South African Journal of Botany 154 (2023) 336–345

Contents lists available at ScienceDirect

South African Journal of Botany

journal homepage: www.elsevier.com/locate/sajb

Weed biological control in Zimbabwe: Challenges and future prospects

Gerald Chikowore[a,k,*], Grant D. Martin[a,i], Frank Chidawanyika[b,j], Martin Hill[a], Stefan Neser[c,1], Michael Day[d], Tony Grice[e,1], Godfrey Chikwenhere[f,1], Eunice Mangosho[g], Andy Sheppard[h]

[a] Centre for Biological Control, Department of Zoology and Entomology, Rhodes University, Grahamstown, South Africa
[b] International Centre for Insect Physiology and Ecology (ICIPE), P.O. Box 30772-00100, Nairobi, Kenya
[c] Weeds Research Division, ARC - Plant Health and Protection, Private Bag x134, Queenswood 0121, South Africa
[d] Queensland Department of Agriculture and Fisheries, GPO Box 267, Brisbane, QLD 4001, Australia
[e] CSIRO Ecosystem Sciences Private Mail Bag PO, Aitkenvale, QLD 4814, Australia
[f] Department of Agricultural Research and Specialist Services, Research Services Division, Plant Protection Research Institute, Harare, Ministry of Lands, Agriculture, Water and Rural Development, Zimbabwe
[g] Department of Agricultural Research and Specialist Services, Henderson Research Station, Mazowe, Agronomy Research Institute, Ministry of Lands, Agriculture, Water and Rural Development, Zimbabwe
[h] CSIRO, GPO Box 1700, Canberra, ACT 2601, Australia
[i] Afromontane Research Unit, Department of Zoology and Entomology, University of the Free State, Phuthaditjhaba, South Africa
[j] Department of Zoology and Entomology, University of the Free State, Bloemfontein, South Africa
[k] Department of Crop Science, Marondera University of Agricultural Sciences and Technology, Marondera, Zimbabwe

ARTICLE INFO

Article History:
Received 7 September 2022
Revised 7 January 2023
Accepted 30 January 2023
Available online 7 February 2023

Edited by: Dr S. Geerts

Keywords:
Biological Control Target Selection (BCTS)
Ecosystem
Invasive alien plants
Lantana camara
Prioritisation

ABSTRACT

In Zimbabwe, the structure and integrity of various ecosystems is rapidly deteriorating, in part due to invasive alien plants. While there is recognition of the challenges posed by invasive alien plants and the complexity surrounding their successful management, very little has been done, documented or evaluated in the country recently, including classical weed biological control activities. We review the current status of invasive alien plants and classical weed biological control in Zimbabwe especially their management and legislation governing this management. We record the presence and distribution of weed biological control agents currently in Zimbabwe. The Biological Control Target Selection (BCTS) system was used to identify invasive plant species in Zimbabwe that could benefit from on-going or new classical biological control programmes. While biological control has been implemented in the country since the 1960s, and significant control has been achieved on floating aquatic macrophytes, no biological agent has been released on a terrestrial weed since 1961. However, 10 agents released in neighbouring South Africa have spread naturally into the country on contiguous plant populations and some are providing gratuitous control of some of the weeds. We identified 19 invasive alien plants that could be successfully managed through classical weed biological control, and for 12 of these, this could be achieved at minimal cost, as agents are available within the region. Zimbabwe, perhaps with the help of international aid organisations investing in the region, could: a) conduct extensive surveys of established biological control agents already present in the country; b) redistribute these agents into areas of the country where they are not already present and foster those spreading north in South Africa and likely to arrive eventually through natural spread, and; c) initiate new weed biological control programmes against new targets by importing new agents available from South Africa or Australia.

1. Introduction

In Africa, biological control has been used for more than a century, achieving varying levels of success (Moran et al., 2013). The most recent world catalogue on weed biological control records 31 weed biological control agents have been deliberately released into 26 African countries other than South Africa, targeting 10 different weed species (Winston et al., 2022; Zachariades et al., 2022). Biological control of weeds in Zimbabwe began in 1961, when the lacebug, *Teleonemia scrupulosa* Stål (Hemiptera: Tingidae) was introduced from Kenya for the control of *Lantana camara* L. (Verbenaceae). Since then, nine arthropod agent species have been intentionally released against five weed species, with no new releases since 2009 (Sheppard et al., 2012; Winston et al., 2022). With the exception of *L. camara*, these releases were mainly on floating aquatic macrophytes. Another 11 insect species, some of which are regarded as successful biological

* Corresponding author at: Centre for Biological Control, Department of Zoology and Entomology, Rhodes University, Grahamstown, South Africa.
E-mail address: Gerald.Chikowore@ru.ac.za (G. Chikowore).
[1] Deceased authors

https://doi.org/10.1016/j.sajb.2023.01.054
0254-6299/

control agents in neighboring South Africa, have also been recorded in Zimbabwe, purportedly having arrived through natural spread (Sheppard et al., 2012; Winston et al., 2022). One example is *Dactylopius tomentosus* (Lamark) (Hemiptera: Dactylopiidae) (Klein et al., 2020) which was released close to the border in South Africa and is now controlling populations of *Cylindropuntia fulgida* var. *fulgida* Engelm. (Cactaceae) and *C. fulgida* var. *mamillata* in Zimbabwe.

Zimbabwe is divided into five agro-ecological regions, based on temperature and precipitation. In all these regions, weeds are perceived to be a major constraint to sustainable smallholder agriculture for cropping and grazing, and clean water resources (Chikwenhere and Keswani, 1997; Mashingaidze et al., 2012). In 2012, Australian Aid (AusAid) (dfat.gov.au/development/australias-development-program) and the Australian Centre for International Agricultural Research (ACIAR) (www.aciar.gov.au) at the invitation of the Zimbabwean government and the Food and Agriculture Organisation (FAO) Zimbabwe, commissioned a review of the impacts of weeds and assessment of introduced weed biological control agents in Zimbabwe in smallholder cropping systems, rangeland grazing systems and terrestrial and aquatic natural ecosystems (Sheppard et al., 2012). This was prompted by the lack of recent information on biological control activity, progress or impact in Zimbabwe. Findings from this mission confirmed the presence of intentionally released biological control agents on some weed species and undocumented arrivals. Furthermore, some species which could benefit from transfer projects within the region and elsewhere were identified. Unfortunately, no substantive steps were taken following that review.

Here we investigate the current legislative frameworks governing invasive species, their management and biological control in Zimbabwe. We also conduct a decennial review of the status of major weed species in the country, and recent agent releases and spread that have not previously been documented. We conclude by making recommendations for potential biological control targets and other weed management options for Zimbabwe.

2. Methods

A literature search was conducted on Google Scholar™ including, 'Zimbabwe', followed by relevant keywords including 'invasive alien species', 'management', 'biological control', 'biocontrol', 'legislation'. In addition, 'grey literature' was obtained from various experts who are currently or have previously worked on invasive alien plants control in the country.

These data sources were used to compile the list of problematic invasive alien plants in Zimbabwe as well as current management efforts. The list of biological control agents released and/or present in Zimbabwe was compiled from a mission report by Sheppard et al. (2012) and from the world catalogue of biological control agents by Winston et al. (2022). Finally, using the Biological Control Target Selection (BCTS) system (Canavan et al., 2021; Downey et al., 2021; Paterson et al., 2021a), we selected problematic IAPs in Zimbabwe that could benefit from ongoing biological control programmes within the region (Sheppard et al., 2012; Zachariades, 2021). The BCTS system makes use of 13 attributes assigned to each of three sections viz. impacts, likelihood of success and investment required, which can be used to assign a score for each plant species under consideration (Canavan et al., 2021; Downey et al., 2021; Paterson et al., 2021a). However, we adapted the system to the Zimbabwean context due to lack of information on some of the scoring aspects. Those species which had biological control agents released against them and were under complete biological control were excluded as potential targets. For the remaining species, the following criteria were used for inclusion into the list of potential targets: 1. the level of impact and ecosystem affected. 2. the likelihood of success based on success of biological control programmes on the target plant elsewhere. 3. the investment required where those plant species with agents available regionally were highly ranked.

