AUTHORS:
Erwin J.J. Sieben[1]
Şerban Procheş[1]
Aluoneswi C. Mashau[2]
Moleseng C. Moshobane[2,3]

AFFILIATION:
[1]School of Agricultural, Earth, and Environmental Sciences, University of KwaZulu-Natal, Durban, South Africa
[2]National Herbarium, South African National Biodiversity Institute (SANBI), Pretoria, South Africa
[3]Department of Biology, Sefako Makgatho Health Sciences University, Pretoria, South Africa

CORRESPONDENCE TO:
Erwin Sieben

EMAIL:
siebene@ukzn.ac.za

DATES:
Received: 22 June 2021
Revised: 10 Sep. 2021
Accepted: 13 Sep. 2021
Published: 27 Jan. 2022

HOW TO CITE:
Sieben EJJ, Procheş S, Mashau AC, Moshobane MC. The alignment of projects dealing with wetland restoration and alien control: A challenge for conservation management in South Africa. S Afr J Sci. 2022;118(1/2), Art. #11540. https://doi.org/10.17159/sajs.2022/11540

ARTICLE INCLUDES:
☒ Peer review
☐ Supplementary material

DATA AVAILABILITY:
☐ Open data set
☒ All data included
☐ On request from author(s)
☐ Not available
☐ Not applicable

EDITOR:
Teresa Coutinho

KEYWORDS:
invasive species, Expanded Public Works Programme, ecological restoration, revegetation, wetland plants

FUNDING:
Water Research Commission (project K5/1980)

The alignment of projects dealing with wetland restoration and alien control: A challenge for conservation management in South Africa

An inventory of wetland vegetation across the country generated a list of the most common invasive alien plants across South Africa. Many of the plants on that list do not correspond with the priorities in the programmes for alien control across the country, as they are not listed on a government produced list that guides the priorities for alien control. We explore the reasons for this situation. We argue that because wetlands are such important parts of the landscape, invasive aliens in wetlands are of special concern, and there should be more alignment between alien control programmes and wetland rehabilitation programmes. This alignment starts by considering the full number of species that form a threat to wetland habitats, but also considers which pesticides to use, erosion and recolonisation in wetlands, planting indigenous vegetation after aliens have been removed, and strategising by working from upstream to downstream. Existing alien control programmes for specific grasses (some relatively new to the country and in the phase of early detection) and floating aquatic plants may guide how to tackle the invasions of grasses and forbs that have been established in South African wetlands for an extended period of time.

Significance:

- Wetlands have a distinct set of alien invasive plants that affect their ecology and functioning and many of these plants are not listed as priorities in alien control programmes.
- Many restoration projects have an element of removing invasive plants and revegetating. Wetland restoration and alien control need to be integrated to preserve water resources.

Introduction

Two of the biggest conservation challenges that South Africa faces are the control of invasive alien plants and the prevention of the loss of wetland resources against land degradation. The government invests heavily in programmes that address these challenges while employing large numbers of low-skilled workers in public works programmes.[1,2] These programmes profess to pursue the same goals, which are the protection of biodiversity and enhancement of ecosystem services, which, in the context of a semi-arid country, revolve for a large part around protecting the condition of water resources. It is therefore surprising to find that there is little alignment between the programmes that aim to restore wetland habitats and those that remove invasive alien plants from them as most of the species that are targeted for alien control do not correspond with the invasive species that are commonly found in wetlands. Therefore, many of the invasive species that particularly affect wetland ecosystems are considered to have a low priority in alien control programmes.

Many invasive plant species are known to thrive in habitats that are regularly disturbed, such as riverbanks, which are naturally subject to regular flooding and removal of vegetation, and rivers also aid in the dispersal of seeds.[3] Rivers and their immediate environments are often among the worst invaded parts of a landscape,[4] and many of the efforts in alien control have focused on these areas. Therefore, there is an awareness of the connection between drainage networks and alien invasion, but this has not yet translated into systematic on-site control of invasive aliens in wetlands, when we recognise wetlands as distinct habitats within the drainage network, that are different from riverbanks. Invasive aliens growing along riverbanks are known to use excessive amounts of water and this is one of the reasons for their systematic removal from important catchments. They have their own dynamics; and guidelines for managing invasive alien plants in these areas are well developed.[5,6]

