihood of successful biocontrol. Sexual reproduction was assigned to target plants that can reproduce sexually (including those that can also use vegetative reproduction). Information was primarily obtained from the CABI databases under the plant type category (www.cabi.org/isc/datasheet) and the International Union for Conservation of Nature (IUCN) global invasive species database under the reproduction category (http://www.iucngisd.org/gisd/search.php).

Attribute 2D – habitat stability

Attribute 2D assessed the habitat stability of a target's plant invasive range in South Africa. Habitats that are cultivated for agriculture or are improved pastures were considered to be unstable habitats as they encounter frequent disturbance. Information was primarily taken from the CABI (https://www.cabi.org/isc/datasheet) and the IUCN (http://www.iucngisd.org/) databases. Target plants that are recorded as having their primary habitat in cultivated land, 'agricultural' and 'agrestals' weeds are considered species that predominantly invade sites with severe human disturbance and thus were given a lower score (score of 5).

Attribute 2E – life cycle

The target plant's life cycle was considered in attribute 2E. Target plants that are annuals are predicted to be less likely to have a successful biocontrol programme implemented on them and are given a lower score (score of 5). Information on plant life cycle was obtained primarily obtained from the CABI (https://www.cabi.org/isc/datasheet) and the IUCN (http://www.iucngisd.org/) databases. Plants that are both annual or perennial depending on the climatic conditions of the invaded site (i.e. species that are annuals in cold conditions) were scored as perennials (score of 10). Much of South Africa is situated within the subtropics and only a small percentage of areas are prone to freezing conditions, mostly in montane areas in the high altitude central plateau (Van Der Walt & Fitchett, 2021). All target plants that can have both life cycles were found to be widespread in warmer areas where they are perennials and were therefore scored as perennials.

Section 3. Investment required

Attribute 3A – uncertainty in plant origin or taxonomy

Attribute 3A assessed the current available knowledge of the target plant's origin and taxonomy. For plant origin, literature was searched for records of whether or not the extent of the native range is known. The Henderson (2001) handbook provided information on the native range for most target plants listed.

The target plant's taxonomic status was first checked to determine if it is accepted in the Integrated Taxonomic Information System (https://www.itis.gov/). The plants were then assessed for any taxonomic issues, Google Scholar™ searches were carried out with the following words 'taxonomy', 'hybrids/hybridisation', 'cultivar' and the CABI database under the taxonomy category (www.cabi.org/isc/datasheet) was also consulted. Any potential complications involving the plant's taxonomic status were only accounted for if they have been recorded to occur in South Africa and would have a biological significance to a biocontrol programme, i.e. viable hybrid progeny occurring with native congeners that have been shown to be naturalised. For example, alien invasive *Tamarix* spp. have been shown to hybridise with the native *Tamarix usneoides* E. Mey. ex Bunge (Tamaricaceae) in naturalised populations in South Africa (Mayonde et al., 2015). This may present challenges to the anticipated use of biocontrol due to the threat of homogenisation and potential non-target effects from biocontrol agents (Mayonde et al., 2019), and this additional risk factor has resulted in a need for more extensive host specificity testing in quarantine (Marlin et al., 2017). When no literature was available for the native range and/or there is evidence of a lack of taxonomic clarity, then the lowest score was assigned (score of 1).

Attribute 3B – information on natural enemies

This attribute determined whether or not literature is available on the natural enemies of the target plants. Evidence was primarily obtained from Google Scholar™ using searches of the target plant species name followed by the keywords, 'herbivores', 'natural enemies', 'pests' and 'insects'. An important source of information was also the CABI website datasheets under the natural enemies category (www.cabi.org/isc/datasheet). The highest score (score of 10) was only given for target plants that have had biocontrol implemented elsewhere or have had significant research carried out on their natural enemies that would likely contribute to biocontrol research such as evidence of host-specific herbivores. An intermediate score (score of 5) was given to target plants that have had some research carried out on the herbivores associated with the plant.

Target plants that have had biocontrol programmes initiated in South Africa that are currently ongoing but have not yet had releases of agents were noted in the rationale of this attribute. The progress of these programmes is intended to be monitored and updated when advances have been made.

Attribute 3C – sourcing agents

Attribute 3C evaluated the ease at which biocontrol surveys for natural enemies can be carried out in the native range. Each target plant's native range was assessed on firstly whether or not biocontrol facilities exist. If not, the countries level of safety was considered and its infrastructure, areas that are likely to be unsafe or have poor facilities were given the lowest score (score of 1) and if they are safe and developed a higher score (score of 3). A region with a biocontrol lab or supporting facilities (e.g. university research groups or agricultural departments with relevant experts) is seen as optimum and thus was given a high score (score of 6). Lastly, if a biocontrol agent is available and can readily be imported the highest score was given (score of 10). The existence of a biocontrol lab or accommodating research facility was primarily determined by records in Winston et al. (2014) that outline the various research institutes globally. A subsequent review of the safety of the country was then done by using current measures of stability and infrastructure including the Global Peace Index (GPI) and governmental travel advisories (e.g. www.travel.state.gov).