3. Results

3.1. Research into invasive alien species

The literature searches on Google Scholar yielded 53 publications on invasive alien plants in Zimbabwe between 2010 and 2022. Most of the articles were published between 2017 and 2019 (Fig. 1) and provide an inventory of IAPs in Zimbabwe, together with distribution records, impacts and management activities. While some of the publications looked at IAPs in general, others focused on 16 specific species.

3.2. Invasive alien plants in Zimbabwe

Zimbabwe, like many other countries, has an abundance of plant species of alien origin and over 2000 such species have been collected and housed at the National Herbarium (Maroyi, 2017). Species occurrence data are also available on online sources such as iNaturalist, GBIF and the Flora of Zimbabwe (www.florazimbabwe.co.zw). Of the three sources, the Flora of Zimbabwe is most comprehensive, with nearly 6400 species of both native and naturalised plants in Zimbabwe, together with their geolocations (Hyde et al., 2022). Approximately 391 alien taxa have established, with 84 (21.5%) becoming invasive and the rest occurring as naturalised or casual invaders (Maroyi, 2012). Furthermore, a recent review by Mujaju et al. (2021) identified 34 terrestrial and aquatic species as the worst invasive plants, while roadside and targeted surveys by Sheppard et al. (2012) produced a list of 68 invasive alien plants encompassing woody, herbaceous and aquatic plants. Therefore, there is no consensus on invasive or potentially invasive species for the country, or data on their extents and rates of expansion, impacts on public goods and services and biodiversity, or the potential exacerbation by climate change, to guide policy and mitigation measures (V.R. Clark pers. comm. 2022; Mujaju et al., 2021).

3.2.1. Afromontane bioregion

Invasive alien plants in the Eastern Highlands have been a known problem since at least the 1980s (Childes, 1997). Most of the species are also problematic elsewhere in southern Africa where they have been introduced for commercial forestry and to private gardens (Lyut et al., 1986; Nyoka, 2003). The most extensive infestations are of woody species, particularly *Pinus patula* Schiede ex Schltdl. & Cham. (Pinaceae), *Acacia dealbata* Link, *A. mearnsii* De Wild, *A. melanoxylon* R.Br. (all Fabaceae) and

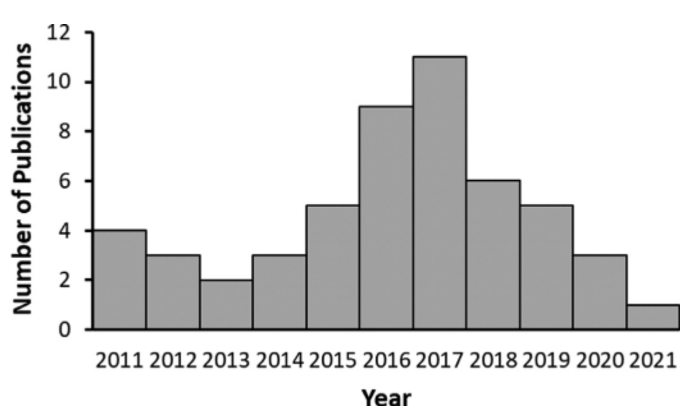

Fig. 1. : Number of publications on invasive alien plants in Zimbabwe between 2010 and 2012. Data source: Google Scholar™.

Eucalyptus grandis W.Hill ex Maiden (Myrtaceae) (Nyoka, 2003). By 2003, *P. patula*, considered to be one of the most serious montane invaders in southern Africa (Moran et al., 2000), was estimated to have invaded as much as 1000 km^2 (12%) of the Manica Highlands, and *A. mearnsii*, one of the top worst invaders globally, was estimated to have invaded c.2000 km^2 (24%; Nyoka, 2003). A number of other species (woody and other), such as *Hedychium gardnerianum* L. (Zingiberaceae) and *Vernonanthura polyanthes (=phosphorica)* (Spreng.) Vega & M. Dematteis (Asteraceae), are more problematic locally, in the Bvumba region. This latter species is a recently recognised invader originating from Brazil and for which there is little ecological knowledge for management (Ngarakana and Kativu, 2017). The endemic-rich grasslands are the worst affected biome, although indigenous and riparian forests are also affected (Childes, 1997; van Wyk and Smith, 2001; Nyoka, 2003), while many water bodies are extensively infested with invasive aquatic plants. The two national parks in the region, Nyanga and Chimanimani, have reportedly deteriorated from a moderate to a poor state between 2001 and 2008, mainly due to invasion by alien plants (Mukwashi and Matsvimbo, 2008). The spread and ecosystem deterioration has continued, despite a few localised management interventions (V.R. Clark, pers. comm. 2022).

3.2.2. Rangelands

While the most prolific and widespread IAP in rangelands is L. *camara*, other species are also exerting pressure on the grazing resources and the environment in general. For instance, *C. fulgida* was reported as the worst rangeland weed in the extreme southern parts of the country (Ministry of Environment, 2014). In addition, *Jatropha gossypiifolia* L. (Euphorbiaceae) reportedly covers wide tracts of disturbed rangelands (Sheppard et al., 2012). Other species of cacti are also present in the country, including: *Cereus jamacaru* DC. which is sparsely naturalised at several sites, with copious fruiting and many seedlings in both northern and southern extremities of Zimbabwe; *Opuntia monacantha* (Wild.) Haw., south of Mutare; and *Opuntia engelmannii* Salm-Dyck ex Engelm. var. *lindheimeri* at Shurugwi junction on the Beitbridge - Masvingo national road. *Pereskia aculeata* Mill. is common as a hedge plant mainly in urban areas, particularly suburbs of Harare, Chinhoyi and Mutare, although Sheppard et al. (2012) also observed infestations at Masimbiti (near Chiredzi) in Masvingo Province. It is considered a significant weed in South Africa where there is a biological control programme targeting it (Paterson et al., 2021b). *Opuntia microdasys* (Lehm.) Pfeiff. is occasionally present, particularly at Chisumbanje (south of the city of Mutare) in Manicaland Province.

3.2.3. Aquatic ecosystems

In aquatic ecosystems, five dominant species, *Salvinia molesta* D.S. Mitchell (Salviniaceae), *Pontederia crassipes* (Martius) Solms-Laubach (Pontederiaceae), *Pistia stratiotes* L. (Araceae), *Azolla filiculoides* Lam. (Salviniaceae) and *Myriophyllum aquaticum* (Vell.) Verdc. (Haloragaceae) have been reported (Chikwenhere and Forno, 1991; Chikwenhere and Keswani, 1997; Chikwenhere, 2001). All these, had biological control agents released against them and are deemed to be under control in some localities (Sheppard et al., 2012). New species such as *Limnobium laevigatum* (Humb. & Bonpl. ex Willd.) Heine (Hydrocharitaceae) are emerging in southern African countries, including Zimbabwe (Sheppard et al., 2012; Howard et al., 2016). In addition, there is little information on submerged aquatic macrophytes, although Sheppard et al. (2012) noted the possibility of their presence and Hyde et al. (2022) reported *Hydrilla verticillata* L. (Hydrocharitaceae) in Northern Zambezi and there are unconfirmed reports of *Egeria densa* Planch (Hydrocharitaceae) being present but with no specific localities.

3.3. Policy framework for the management of invasive alien species

Zimbabwe is party to the Convention on Biological Diversity (CBD), which calls on parties to prevent the introduction of, control or eradicate those alien species which threaten ecosystems, habitats and biodiversity (Article 8(h)). The CBD's Aichi Biodiversity Target 9 states that by 2020, invasive alien species and pathways should be identified and prioritized, that priority species are controlled or eradicated, and measures are in place to manage pathways to prevent their introduction and establishment. There is no CBD assessment of Target 9 post 2020 for Zimbabwe, but generally sub-Saharan Africa had made "no progress" or progress at an "insufficient rate" (https://www.cbd.int/aichi-targets/target/9). Target 10 of the Global Strategy for Plant Conservation 2011–2020 also advocates for effective management plans to prevent new biological invasions and to manage important areas supporting plant diversity that are invaded. These conventions are also linked to Sustainable Development Goal (SDG) 15.8 which targets the introduction of measures to prevent the introduction and significantly reduce the impact of invasive alien species on land and water ecosystems and control or eradicate the priority species by 2020. Zimbabwe is also a signatory to the International Plant Protection Convention (IPPC) whose aim is to protect cultivated and wild plants by preventing the introduction and spread of pests.