Wetlands in this study are defined as any terrestrial area where water is present at or close to the surface area for at least part of the year, the depth of which is never higher than 6 m.[7] This definition includes seepages, rivers, shallow lakes and saline pans, which are all areas that are inundated for extended periods of time and this inundation represents the main stress on vegetation. However, riverbanks are high-energy disturbance-prone environments that often do not get inundated for prolonged times and therefore not all riparian corridors can be regarded as wetlands. Wetlands are limited in extent but have a disproportionate role in many landscape-level ecosystem processes, often being referred to as the 'kidneys of the landscape' with reference to their role in biogeochemical cycles.[8] Invasions in these parts of the landscape should therefore be regarded as having high consequences for the landscape as a whole, even though the invaded areas may be limited in size due to the restrictions imposed by the size of the wetland. There are specific groups of plants that thrive in wetland environments that are defined as such, and these are not necessarily the same species as those that thrive on riverbanks.

When biological invasions take place in wetland environments, it should be a priority to understand what impact they have on wetland functioning and on the broader water cycle in the surrounding landscape. Wetlands are positioned in such a way in the landscape that it is nearly certain that invasions in them will have high social and ecological consequences[9], and this has implications for strategic planning around invasions in wetlands[1]. Species that are capable of surviving and establishing in a wetland environment need to have a certain number of morphological and physiological adaptations, but many of the traits required for this survival are also traits that benefit the invasiveness of organisms (clonal growth, large numbers of light seeds, high rate of resource capture[10]) and it is therefore expected that there will be a subset of the invasive species in South Africa that is particularly successful in invading wetland habitats. It also means that combating alien invasives in these habitats must not affect indigenous species with similar properties.

In this paper, we provide an overview of the problem of alien invasive species and how in particular they affect wetland ecosystems, with regard to species composition and ecological restoration. We focus on which species are mostly problematic in wetland habitats, speculate on why they may have been neglected in alien eradication programmes, and discuss some general problems that we have to face when dealing with invasion in wetland habitats.

Species that invade wetland habitats

Within the group of plants that have invaded South Africa so far, a limited number of species have created such problems that they have been prioritised for clearing and targeted for alien control.[11] Which species are included on the list of invasive species targeted to this effect, represents a critical decision within every integrated plan for control of invasives.[12,13] Legislation around alien control in South Africa's natural ecosystems is provided by the *National Environmental Management: Biodiversity Act No. 10 of 2004* (NEMBA). The invasive species that are targeted for alien control programmes are listed in the NEMBA legislation, whereby the species are categorised in different classes, with different strategies to prevent their further spread and their eventual eradication.[14] If wetland species are well represented on this NEMBA list, we would expect the majority of the most common alien invaders in wetlands to feature prominently on this list, as widespread occurrence of an alien invader is a suitable indicator for the level of threat that they pose.

The National Wetlands Vegetation Database provided the data on which this assessment of invasion of wetland habitats by invasive aliens is based.[15] Firstly, the most common invasive species in wetlands are listed and ranked in Table 1. Here it can be clearly seen that many of the most common species in this database are not listed in the NEMBA list of species. When all alien plant species (whether invasive or not) found in the wetlands of South Africa are cross-referenced with the NEMBA list for prioritisation for alien control, it appears that only a fraction of the invasive alien species in wetlands are listed as priorities for eradication and that this fraction is independent of their frequency of occurrence (Table 2).This can be tested with a chi-square test and it appears that the likelihood of a species to be found in wetlands and the likelihood for a species to be listed on NEMBA are independent of each other and therefore that the most important wetland invasive alien species are underrepresented when it comes to priorities in alien control.

Discussion

Species that are regularly found invading in wetland habitats have been largely overlooked in strategic planning around invasive plants. Exploring the reasons why such species are not targeted in alien control programmes and the difficulties that are faced when clearing wetlands of invasive species, may lead to an improvement in the overall management of invasive aliens and valuable water resources in the country.