Attribute 3D – potential to find host-specific agents

Attribute 3D assessed the presence of any related congeneric species within South Africa that may present challenges to host specificity work. The primary resource used was the 'Plants of South Africa: an annotated checklist' (Germishuizen & Meyer, 2003), that provides a list of plants native to South Africa. The genus of the target plant was searched within this database.

Results

The top twenty target plants for biocontrol in South Africa produced through the use of the BCTS system are presented in Table 2 and the full list of NEMBA ranked species along with all the individual attribute scores, justifications and references, is presented in Table S1 (available online: https://biocontrol-bcts.netlify.app/index.html). Ten of the top twenty prioritised target plants are likely to be good transfer programmes in South Africa (Table 2), due to the fact that biocontrol has already been implemented elsewhere. For these projects, biocontrol agents are available and can be imported into quarantine for host specificity testing. The system has highlighted which of these programmes will likely provide the most benefit given the target plants status in the region. *Arundo donax* L. (Poaceae) which was ranked as the top priority, is considered one of the worst IAPs in South Africa, having major impacts and is widespread across the country (Visser et al., 2017). Nine of the top ranked species have had biocontrol programmes initiated in South Africa. These species have already been recognised to be good targets for biocontrol and thus have received funding to start research but at present have not yet had any agents released.

Table 2 . The list of top twenty priority target plants for biocontrol based on the BCTS system.

Ranking	Target plant	Common name	Transfer project	Section 1 Impact/ importance of target weed	Section 2 Likelihood of achieving success	Section 3 Investment required
1	*Arundo donax**	Giant reed	Yes	40	58	40
2	*Robinia pseudoacacia**	Black locust	No	40	36	36
3	*Mimosa pigra*	Giant sensitive plant	Yes	30	55	40
4	*Cryptostegia grandiflora*	Rubber vine	Yes	35	40	40
5	*Sagittaria platyphylla**	Delta arrowhead	No	36	41	36
6	*Araujia sericifera*	Moth catcher	Yes	36	36	40
7	*Hedychium gardnerianum*	Kahili ginger lily	No	38	36	36
8	*Echium plantagineum**	Patterson's curse	Yes	35	38	40
9	*Pontederia cordata*	Pickerel weed	No	36	43	31
10	*Ailanthus altissima*	Tree-of-heaven	No	36	36	36
11	*Cylindropuntia pallida**	Thistle cholla	Yes	30	50	36
12	*Iris pseudacorus**	Yellow flag	No	33	41	36
13	*Pueraria montana*	Kudzu vine	No	35	36	36
14	*Melia azedarach**	Seringa	No	35	36	36
15	*Convolvulus arvensis*	Field bindweed	Yes	38	35	31
16	*Schinus terebinthifolius*	Brazilian pepper tree	Yes	33	44	31
17	*Genista monspessulana*	Montpellier broom	Yes	28	48	40
18	*Xanthium strumarium*	Large cocklebur	Yes	35	32	40
19	*Hakea drupacea**	Sweet hakea	No	33	38	36
20	*Opuntia elata**	Orange tuna	No	33	38	36

Notes: Whether or not the target plant has had biocontrol programmes initiated elsewhere and would therefore represent a transfer project to South Africa is indicated. The BCTS score for each section is shown for each target weed.
*Indicates target plants that have had biocontrol research programmes initiated (*Hakea drupacea* and *Melia azedarach* have since had their research programmes shelved due to non-continuation of funding) in South Africa but at present have not had biocontrol agents released on them (see further detail in rationale (Supplementary Table S1, https://biocontrol-bcts.netlify.app/index.html)).

Some of the top ranked species are presently considered emerging invasive species, including the rubber vine, *Cryptostegia grandiflora* R. Br. (Apocynaceae) and *Mimosa pigra* L. (Fabaceae). For these species, the additional attributes such as impact and growth form of the plant, highlighted the need for and potential benefit of biocontrol despite their current restricted invasive range.

The system did not only prioritise target plants for which there was a previous success. Ten of the top twenty target plants have not been the subject of biocontrol globally (Table 2). The scoring and weighting of the additional attributes were demonstrated to be appropriate because novel targets that show high potential for biocontrol are still given high priority.

The scoring was relatively continuous and there were no distinct groupings or dominance of particular attributes. The scoring of only one attribute was constrained by the availability of literature – attribute 1A threat of impact of the target plant. For this attribute, most target plants on the NEMBA list have not had sufficient research conducted to assess their impacts with a high degree of confidence. Studies on the impacts of the target plants on the NEMBA list are currently ongoing and plan to be updated, and this will be of value to the system when available. All other attributes could be scored with reasonable confidence given the availability of literature. The lowest ranking species were expected and consisted primarily of species that are not yet introduced or have restricted distributions so that they could potentially be eradicated.