The country has several domestic policy instruments to manage invasive alien species. The Environmental Management Act (CAP 20:27) of 2002 administered by the Minister responsible for the environment is the overarching legislation on the management of IAS. There is also the Noxious Weeds Act (CAP 19:07) of 1927 (revised in 1996), which is administered by the Minister responsible for agriculture, but has been imported in its entirety into the environment ministry. Both Acts place the responsibility of managing specified alien species on landowners. Other legislation such as the Forestry and the Parks and Wildlife Acts provide for the control of invasive alien species in managed forests and national parks respectively.

While mechanical removal of weeds is the specified method of control, other management techniques require the authority of the responsible Ministers. For biological control, the importation of agents is governed by the Plant Pests and Diseases (Importation) Regulations (CAP 19:08) of 1976. Although the legislation primarily serves to protect plants against injurious organisms, section 2(b) provides for the importation of these organisms for experimental purposes. Under these regulations, there is need to obtain an import permit from the Ministry of Agriculture and potential agents are kept in quarantine and subjected to host-specificity tests before permission to release is granted. These regulations have allowed classical biological control to be applied against invasive alien arthropod and weed pests in the country.

3.4. Current control efforts

The Zimbabwe National Biodiversity Strategy and Action Plan (2014–2020) specifies the need to manage invasive alien species to conserve native biodiversity (NBSAP, 2014). To date, most effort and expense towards invasive alien control in Zimbabwe has been aimed at agricultural pests and invasive aquatic plants (Lyons and Miller, 2000; MacDonald et al., 2003). Meeting national targets on other invasive species has been hampered by lack of technical expertise and funds, especially in national park areas (CBD, 2022). Nevertheless, sporadic efforts have been initiated to manage IAPs from a local (Manica Highlands) to a regional perspective, with much of the initiative led by the Centre for Agriculture and Bioscience International (CABI) (V.R. Clark, pers. comm. 2022; Witt, pers. comm. 2022). However, some proposals to manage IAPs in the country were not implemented partly because of funding and administrative challenges. These challenges are common in sub-Saharan Africa, where financial constraints have led to authorities ignoring the problem of biological

Table 1
Weed biological control agents deliberately released in Zimbabwe (adapted and extended from Sheppard et al., 2012).

Scientific name and author Common name Region of origin	Biological control agent	Feeding guild	Biological control status	Level of damage inflicted	Origin & Source of biological control agent	Key references and other sources of information
ARACEAE						
Pistia stratiotes L. Water lettuce South America	*Neohydronomus affinis* Hustache (Coleoptera: Curculionidae)	Leaf & stem Borer	Introduced in 1988, established	Extensive	*Argentina and *Brazil; Australia and South Africa	2022; Sheppard et al., 2012; Winston et al., 2022
PONTEDERIACEAE						
Pontederia crassipes Mart. [formerly *Eichhornia crassipes* (Mart.) Solms] Water hyacinth South America	*Niphograpta albiguttalis* (Warren) (Lepidoptera: Crambidae: Spilomelinae)	Petiole borer	Introduced 1990, establishment unconfirmed	Unknown	*Argentina; Australia	Sheppard et al., 2012; Winston et al., 2022
	Neochetina bruchi Hustache (Coleoptera: Curculionidae)	Stem borer	Introduced 1990, established	Extensive	*Argentina; Florida, USA and Benin	Chikwenhere, 1993; Sheppard et al., 2012; Moyo et al., 2013; Winston et al., 2022
	Neochetina eichhorniae Warner (Coleoptera: Curculionidae)	Stem borer	Introduced 1990, established	Extensive	*Argentina; Florida, USA and Benin	Chikwenhere 1993; Sheppard et al., 2012; Winston et al., 2022
	Eccritotarsus catarinensis (Carvalho) (Hemiptera: Miridae)	Leaf sucker	Introduced 2001, did not establish	–	*Brazil; South Africa	Sheppard et al., 2012; Winston et al., 2022
SALVINIACEAE						
Azolla filiculoides Lam. Red water fern South America	*Stenopelmus rufinasus* Gyllenhal (Coleoptera: Curculionidae)	Frond feeder	Introduced 1998, established	Extensive	*North America, *Central America, *South America; South Africa	Chikwenhere, 2001; Sheppard et al., 2012; Winston et al., 2022
Salvinia molesta D.S. Mitch. Giant salvinia Argentina, Brazil, Paraguay, Peru, Uruguay	*Cyrtobagous salviniae* Calder & Sands (Coleoptera: Curculionidae)	Stem borer	Initially spread from Zambia in 1984, Introduced 1992, established	Extensive	*Brazil; Botswana	Chikwenhere, 1996; Sheppard et al., 2012; Winston et al., 2022
	Paulinia acuminata (De Geer) (Orthoptera: Acrididae)	Leaf eater	Introduced 1971, initially established, current status unknown	Trivial	Trinidad and Uruguay	2022; Winston et al., 2022
VERBENACEAE						
Lantana camara L. (sensu lato) *Lantana* Tropical and subtropical Americas	*Teleonemia scrupulosa* Stål (Hemiptera: Tingidae)	Leaf & flower Sucker	Introduced 1961, established	Medium	*Mexico;Kenya	Urban et al., 2011; Sheppard et al., 2012; Winston et al., 2022

* Indicates origin of the biological control agent.

invasions (Boy and Witt, 2013). In general, invasive species management has only been localised and poorly co-ordinated.

3.4.1. Conventional control

There are isolated efforts to manage invasive alien species in Zimbabwe. For example, the Parks and Wildlife Authority has an annual budget of USD3,600 to manage invasive alien species in National Parks in the eastern highlands, while plantation companies in the same region reportedly spend USD100,000 annually on invasive alien species (Mujaju et al., 2021). The primary means of control in all cases is mechanical removal. For example, the cut and ring barking method has been used to control *A. mearnsii* in Nyanga National Park, with results showing improved efficacy on trees older than 12 years, with diameters exceeding 16 cm (Muvengwi et al., 2018). Despite these efforts, populations of *A. mearnsii* have continued expanding. Communities in the southern parts of the country have also attempted to reclaim rangelands from L. *camara* and *C. fulgida* infestations using mechanical means, with marginal gains (Dube et al., 2017).

3.4.2. Biological control

Biological control has been implemented on a limited scale, involving a few taxa (Table 1). However, other agents have dispersed naturally from neighbouring countries (Table 2; Sheppard et al., 2012). The main programmes are described in more detail below.

Lantana camara has the longest history of biological control in Zimbabwe, with the release of *T. scrupulosa* in 1961. The agent was reported to have initially established but died out by 1965, without achieving control (Winston et al., 2022). Other agents released elsewhere have since been reported on the weed in Zimbabwe. These include the fruit-flesh-mining 'seed' fly *Ophiomyia lantanae* (Froggatt) (Diptera: Agromyzidae) reported in Zimbabwe prior to 1971 (Greathead, 1971), presumably having spread from South Africa. Sheppard et al. (2012) also noted several agents on L. *camara* that had been released in South Africa and were found in Zimbabwe for the first time. These include the leaf-mining fly *Calycomyza lantanae* (Frick) (Diptera: Agromyzidae), the flower bud-boring moth *Crocidosema* (=*Epinotia*) *lantana* Busck (Lepidoptera: Tortricidae), the leaf-feeding moth *Hypena laceratalis* Walker (Lepidoptera: Erebidae) (considered by some to be indigenous). They also recorded that *T. scrupulosa* was still present. Damage similar to that caused by the plume moth *Lantanophaga pusillidactyla* (Walker) (Lepidoptera: Pterophoridae) was also seen. Two other agents, *Ophiomyia camarae* Spencer (Diptera: Agromyzidae) and *O. lantanae* that had been previously reported in Zimbabwe were also seen during surveys by Sheppard et al. (2012). The moth, *Aristaea onychota* (Meyrick) (Gracillariidae), believed to be indigenous, was also recorded. Although no quantitative assessments of the level of damage by biological control agents have been made, *L. camara* is not considered under adequate control.