The reasons why wetland invasive aliens do not feature very highly on the NEMBA list may partially be linked to properties of the plants themselves, but also to properties of the invaded habitats, the wetlands. The criteria that are used to list which invasive alien species are prioritised in national legislation are given by Nel et al.[16] and Moshobane et al.[17] It is worth looking more closely at the specific aspects of wetland plants that may create hurdles for the implementation of alien control in wetlands. Prioritisation in alien control considers the feasibility of success and these aspects may prevent action on alien control in wetlands as the risk of a poor return on investments is considered too high. Nevertheless, it is worth explaining the possible reasons explicitly, before looking at potential solutions of how to deal with the frequent occurrence of alien invasion in wetland habitats.

(1) Focus on ecosystem transformers creates a bias against herbaceous plants

Alien invaders that are known as 'transformers' change the landscape and the potential for humans to benefit from certain ecosystem services.[18-20] Because larger species have a proportionally larger impact on ecosystem processes,[21] it may seem to make sense to particularly focus on invasive species that produce high biomass such as trees and shrubs. Indeed, woody trees and shrubs often receive special attention in invasive biology[22] and many of the more aggressive invasive alien plants are known to have a woody habit.[23,24] These species also have an impact on local hydrology because of their deep taproots.

Many of the problematic plants in wetlands are herbaceous plants that can produce significant biomass although this is less obvious than with trees and shrubs, as they expand horizontally via rhizomes. Wetlands are naturally often dominated by clonal plants, especially those propagating by means of fragmentation (many aquatic plants) and those propagating by means of rhizomes.[25] This is probably because sexual reproduction requires germination, which is particularly problematic in anoxic environments. This means that alien invaders that have such means of propagation can be successful as invaders in wetlands. Whether they are alien or indigenous, clonally propagating species may often lead to monodominance.[26] In this case, grasses, especially, have been recognised as an important category of potentially invasive species[27] and species listed for eradication should be more inclusive of them[28]. Grasses of the genus *Paspalum* L. may have been overlooked because of their generally low stature and low biomass but represent true problems for wetland ecosystems.[29]

(2) Focus on invaders of recent wave of globalisation creates a bias against species from older waves of invasion

When invasive alien species are targeted for eradication, it is done generally because there is a fear that they will still expand and grow in extent, forming a threat to existing pristine ecosystems. Therefore, they tend to be species that have been brought in by the most recent wave of globalisation, in the last 50 or 100 years. However, human trade and traffic on an intercontinental scale has already been taking place for more than 500 years.[30] Species that have been introduced in earlier periods within Europe or the Middle East are generally known as archaeophytes.[31,32] But also, in other parts of the world, many species have been present long enough to have established and it is quite possible that some species are ignored as alien invaders simply because the landscape is already saturated with them.[33] They have occupied all their potential niches, and have stable populations that are no longer growing.

For many herbaceous wetland species in South Africa, the majority of local conservation practitioners are not aware of the fact that these species are alien, or their status is regarded as ambiguous (EJJS personal observation). It can be very difficult to establish whether a species has been part of a 'natural' jump dispersal event, or whether human traffic facilitated the process.[34] These introduced species may already have been present before extensive records of native biodiversity became established. But even in the long term, they may still pose problems as they change genetically and become better adapted to their new environment.[35] In South Africa, some widespread wetland species in this category that are locally dominant are *Carex acutiformis* Ehrh. and *Juncus inflexus* L. It is not known which indigenous plant communities they have replaced, as these are clonal dominants that cover the entire surface in their area of occurrence.

(3) Focus on transformed landscapes creates a bias against species that are capable to invade natural habitats slowly

Most invader species are being noticed because they tend to become dominant in certain areas over a very short period and become dominant in their local landscapes. These tend to be the landscapes that are close to urban centres, from where most invasions are starting.[36] But it is also possible that species start to spread geographically without

Table 1: Alien species prominent in wetland habitats ranked according to their frequency in the National Wetlands Vegetation Database[15]