Discussion

The BCTS system ranked the top priority target plants for biocontrol in South Africa. High priority targets represent good investments based on the threat they pose and the prospects for implementing biocontrol safely and cost effectively. Of the target species ranked in the top twenty, nine species have had biocontrol research programmes initiated in South Africa as they were recognised to be important targets for control. The remaining eleven prioritised species have not yet received funding for any biocontrol research. According to the BCTS system, these species should be considered for biocontrol as they have attributes that would make them good targets. The fact that eleven possible targets that were not prioritised by researchers in the past ranked in the top 20 targets is evidence that direction in terms of target selection for biocontrol in South Africa is warranted.

The accuracy and validity of the BCTS system rely on the quality of available information. With increased investment in biocontrol, there will be an improvement in data and research publications, thus improving the efficacy of this tool. The establishment of the WfW programme improved and enhanced research on the extent of alien plant invasions in the country (Ntshotsho et al., 2015). Research outputs such as the SAPIA project (Henderson, 1998) and the establishment of the Centre for Invasion Biology (Van Wilgen et al., 2014) have provided pivotal information for this system. The inclusion of rationale and accompanying references within this system will also help outline research gaps that may exist for the target plants so that any new research that becomes available can be included to ensure that this list stays relevant. The NEMBA list does not include all alien plants currently naturalised in South Africa (at present there are 775 recorded alien species (Van Wilgen, Raghu, et al., 2020, Van Wilgen, Wilson, et al., 2020)) and many of these unlisted species may need control options including biocontrol in the future. These species can readily be incorporated into the BCTS system.

Optimal biocontrol investment should ideally include an investment portfolio of a range of weeds that contain: some targets that will require relatively little investment, and are likely to carry lower risk and will achieve benefits of reduced impact of the IAP, and others that require larger investment associated with higher risks but if successful will generate major benefits through management of the IAP (Morin et al., 2013). The BCTS system determined a range of top priority target plants that would represent both ‘easy’ programmes (transfer projects) and then ‘harder’ programmes (no previous biocontrol implemented). Transfer programmes are likely to take up less resources and time (Ehlers et al., 2020), typically these programmes take an average of 2.8 years per agent (Moran et al., 2005). New biocontrol programmes will take longer to develop, typically taking a minimum commitment of ten years, with an average of about four years to develop each agent (Moran et al., 2005). The choice of which of these prioritised species to commit to will lie with the decision makers and the level of risk they wish to take. Most governments have typically been found to be risk-averse (Palmer & Miller, 1996) and thus may favour implementation of the projects that have the greater chance of success (proof of successful biocontrol elsewhere). However, hopefully the BCTS system will outline that implementing research on the prioritised 'harder' targets and reducing the impacts of these major invaders will likely out-weigh the costs. For example, one of the top ranked species here, *Hakea drupacea* Roem. & Schult (Proteaceae) has high impacts in the region and is widespread, and has known potential biocontrol agents that could be investigated. This target plant had a biocontrol programme that has since been shelved, making it a 'hard' target (Zachariades et al., 2017); but the scoring in this system reflects a need to reinstate this research programme.

Five of the high priority target plants are considered at the early stages of their invasions and a number of targets plants that were ranked high in the system are considered 'proactive targets' (Zachariades et al., 2017). Targeting IAPs at the early stages of their invasions can enhance the prospects for success (Olckers, 2004; Zimmermann et al., 2004) as the introduction of biocontrol agents while weed populations are still small and localised can prevent the spread and impact of the target IAP (Van Wilgen et al., 2000). It also takes many years to develop a new biocontrol programme and in the time that safe and effective agents are sourced and studied the invasion may increase along with the weed's negative impacts. Targeting emerging weeds has generally not been done internationally as biocontrol is usually initiated as a last resort when other control methods fail (Olckers et al., 1998). South African biocontrol has however often launched projects on emerging species and in fact the WfW programme was the first to designate a specific budget to emerging weeds (Moran et al., 2005). Olckers (2004) stated that there is a need to further develop the rationale of targeting emerging weeds. The placement of these species within this model should contribute towards this goal and highlight the potential higher chances of successfully reducing their invasiveness.

The South African government's general procurement guidelines rest on five principles of procurement, (1) value for money, (2) open and effective competition, (3) ethics and fair dealing, (4) accountability and (5) reporting, and equity. The BCTS produced a list of species ranked in order of priority for biocontrol research funding that could help the DEFF to ensure procurement of research and implementation of findings are carried out in accordance with these principles. Biocontrol is underfunded compared to other forms of control and there is adequate evidence for the justification to increase these funds (Van Wilgen & De Lange, 2011). It is hoped that this prioritisation work will aid in highlighting the potential benefits from targeting these IAPs. The system is intended to be updated every three years along with the 'Status of biological invasions and their management in South Africa' report (Van Wilgen, Raghu, et al., 2020, Van Wilgen, Wilson, et al., 2020). The status report aims to inform on the development and adaptation of policies and control measures of invasive species in South

Africa. As such, the alignment of the prioritisation system should add value to these assessments as well as ensure that relevant information generated from these reports can be incorporated into the system.

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