Biological control of aquatic weeds began in Zimbabwe in 1969, with the introduction of the grasshopper *Paulinia acuminata* (De Geer) (Orthoptera: Pauliniidae) to control *S. molesta* on Lake Kariba. The insect was reported to have established (Chikwenhere and Keswani, 1997), but it has not been recovered for many years (G. Chikwenhere pers. observ. 2012). In 1984, the weevil *Cyrtobagous salviniae* Calder and Sands (Coleoptera: Curculionidae), another biological control agent for *S. molesta*, was introduced from Zambia,

Table 2
Weed biological control agents that have dispersed from elsewhere into Zimbabwe (adapted from Sheppard et al., 2012).

Scientific name and author Common name Region of origin	Biological control agent	Feeding guild	Biological control status	Level of damage inflicted	Possible Source of biological control agent	Key references and other sources of information
ASTERACEAE						
Ageratina adenophora (Spreng.) R. M. King & H. Rob. Crofton weed Mexico	*Ragnhildiana perfoliati* (Ellis & Everh.) U. Braun, C. Nakash., Videira & Crous [formerly *Passalora ageratinae* Crous & A.R. Wood] (Capnodiales: Mycosphaerellaceae)	Leaf spot pathogen	Observed 2012, widespread	Trivial	South Africa	Sheppard et al., 2012
Xanthium strumarium L. Rough cocklebur Southern Europe, Asia	*Puccinia xanthii* Schwein. (Pucciniales: Pucciniaceae)	Rust pathogen	Observed 2012, widespread	Trivial	Unknown	Sheppard et al., 2012;
CACTACEAE						
Cylindropuntia fulgida (Engelm.) F.M. Knuth var. *fulgida* Chain-fruit cholla Mexico, south-western USA	*Dactylopius tomentosus* (Lamark), 'cholla' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Observed 2012, localised	Extensive	South Africa	Sheppard et al., 2012; Winston et al., 2022
Cylindropuntia fulgida (Engelm.) F.M.Knuth var. *mamillata* (A.Schott ex Engelm.) Backeb. Boxing-glove cactus Mexico, south-western USA	*Dactylopius tomentosus* (Lamark), 'cholla' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Observed 2012, localised	Extensive	South Africa	Sheppard et al., 2012; Winston et al., 2022
Opuntia ficus-indica (L.) Mill. mission prickly pear, sweet prickly pear Mexico	*Dactylopius opuntiae* (Cockerell), 'ficus' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	Reported 2011, observed 2021, localised	Extensive	South Africa	P. Bristow, H. Zimmermann pers. comm. 2011; G. Chikowore pers. observ. 2021
HALORAGACEAE						
Myriophyllum aquaticum (Vell.) Verdc. Parrot's feather South America	*Lysathia* sp. (Coleoptera: Chrysomelidae: Galerucinae)	Leaf feeder	Observed 2012, localised	Extensive	South Africa	Sheppard et al., 2012; Winston et al., 2022
PONTEDERIACEAE						
Pontederia crassipes Mart. [formerly *Eichhornia crassipes* (Mart.) Solms] Water hyacinth South America	*Orthogalumna terebrantis* Wallwork (Acari: Sarcoptiformes: Galumnidae)	Leaf miner	Observed 1996, localised	Moderate	South Africa	Sheppard et al., 2012; Winston et al., 2022
VERBENACEAE						
Lantana camara L. (sensu lato) Lantana Tropical and subtropical Americas	*Calycomyza lantanae* (Frick) (Diptera: Agromyzidae)	Leaf miner	Observed 2012, widespread	Trivial	South Africa	Sheppard et al., 2012; Winston et al., 2022
	Ophiomyia camarae Spencer (Diptera: Agromyzidae)	Leaf miner	Observed 2012, widespread	Trivial	South Africa	Sheppard et al., 2012; Winston et al., 2022
	Ophiomyia lantanae Froggatt (Diptera: Agromyzidae)	Fruit miner	Observed 1970s, widespread	Trivial	South Africa	Sheppard et al., 2012; Winston et al., 2022
	Hypena laceratalis Walker (Lepidoptera: Erebidae)	Defoliator	Observed 2012, widespread	Moderate	Native	Sheppard et al., 2012; Winston et al., 2022
	Lantanophaga pusillidactylus Walker (Lepidoptera: Pterophoridae)	Flower miner	Observed 2012, widespread	Trivial	South Africa	Sheppard et al., 2012; Winston et al., 2022
	Crocidosema lantana Busck (Lepidoptera: Tortricidae)	Flower & receptacle miner	Observed 2012, widespread	Trivial	South Africa	Sheppard et al., 2012; Winston et al., 2022

which had previously introduced the weevil from Australia (Winston et al., 2022). In 1991, the beetle was reported to be present on Lake Kariba, and to be controlling the weed there. *Cyrtobagous salviniae* was subsequently redistributed around the country, resulting in control of *S. molesta* in all water bodies in which it was released. *Salvinia molesta* is no longer considered a problem in Zimbabwe (Chikwenhere and Keswani, 1997). In 2021, a culture of *C. salviniae* was imported into Zimbabwe from South Africa for release on small ponds in the Marondera region of Zimbabwe (M. Hill unpubl. report, 2022).

In 1971, the weevil *Neochetina eichhorniae* Warner (Coleoptera: Curculionidae) was introduced to control *P. crassipes* but establishment was never confirmed. The beetle, along with a congener *N. bruchi* Hustache was re-released in 1990 into the Manyame River system, near Harare, where both species quickly established and achieved significant control in less than three years (Chikwenhere and Phiri, 1999). Both beetles were subsequently released on Lake Mutirikwi in 1993, Lake Kariba (1996) and Kudzwe Dam (1998) (Chikwenhere, 1993, 1994a, 2000, 2001). *Niphograpta* (=*Sameodes*) *albiguttalis* Warren (Lepidoptera: Crambidae) was released against

P. crassipes in 1994 but did not establish (Chikwenhere, 1994b; Winston et al., 2022).

In 1988, the weevil *Neohydronomus affinis* Hustache (Coleoptera: Curculionidae) was introduced to control *P. stratiotes* L. (Araceae) (Chikwenhere and Forno, 1991) and within 15 months, the weed was controlled (Chikwenhere, 1994c). The beetle is reported to be controlling *P. stratiotes* throughout its current range in Zimbabwe and the weed's population had decreased dramatically (G. Chikwenhere pers. observ. 2012).

The weevil *Stenopelmus rufinasus* Gyllenhal (Coleoptera: Erirhinidae) was introduced in 1998 from South Africa to control the floating fern *A. filiculoides* Lam. (Salviniaceae). The weevil was widely distributed and control of the weed was achieved throughout its observed range (McConnachie et al., 2004; G. Chikwenhere pers. observ. 2012).

Despite the presence and documented impacts of cacti in Zimbabwe, no formal biological control programme has been initiated on the family. However, biological control agents have been observed on two species, *Cylindropuntia fulgida* (Engelm.) F.M. Knuth var. *fulgida* and *C. fulgida* var. *mamillata* (coral cactus) and *Opuntia ficus-indica* (Table 2; Sheppard et al., 2012). The cochineal mealybug *Dactylopius tomentosus* (Lamark) (biotype: "cholla") was found to be present on most plants of both varieties of *C. fulgida* around Beitbridge and up to 85 km north-west along the road to Bulawayo. The insect had been previously released around Musina, South Africa, in 2011 and presumably spread north into Zimbabwe on contiguous populations of the weeds (Klein et al., 2020). In most cases, both varieties were heavily attacked and were dead or dying (Sheppard et al., 2012). The agent for *O. ficus-indica, Dactylopius opuntiae* (Cockerell) (Hemiptera: Dactylopiidae) was also observed near Darwendale, a small town in southern Zvimba District of Mashonaland West and had been previously reported as a pest of planted prickly pear near Beitbridge (P. Bristow, H. Zimmermann pers. comm., 2011).

Biological control agents that were recorded on two other IAPs during the survey by Sheppard et al. (2012) also likely spread from South Africa. These include, the leaf spot pathogen*, Ragnhildiana perfoliati* (Ellis & Everh.) U. Braun, C. Nakash., Videira & Crous, previously released on *Ageratina adenophora* (Spreng.) R.M.King & H.Rob. (Asteraceae) in South Africa and *Puccinia xanthii* Schwein. (Pucciniaceae) on *Xanthium strumarium* L. (Asteraceae).