Rank	Species	Fraction of wetland plots	Legal category	Growth form / functional type	Wetness zone
1	*Paspalum dilatatum* Poir.	9.43%		Tufted graminoid	S,T
2	*Verbena bonariensis* L.	4.94%	1b	Perennial forb	T
3	*Conyza albida* Spreng.	2.93%		Annual	T
4	*Juncus effusus* L.	2.93%		Tufted graminoid	P,S
5	*Cirsium vulgare* (Savi) Ten.	2.91%	1b	Rosette	S,T
6	*Persicaria lapathifolia* (L.) Gray	2.84%		Annual	S,T
7	*Paspalum distichum* L.	2.83%		Mat graminoid	P,S
8	*Paspalum urvillei* Steud.	2.83%		Tufted graminoid	S,T
9	*Oenothera rosea* L'Hér. ex Aiton	2.62%		Perennial forb	T
10	*Verbena brasiliensis* Vell.	2.24%	1b	Perennial forb	T
11	*Conyza bonariensis* (L.) Cronquist	2.13%		Annual	T
12	*Hypochaeris radicata* L.	2.11%		Rosette	T
13	*Tagetes minuta* L.	2.05%		Annual	T
14	*Veronica anagallis-aquatica* L.	1.94%		Annual	P,S
15	*Juncus inflexus* L.	1.87%		Tufted graminoid	S
16	*Carex acutiformis* Ehrh.	1.77%		Mat graminoid	P
17	*Alternanthera sessilis* (L.) DC.	1.73%		Perennial forb	P
18	*Cyperus esculentus* L.	1.70%		Tufted graminoid	S,T
19	*Bidens pilosa* L.	1.49%		Annual	T
20	*Xanthium strumarium* L.	1.44%	1b	Annual	T
21	*Lolium perenne* L.	1.40%		Mat graminoid	T
22	*Schkuhria pinnata* (Lam.) Cabrera	1.39%		Annual	T
23	*Senecio inaequidens* DC.	1.25%		Perennial forb	T
24	*Spergularia media* (L.) C. Presl.	1.21%		Annual	S,T
25	*Paspalum vaginatum* Sw.	1.09%		Mat graminoid	S
26	*Ageratum houstonianum* Mill.	1.09%	1b	Annual	S,T
27	*Ciclospermum leptophyllum* (Pers.) Eichler	1.07%		Annual	T
28	*Chenopodium album* L.	1.06%		Annual	S,T
29	*Amaranthus hybridus* L. s. *hybridus*	0.80%		Annual	T
30	*Alternanthera nodiflora* R.Br.	0.75%		Annual	P,S
31	*Pennisetum clandestinum* Chiov.	0.71%	1b	Mat graminoid	S,T
32	*Gamochaeta pennsylvanica* (Willd.) Cabrera	0.69%		Annual	T
33	*Acacia mearnsii* De Willd.	0.68%	2	Shrub	T
34	*Acacia saligna* (Labill.) H.L. Wendl.	0.66%	1b	Shrub	T
35	*Physalis viscosa* L.	0.61%		Perennial forb	T
36	*Bidens bipinnata* L.	0.59%		Annual	T
37	*Medicago laciniata* (L.) Mill.	0.57%		Annual	T
38	*Conyza canadensis* (L.) Cronquist	0.57%		Annual	T

T, temporary wet; S, seasonally wet; P, permanently wet

Table 2: Different categories of alien species in terms of their frequency of occurrence and the number of species that are NEMBA listed. The frequency of species found that are also listed on NEMBA does not differ significantly between rare and common species ($\chi^2 = 2.67$, d.f.$= 4$, $p=0.18$), which means that the NEMBA list does not effectively capture the most frequent species in wetlands.

	No. of species not listed on NEMBA	No. of species listed on NEMBA	Total number of species
Very rare (less than 0.18% of plots)	126	64	190
Rare (0.18–0.32% of plots)	15	5	20
Infrequent (0.32–0.52% of plots)	17	5	22
Occasional (0.52–1.5% of plots)	15	5	20
Frequent (1.5–10% of plots)	14	4	18
Total	187	83	270

attaining high-density local populations.[37] Compared to heavily disturbed landscapes, few alien plants can invade natural habitats, but many landscapes are subject to small-scale disturbances that can create local niches for invasive aliens, for example by means of subtle fire or grazing regime changes.[38] If the plant does not attain high densities and affect local ecosystem functioning in immediately obvious ways, it is likely to go unnoticed and ignored in eradication plans. Therefore, if a species is capable of invading natural or semi-natural ecosystems with minimum disturbance, it might mean that it is quietly spreading and might have delayed effects that may become evident only after environmental change takes place.