3.5. Selection and prioritization of target species

The list of gazetted noxious weeds in Zimbabwe is limited to 10 weed species that are listed in both the EMA and Noxious Weeds Acts (Table 3). In comparison, the National Environmental Management Biodiversity Act of 2004 (NEM:BA) of South Africa, lists 383 fresh water, terrestrial and marine plant species in South Africa and ninety weed species have been targeted for biological control, 310 exotic natural enemies considered, and 92 established in the field on 66 target weeds (DEA, 2016; Zachariades, 2021). Most importantly, the availability of highly effective and host specific biological control agents is key in determining target species for biological control (Canavan et al., 2021). In southern Africa, it is generally considered that weed biological control is the method of last resort following unsuccessful chemical and mechanical attempts (Olckers, 2004). Nevertheless, biological control is a particularly appealing solution because it is non-toxic, pathogenic or dangerous to humans. It also has the advantage of being self-perpetuating once agents have established and when scientifically risk assessed, does not harm non-target organisms found in the environment. Results of the BCTS system showed that L. *camara* ranks highly as a priority weed as it is widely distributed across the country (Table 4). Although Australian *Acacias* are confined to the Eastern Highlands, they also ranked highly due to the sensitivity of the affected biome. From the prioritisation process, it is also evident that plants from the Asteraceae family are increasingly becoming problematic. While there are no agents for *V. polyanthes* within the region, its threats to natural ecosystems and potential spread to neighbouring countries resulted in its inclusion on the priority list. Several high impact weeds found in Zimbabwe have highly effective agents released on them in the region and/or in similar environments such as South Africa, Kenya and Australia.

4. Discussion

The threat of weeds to ecosystems, biodiversity and human livelihoods in Zimbabwe is becoming increasingly evident. This review, capturing the main results from Sheppard et al. (2012), shows that the country has achieved measurable success in the management of some of the worst weeds, especially in aquatic environments, mainly through biological control. It also shows that Zimbabwe has benefited in recent years from natural spread of biological control agents released in South Africa. There is, however, a gap in the implementation of management, including biological control, in recent years. Recent research on IAPs covers only a few species, and has mainly focussed on the extent of their invasion and impacts on ecosystems (Mujaju et al., 2021; Chakuya et al., 2022).

Results of the BCTS analysis in Table 4 illustrate the target weeds for which biological control is a management option in Zimbabwe. Despite the benefits Zimbabwe has gained from weed biological control agents that have spread from South Africa, only one biological control agent has been released in Zimbabwe in the past 20 years. There is now evidence of the country's readiness to re-embrace classical biological control considering recent releases of biological control agents on arthropod pests. We identified 19 invasive alien plants that could be successfully managed through classical weed biological control, and for 12 of these, this could be achieved at minimal cost as agents are available within the region.

The issue of funding and technical expertise capacity are the major constraints in tackling the problem of IAPs in Zimbabwe and other countries in the region other than South Africa. This limitation also explains the absence of documentation and or research in Zimbabwe on IAP post-control evaluation. In contrast, South Africa

Table 3
Weeds specified in the Noxious Weeds and Environmental Management Acts of Zimbabwe.

Family	Botanical Name	Common Name	Habitat
Araceae	*Pistia stratiotes* L.	Water lettuce	Aquatic
Cactaceae	*Harrisia martinii* (Labour.) Britton	Moonflower cactus	Terrestrial
	Opuntia aurantiaca Lindl.	Jointed cactus	Terrestrial
Convolvulaceae	*Cuscuta* spp.	Dodder	Terrestrial (parasitic)
Poaceae	*Avena fatua* L.	Wild oat	Terrestrial
Pontederiaceae	*Pontederia crassipes* (Mart.) Solms	Water hyacinth	Aquatic
Salviniaceae	*Azolla filiculoides* Lam	Water fern	Aquatic
	Salvinia auriculata Aubl.	Butterfly fern	Aquatic
	Salvinia molesta D.S. Mitch	Kariba weed	Aquatic
Verbenaceae	*Lantana camara* L.	Lantana	Terrestrial

Table 4
Potential target weeds for biological control in Zimbabwe according to the Biological Control Target Selection (BCTS), and specialist consultation.

Weed family	Species	Impact	Investment/Available agents	Mode of action	Source of agents	Likelihood of success
VERBENACEAE	*Lantana camara* L.	High. Invades rangelands and abandoned fields	*Aceria lantanae* Cook (Acari: Eriophyidae)	Flower bud galler	RSA, Australia, Zambia, Malawi	High, agent substantially reduces flowering and seeding
			Longitarsus bethae Savini & Escalona (Chrysomelidae: Alticinae)	Root feeder	RSA	High, substantially supresses root growth and flower production
FABACEAE	*Acacia mearnsii* De Wild. & *A. dealbata* Link	High, invades montane grasslands and conservation areas	*Melanterius maculatus* Lea (Coleoptera: Curculionidae)	Seed feeder	RSA	High, substantially reduces seed banks
			Dasineura rubiformis Kolesik (Diptera: Cecidomyiidae)	Flower bud galler	RSA	High, could easily establish in the eastern highlands
	Acacia melanoxylon R.Br.	High, problematic in montane grasslands	*Melanterius acaciae* Lea (Coleoptera: Curculionidae)	Seed feeder	RSA	High, reduces seed banks
	Leucaena leucocephala (Lam.) de Wit	A widely spreading agroforestry tree	*Acanthoscelides macrophthalmus* Schaeffer (Chrysomelidae)	Seed feeder	RSA	Low, agent impact limited
	Sesbania punicea (Cav.) Benth.		*Trichapion lativentre* Béguin-Billecocq (Brentidae)	Flower bud feeder	RSA	High
		Not fully known; highly invasive in RSA	*Neodiplogrammus quadrivittatus* Olivier (Curculionidae)	Stem borer	RSA	High
			Rhyssomatus marginatus Fåhraeus (Curculionidae)	Seed feeder	RSA	High
ASTERACEAE	*Ageratina adenophora* (Spreng) R. M.King &H.Rob.	High, threatens human and animal health	*Procecidochares utilis* Stone (Tephritidae)	Stem galler	RSA, Australia	Moderate
	Vernonanthura polyanthes (Spreng.) Vega & M. Dematteis	High, invades disturbed lands and interferes with pollination	High investment, no agents available	N/A	Native range	A good target for biological control considering impacts
	Tithonia rotundifolia (Mill.) S.F.Blake	High, invades disturbed areas and spreads quickly	*Zygogramma piceicollis* & *Z. signatipennis* Stål			
(Coleoptera: Chrysomelidae)	Leaf feeders	RSA	Moderate			
	Xanthium strumarium L.	High, invading disturbed agricultural landscapes	*Nupserha antennata* Gahan (Coleoptera: Cerambycidae)	Root feeder	Australia	Agent still under evaluation: results promising
ZINGIBERACEAE	*Hedychium gardnerianum* Sheppard ex Ker Gawl.	High, displacing blue swallows in the eastern highlands	*Metaprodioctes trilineata* Hope (Coleoptera: Curculionidae)	Rhizome feeder/ Stem and Shoot feeder (adults)	New Zealand	Agents still under evaluation
			Merochlorops dimorphus Cherian (Diptera: Chloropidae)	Stem miner	New Zealand	
EUPHORBIACEAE	*Jatropha gossypiifolia* L.	Highly toxic; invasive in degraded land	*Stomphastis* sp. (Lepidoptera: Gracillariidae)	Leaf miner	Australia	Agent under evaluation
			Prodiplosis hirsuta Kolesik (Diptera: Cecidomyiidae)	Shoot tip feeder	Australia	Agent under evaluation
COMMELINACEAE	*Tradescantia fluminensis* Vell	Emerging invader in the eastern highlands	*Neolema abbreviata* Lacordaire (Coleoptera: Chrysomelidae)	Shoot tip & leaf feeder	RSA	High; weed population still small
CACTACEAE	*Opuntia ficus-indica* (L)Mill..	Moderate, potential distribution wide	*Dactylopius opuntiae* (Cockerell) fi-form (Dactylopiidae)	Cladode sucker	Zimbabwe & RSA	High, Redistribution of available agents
	Cereus jamacaru DC. *and C. hildmannianus* K.Schum.	Moderate, potential distribution wide	*Hypogeococcus* sp. Granara de Willink (Hemiptera: Pseudococcidae)	Stem sucker	RSA	High
	Opuntia engelmannii Salm-Dyck ex Engelm. [formerly 'Northern Cape variety of *O. engelmannii*']	Not fully known; highly invasive in RSA	*Dactylopius opuntiae* (Cockerell), 'ficus' biotype (Hemiptera: Dactylopiidae)	Cladode sucker	RSA, Australia	Moderate, chance wrong biotype in Zimbabwe
	Opuntia monacantha Haw.	Moderate, potential distribution wide	*Dactylopius ceylonicus* (Green) (Hemiptera: Dactylopiidae)	Cladode sucker	RSA, Australia	High, redistribution of available agents
	Pereskia aculeata Mill.	Invasive in urban areas	*Catorhintha schaffneri* Brailovsky & Garcia (Hemiptera: Coreidae)	Stem wilter	RSA	High, agents mass reared in South Africa
			Phenrica guerini (Bechyné) (Coleoptera: Chrysomelidae: Alticinae)	Leaf feeder	RSA	High, agents mass reared in South Africa

(*continued*)

Table 4 (*Continued*)

Weed family	Species	Impact	Investment/Available agents	Mode of action	Source of agents	Likelihood of success
PONTEDERIACEAE	*Pontederia crassipes* Mart. [formerly *Eichhornia crassipes* (Mart.) Solms]	High, infesting inland water bodies	*Eccritotarsus catarinensis* (Carvalho) (Hemiptera: Miridae)	Leaf sucker	RSA	High, agents mass reared in South Africa
			Eccritotarsus eichhorniae Henry (Hemiptera: Miridae)	Leaf sucker	RSA	High, agents mass reared in South Africa
		HYDROCHARITACEAE	*Limnobium laevigatum* (Humb. & Bonpl. ex Willd.) Heine	High, spreading across southern Africa & on the Zambezi River	*Listronotus cinnamomeus Hustache* (Coleoptera: Curculionidae)	Leaf feeder, stem miner
Argentina						High

implements an area-wide integrated management approach through the Expanded Public Works Programme (encompassing the Working for Water programme) (van Wilgen et al., 2020; Paterson et al., 2021c).

Zimbabwe, as well as other southern African countries, stands to benefit from well-developed biological control infrastructure and expertise available within the region (Paterson et al., 2019; Langa et al., 2020), particularly if active weed biological control agent redistribution programmes were supported in the region to speed up benefits observed through natural spread of agents released elsewhere (Sheppard et al., 2012). Day et al. (2020), estimated the cost of introducing agents tested elsewhere or through active repeat/transfer or agent redistribution programmes into Low- and Middle Income Countries (LMIC) would be in the range of US$20,000-$50,000 compared to more than US$300,000 per agent where foreign exploration and host specificity testing is required before their release. Although the costs of foreign exploration and host specificity testing seem higher, they are outweighed by the benefits. However, due to resource limitations, several problematic species mentioned in Table 4 in Zimbabwe could be managed using agents developed and tested in neighbouring South Africa at minimal cost. Several studies have also shown that repeat/transfer programmes achieve a higher success rate (Hayes, 2000; Byrne et al., 2021) due to availability of information on the performance of the agents. We now discuss these opportunities across three dominant ecosystems.

4.1. Rangelands

Our results showed that cacti and lantana are the major and widespread rangeland weeds across Zimbabwe. However, some previously undocumented species such as *J. gossypiifolia* are emerging to be problematic in some localities. These weeds have been targets for biological control elsewhere. Hence, biological control would be a key tool for species-based weed management as such alien weeds are more often woody perennials against which biological control has proved quite effective globally (Markin et al., 1992). Given that rangeland weeds are generally symptoms of a degraded habitat due to poor land management, new biological control research would need to be positioned within a holistic and integrated management system context.

The *Opuntia* and *Cylindropuntia* cacti are the most feasible targets. Apart from *O. microdasys*, the *Opuntia* spp. observed in Zimbabwe have all been target of biological control with consistent success (Winston et al., 2022). It would be beneficial to consider the redistribution of the effective agents already present in the country and the introduction of agents available in South Africa and elsewhere, to target the Cactaceae present in these grazing systems. Beyond this group, biological control options, where work has already been undertaken elsewhere, are limited.

Effective biological control agents for L. *camara* have been elusive globally since research began more than 100 years ago (Winston et al., 2022). Zimbabwe lacks many of the agents already released in South Africa and other parts of the world. There are various agents that are seasonally damaging or damaging some forms of the plant in South Africa and Australia and that may spread naturally or could be released in Zimbabwe to assist or improve control (cf. Day et al., 2003). In the short term, Zimbabwe might benefit from the introduction of selected agents, such as *Aceria lantanae* (Cook) (Acari: Eriophyidae), which have been shown to considerably suppress lantana reproduction (Urban et al., 2011). In the long term, effective biological control of lantana in Zimbabwe, as elsewhere, needs further research on new, host-specific agents adapted to extreme, inland (continental) climates with cool dry winters.

4.2. Aquatic weeds

Overall, the alien, aquatic weeds found with biological control agents present were under either complete (*P. stratiotes* (water lettuce), *S. molesta* (giant salvinia), *M. aquaticum* (parrot's feather), and *A. filiculoides* (red water fern)) or significant (*P. crassipes*) biological control (Sheppard et al., 2012). For water hyacinth, local perceptions of the scale of the weed problem seemed overestimated, where mere presence was considered a future threat (Sheppard et al., 2012). The high abundance of the agents observed indicates that they may have the capacity to suppress future weed outbreaks, even in the relatively polluted and nutrient rich Lake Chivero. Nonetheless, our results suggested that additional biological control agents such as the sap sucker *Eccritotarsus catarinensis* (Carvalho) (Hemiptera: Miridae), the plant hopper *Megamelus scutellaris* Berg (Hemiptera: Delphacidae) and the petiole-boring moth *Niphograpta albiguttalis* (Warren) (Lepidoptera: Crambidae), already being used in South Africa, could complement the existing agents and provide more effective control in the future. Biological control of water hyacinth could also be more effective if there was a reduction in nutrient levels and water quality could be improved in affected lakes (Coetzee and Hill, 2012).

Information on the broad distribution of aquatic weeds in Zimbabwe is limited. Surveys of all major river systems, particularly next to dams and weirs, to understand the national distribution of the major and problematic introduced aquatic weeds and any biological control agents present, would be valuable. All existing biological control agents for these weeds could, through supported redistribution programmes, be released into river systems and water bodies where they are not already present. Finally, a biological control programme for L. *laevigatum* should be considered for countries in southern Africa. The weevil *Listronotus cinnamomeus* (Hustache) (Coleoptera: Curculionidae), which is specific to L. *laevigatum* has been found in Argentina (Cordo and DeLoach,1982).

4.3. Afromontane bioregion

The eastern Highlands of Zimbabwe are essential to alleviating poverty and encouraging sustainable development by providing unique public goods and ecosystem services of high societal value to Zimbabwe and Mozambique (van Wyk and Smith, 2001). The Highlands are also a local 'hotspot' of endemic and indigenous biodiversity having high island-like evolutionary significance, acting as a corridor between the east and southern African mountains. From the BCTS, Australian *Acacias* emerged as potential targets for biological control. For these species, piggybacking on South Africa's biological control experiences is the best and most realistic long-term way of controlling invasions in the highland regions. In South Africa, there are currently suitable-screened biological control agents for most of the problematic woody IAPs in these areas that could be considered for introduction. Potential weed biological control agents would however, need to be moved deliberately between montane regions because natural spread between such island-like ecosystems from surrounding countries is unlikely. It might be pertinent to survey the region to ensure biological control agents are not already present before any formal project is initiated. This study further showed that emerging invaders such as *H. gardneriunum* and *V. polyanthes* could be potential biological control targets considering their growing impacts, However, this requires considerable investment as there are no currently agents available for these species.

5. Conclusion

There is need for a supported and coordinated approach to better manage IAPs in Zimbabwe. Research and implementing agencies could be better coordinated to enable evaluation and documentation of management initiatives. Since biological control has been demonstrated as effective against many of the IAPs in Zimbabwe, the country and southern Africa more generally would benefit from collaboration with regional partners in reviving the application of this approach supported by current relevant legislation and a science-based regulatory environment. This would assist countries like Zimbabwe in achieving mutually agreed international biodiversity conservation targets under the CBD. Classical biological control is now recognised as an important tool for IAP management by both the IPPC and the CBD. These impacts of IAPs in Zimbabwe and the need and opportunity to take advantage of the local availability of proven weed biological control agents, could be considered a good return on investment for international aid providers supporting agriculture and the environment in the region. This could be through the funding of biological control agent redistribution programs and new weed biological control programmes where likelihood of success is high (Table 4). Undertaking a nationwide survey of biological control agents currently present in the country will inform such future courses of action.

Author contributions

All the authors participated in the writing of the manuscript.

Data availability statement

Data sets analysed during the study are available from authors upon personal request.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Acknowledgements

The Afromontane Research Unit (ARU), National Research Foundation (NRF) and South African Department of Forestry, Fisheries and the Environment (DFFE) are thanked for funding MH, GDM, GC, and FC noting that this publication does not necessarily represent the views or opinions of NRF and DFFE or their employees. AS and MD were funded by CSIRO and AusAID. Dr Ralph Vincent Clark, Prof. Arne Witt and Prof. Iain Patterson are thanked for providing useful expert opinion and revision of earlier drafts of this article. We are grateful to the three anonymous who greatly improved this manuscript.

References

Boy, G., Witt, A., 2013. Invasive Alien Plants and their Management in Africa. CAB Africa.

Byrne, M.J., Mayonde, S., Venter, N., Chidawanyika, F., Zachariades, C., Martin, G., 2021. Three new biological control programmes for South Africa: Brazilian Pepper, tamarix and tradescantia. Afr. Entomol. 29, 965–982.

CABI, 2022. Invasive Species Compendium. CAB International, Wallingford, UK. www.cabi.org/isc.

Canavan, K., Paterson, I.D., Ivey, P., Sutton, G.F., Hill, M.P., 2021. 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 Sci. Technol.. https://doi.org/10.1080/09583157.2021.1918638.

Chakuya, J., Furamera, C.-A., Jimu, D., Nyatanga, T.T.C., 2022. Effects of the invasive *Hedychium gardnerianum* on the diversity of native vegetation species in Bvumba Mountains, Zimbabwe. Int. J. Environ. Stud.. https://doi.org/10.1080/00207233.2022.2069861.

Childes, S., 1997. Invasive alien plants – a serious biological threat to the high altitude grasslands and microphyllous Shrubland of the Nyanga National Park. Poster presented at XVth AETFAT Congress, Harare.

Chikwenhere, G.P., 1993. Establishment of *Neochetina* weevils for control of water hyacinth in Zimbabwe. International Institute of Biological Control (IIBC) UK, Water hyacinth Newsletter 1, 1–2.

Chikwenhere, G.P., 1994a. Floating aquatic weeds in Zimbabwe. Wetlands ecology and priorities for conservation in Zimbabwe. In: Proceedings of a Seminar on Wetlands, Ecology and Priorities for Conservation in Zimbabwe. Harare, Kentucky Airport Hotel 13-15 January 1992, pp. 137–144.

Chikwenhere, G.P., 1994b. Biological control of water hyacinth (*Eichhornia crassipes*) in Zimbabwe – results of pilot study. FAO Plant Prot. Bull. 42, 185–190.

Chikwenhere, G.P., 1994c. Biological control of water lettuce in various impoundments of Zimbabwe. J. Aquat. Plant Manag. 32, 27–29.

Chikwenhere, G.P., 2000. Biological Control of Water hyacinth, *Eichhornia crassipes* (Martius) Solms-Laubach: an Evaluation of Factors Affecting Population Growth of *Neochetina bruchi* Hustache (Coleoptera: Curculionidae). Department of Ecology, The Royal Veterinary and Agricultural University, Copenhagen, Denmark. PhD Dissertation.

Chikwenhere, G.P., 2001. Current strategies for the management of water hyacinth, *Eichhornia crassipes* on the Manyame River system in Zimbabwe. Biological and Integrated Control of Water Hyacinth, Eichhornia crassipes, ACIAR Proceedings No. 102, pp. 105–108.

Chikwenhere, G.P., Forno, I.W., 1991. Introduction of *Neohydronomus affinis* for biological control of *Pistia stratiotes* in Zimbabwe. J. Aquat. Plant Manag. 29, 53–55.

Chikwenhere, G.P., Keswani, C.L., 1997. Economic benefits of biological control of Kariba weed (*Salvinia molesta* Mitchell) at Tengwe in North–Western Zimbabwe – a case study. Int. J. Pest Manag. 43, 109–112.

Chikwenhere, G.P., Phiri, G., 1999. History of water hyacinth and its control efforts on Lake Chivero in Zimbabwe. eds In: Hill, M.P., Julien, M.H., Center, T.D. (Eds.), Proceedings of the First IOBC Global Working Group Meeting for The Biological And Integrated Control of Water Hyacinth, 16–19 November 1998, Harare, Zimbabwe. ARC-Plant Protection Research Institute, Pretoria, pp. 91–100.

Coetzee, J.A., Hill, M.P., 2012. The role of eutrophication in the biological control of water hyacinth, *Eichhornia crassipes*, in South Africa. Biocontrol 57, 247–261.

CBD, 2022. Bioinvasion and Global Environmental Governance: the Transnational Policy Network on Invasive Alien Species. Zimbabwe's Action on IAS. Convention on Biological Diversity. https://www.cbd.int/invasive/doc/legislation/Zimbabwe.pfd. Accessed 11-04-2022.

Cordo, H.A., DeLoach, C.J., 1982. Weevils *Listronotus marginicollis* and *L. cinnamomeus* that feed on *Limnobium* and *Myriophyllum* in Argentina. Coleopterists Bull. 36, 302–308.

Day, M.D., Wiley, C.J., Playford, J., Zalucki, M.P., 2003. *Lantana:* Current Management *Status* and Future Prospects, 102. ACIAR Monograph, Canberra, Australia, p. 128.

Day, M.D., Witt, A., Winston, R., 2020. Weed biological control in low- and middle-income countries. Curr. Opin. Insect Sci. 38, 92–98.

DEA, 2016. Department of environmental Affairs: national environmental management: biodiversity Act, 2004 (Act No. 10 Of 2004). Alien and invasive species lists. Government Gazette No. 40166, Republic of South Africap. 56.

Downey, P.O., Paterson, I.D., Canavan, K., Hill, M.P., 2021. Prioritisation of targets for weed biological control I: a review of existing prioritisation schemes and development of a system for South Africa. Biocontrol Sci. Technol.. https://doi.org/10.1080/09583157.2021.1918636.

Dube, O., Ndlovu, J-N.G., Ncube, N.A., 2017. A Spatial analysis of effectiveness of eradication of invasive species in improving grazing for marginal livestock economies in dryland of Matabeleland South Region, Zimbabwe: a focus on *Lantana camara* and *Opuntia fulgida*. Adv. Ecol. Environ. Res. 2, 429–450.

Greathead, D.J., 1971. A Review of Biological Control in the Ethiopian Region. Technical Communication No. 5. Commonwealth Institute of Biological Control, Farnham Royal, England, CAB, p. 162.

Hayes, L.M., 2000. Technology transfer programs for biological control of weeds - the New Zealand experience. In: Spencer, N.R. (Ed.), Proceedings of the X International Symposium on Biological Control of Weeds 4-14 July 1999. Montana State University, Bozeman, Montana, USA, pp. 719–727. [ed.]..

Howard, G.W., Hyde, M.A., Bingham, M.G., 2016. Alien *Limnobium laevigatum* (Humb. & Bonpl. ex Willd.) Heine (Hydrocharitaceae) becoming prevalent in Zimbabwe and Zambia. Bioinvas. Rec. 5 (4), 221–225.

Hyde, M.A., Wursten, B.T., Ballings, P., Coates Palgrave, M., 2022. Flora of Zimbabwe: home page.https://www.zimbabweflora.co.zw/index.php, retrieved 10 April 2022.

Klein, H., Zimmermann, H.G., Xivuri, T., 2020. Exceptional biological control of two varieties of *Cylindropuntia fulgida* (Cactaceae) in South Africa using a recently-identified different biotype of the cochineal insect, *Dactylopius tomentosus* (Dactylopiidae). Biol. Control 149, 104314.

Langa, S.D., Hill, M.P., Compton, S.G., 2020. Agents sans frontiers: cross-border aquatic weed biological control in the rivers of southern Mozambique. Afr. J. Aquat. Sci. 45, 329–335.

Lyons, EE, Miller, SE (Eds.), 2000. Invasive Species in Eastern Africa: Proceedings of a workshop held at ICIPE, July 5–6, 1999. ICIPE Science, Nairobi.

Lyut, I.E., Mullin, L.J., Gwaze, D.P., 1986. Black wattle (*Acacia mearnsii*) in Zimbabwe. Australian Acacias in developing countries. Proceedings of an international workshop held at the Forestry Training Centre, Gympie, Queensland, Australiapp. 128–132. 4–7 August 1986.

Macdonald, I.A.W., Reaser, J.K., Bright, C., Neville, L.E., Howard, G.W., Murphy, S.J., Preston, G., (Eds). 2003. Invasive alien species in southern Africa: national reports & directory of resources. Global Invasive Species Programme, Cape Town, South Africa.

Markin, G.P., Lai, P.-.Y., Funasaki, G.Y., 1992. Status of biological control of weeds in Hawai'i and implications for managing native ecosystems. Eds Alien Plant Invasions in Native Ecosystems of Hawai'i: Management and Research. University of Hawaii Press, Honolulu, pp. 466–482.

Maroyi, A., 2012. The casual, naturalised and invasive alien flora of Zimbabwe based on herbarium and literature records. Koedoe 54, a1054.

Maroyi, A., 2017. Data on introduced plants in Zimbabwe: floristic changes and patterns of collection based on historical herbarium records. Data Brief 15, 348–369.

Marshal, B.E., Junor, F.J.R., 1981. The decline of *Salvinia molesta* on Lake Kariba. Hydrobiologia 83, 477–484.

Mashingaidze, N., Madakadze, C., Twomlow, S., Nyamangara, J., Hove, L., 2012. Crop yield and weed growth under conservation agriculture in semi-arid Zimbabwe. Soil Tillage Res. 124, 102–110.

McConnachie, A.J., Hill, M.P., Byrne, M.J., 2004. Field assessment of a frond-feeding weevil, a successful biological control agent of red water fern, *Azolla filiculoides*, in southern Africa. Biol. Control 29, 326–331.

Ministry of Environment, Water and Climate, 2014. Zimbabwe's Fifth National Report to the Convention on Biodiversity. Ministry of Environment, Water and Climate, Harare.

Moran, V.C., Hoffmann, J.H., Donnelly, D., Zimmermann, H.G., Van Wilgen, B.W., 2000. Biological control of alien, invasive pine trees (Pinus species) in South Africa. In: Proceedings of the X international symposium on biological control of weeds. 941, Montana State University, Bozeman, MT, USA, pp. 941–953.

Moran, V.C., Hoffmann, J.H., Zimmermann, H.G., 2013. 100 years of biological control of invasive alien plants in South Africa: history, practice and achievements. S. Afr. J. Sci. 109, 9–10.

Moyo, P., Chapungu, L., Mudzengi, B., 2013. A proposed integrated management approach to the control of water hyacinth: the case of of Shagashe River in Masvingo, Zimbabwe. Green. J. Phys. Sci. 3, 229–240.

Mujaju, C., Mudada, N., Chikwenhere, G.P., 2021. Invasive Alien Species in Zimbabwe (Southern Africa). eds Invasive Alien species: Observations and Issues from around the world. Volume 1: Issues and Invasions on Africa. John Wiley and Sons, pp. 330–361.

Mukwashi, K., Matsvimbo, F., 2008. Zimbabwe's Important Bird Areas: national Status Report 2008. Project Funded by the European Commission EuropeAid/ENV/2007/132–278.

Muvengwi, J., Mbiba, M., Jimu, L., Mureva, A., Dodzo, B., 2018. An assessment of the effectiveness of cut and ring barking as a method for control of invasive *Acacia mearnsii* in Nyanga National Park, Zimbabwe. For. Ecol. Manag. 427, 1–6.

NBSAP, 2014. National Biodiversity Strategy and Action Plan 2014–2020. Ministry of Environment: Water and Climate. https://www.cbd.int/doc/world/zw/zw-nbsap-v2-en.pdf.

Ngarakana, E., Kativu, S., 2017. Soil based assessment of the invasive species *Vernonanthura phosphorica* (Vell.) H. Rob. (Asteraceae) in Burma Valley, Zimbabwe. Trans. R. Soc. South Afr. 73 (1), 16–19. https://doi.org/10.1080/0035919X.2017.1369470.

Nyoka, B.I., 2003. Biosecurity in forestry: a case study on the status of invasive forest trees species in Southern Africa. Forest Biosecurity Working Paper FBS/1E. Forestry Department. FAO, Rome. FAO Forestry Paper No 140(Unpublished).

Olckers, T., 2004. Targeting emerging weeds for biological control in South Africa: the benefits of halting the spread of alien plants at an early stage of their invasion. S. Afr. J. Sci. 100, 64–68.

Paterson, I.D., Manheimmer, C.A., Zimmermann, H.G., 2019. Prospects for biological control of cactus weeds in Namibia. Biocontrol Sci. Technol. 29, 393–399.

Paterson, I.D., Hill, M.P., Canavan, K., Downey, P.O., 2021a. Prioritisation of targets for weed biological control II: the South African biological control target selection system. Biocontrol Sci. Technol.. https://doi.org/10.1080/09583157.2021.1918637.

Paterson, I.D., Klein, H., Muskett, P.C., Griffith, T.C., Mayonde, S., Mofokeng, K., Mnqeta, Z., Venter, N., 2021b. Biological control of Cactaceae in South Africa. Afr. Entomol. 29 (3), 713–734.

Paterson, I.D., Den Breeyen, A., Martin, G.D., Olckers, T., 2021c. An introduction to the fourth decadal review of biological control of invasive alien plants in South Africa (2011–2020). Afr. Entomol. 29 (3), 685–692.

Sheppard, A.W., Day, M.D., Grice, A.C., Neser, S., Chikwenhere, G.P., Mangosho, E., 2012. An Assessment of the status, Impact and Management of Weeds in Zimbabwe, with Particular Focus on Biological control, in the Context of Food Security and Sustainable Production from Smallholdings and Water Use in Lakes and Rivers. Australian Centre for International Agricultural Research. Final Report.

Urban, A.J., Simelane, D.O., Retief, E., Heystek, F., Williams, H.E., Madire, L.G., 2011. The invasive '*Lantana camara* L.' hybrid complex (Verbenaceae): a review of research into its identity and biological control in South Africa. Afr. Entomol. 19 (2), 315–348.

van Wilgen, B.W., Measey, J., Richardson, D.M., Wilson, J.R., Zengeya, T.A., 2020. Biological Invasions in South Africa. Springer Nature, p. 975.

van Wyk A.E., Smith, G.F., 2001 Regions of Floristic Endemism in Southern Africa. Umdaus, Hatfield.

Winston, R.L., Schwarzländer, M., Hinz, H.L., Day, M.D., Cock, M.J.W., Julien, M.H., 2022. Biological Control of Weeds: A World Catalogue of Agents and their Target Weeds, 5th edition USDA Forest Service, Forest Health Technology Enterprise Team, pp. 1–838. (Morgantown, West Virginia) FHTET-2014-04.

Zachariades, C., 2021. A catalogue of natural enemies of invasive alien plants in South Africa: classical biological control agents considered, released and established, exotic natural enemies present in the field, and bioherbicides. Afr. Entomol. 29 (3), 1077–1142.

Zachariades, C., Osariyekemwen, U., Hill, M.P., Mersie, W., Molo, R., 2022. The benefits to sub-Saharan Africa of the biological control of weeds: already considerable, but could be far greater. Curr. Opin. Insect. Sci. 52, 100932.