This scenario may be a problem in wetland species as these species always have the potential to start spreading clonally within their habitat as time proceeds. Even when populations do not easily disperse towards other wetlands, they may still form extensive populations within a single wetland. This leads to some species having very extensive but mainly local populations. Some invasive alien grasses that appear in large wilderness areas, such as the Drakensberg in South Africa, may appear in this category; an example is the grass *Deschampsia cespitosa* (L.) P.Beauv.[39] Even so, these species may impact such a wetland to such an extent that its functioning within the catchment as a whole is compromised and eventually seeds or clonal fragments can spread further downstream.

Unique problems associated with working in wetland habitats

An additional reason that many wetlands are neglected in terms of alien eradication programmes is to be found in the difficulties in working in wetland environments. Wetlands that are inward-draining, in particular, form sinks in the landscape (sinks for sediments, nutrients, propagules and eventually also for herbicides and other pollutants that may be used in combating aliens). This property of wetlands not only makes them very vulnerable to invasion, but also means that combating aliens in a wetland is a delicate matter that has the potential to lead to high concentrations of toxicants in the wetland and eventually to ecosystem collapse. It may be that manual control and the active planting of indigenous vegetation is the only remedy that helps in keeping wetlands free of invasive aliens.

We focus here on four aspects of control of alien invasions that we think play an important role for alien control in wetlands and that should be taken into consideration when aligning wetland conservation with control of invasive aliens.

(1) The choice of herbicides

The first issue that needs to be considered in combating aliens in wetlands is the use of herbicides. The challenge with the control of alien plants in wetlands with herbicides is due to the vulnerability or susceptibility of these aquatic environments. Around the world, the use of herbicides is highly regulated, and in South Africa specifically, the use of herbicides for control of weeds and invasive plants must be consistent with provisions in NEMBA and the *Fertilizer, Farm Feeds, Agricultural Remedies and Stock Remedies Act (Act No. 36 of 1947)*. The latter dictates that anyone using herbicides needs to have a valid Pest Control Operators Licence. Additionally, the pesticides that are used must be registered for use in aquatic environments by the Australian Pesticides & Veterinary Medicines Authority. All intended clearing activities should be outlined in the control plans which should be drawn up according to the guidelines required in Section 76 of NEMBA.[40]

Herbicides can be safely used in wetlands to protect the ecosystem from their negative effects, but only if they are applied correctly.[41] There are a number of characteristics that need to be considered when herbicides are applied in wetlands. For example, herbicides should have a low volatility at all temperatures in order to reduce the potential for spray drift.[42] They also should have a low water solubility, in order to reduce the potential for leaching to places of groundwater recharge or surface runoff.[41,43,44] Furthermore, the herbicides should have a low eco-toxicity and a low half-life, so that they cannot accumulate in the wetland, as many wetlands are inward-draining and would be ecological sinks.

Currently in South Africa there are no registered herbicides for use to control *Paspalum dilatatum* in terrestrial wetlands. However, some of the recommended herbicides for the control of this species are thiencarbazone-methyl, foramsulfuron, halosulfuron-methyl, fluazifop and monosodium methanearsonate combined with foramsulfurom.[45-47] The study by Henry et al.[45] has shown nearly 90% control of *Paspalum dilatatum* by multiple applications of monosodium methanearsonate with foramsulfuron during the summer season.

(2) Replanting indigenous vegetation after alien control

Many wetlands occur in key points in the landscape, and within South Africa, they are often very susceptible to erosion. Gully erosion is very common in wetlands and the removal of vegetation should therefore be accompanied by replanting of indigenous vegetation. The indigenous plants chosen for this purpose play an important role in the functioning of the restored ecosystem, in terms of holding the soil together, preventing erosion and preventing the establishment of new invasive alien plants. For this reason, it is important to select species that are viable and competitive in the environment in which they are planted, and that are suited to the hydrology and the substrate of the site in question. An in-field experiment in Wakkerstroom (Mpumalanga, South Africa) showed that an indigenous species such as *Cyperus fastigiatus* Rottb. can be suitable for preventing erosion cutbacks to proceed, even though the often-used species *Vetiveria zizanoides* L. is more effective in retaining soils in place when planted densely.[48] This last species is not indigenous but it has also been shown to be not invasive and is very effective in holding soils together on steep slopes.[49] However, in the long term, rhizomatous species that are local may be more effective in preventing both erosion and re-colonisation by invasive alien species. For this reason, it is important to have a good idea of reference conditions in the area and to choose species from the indigenous species pool that have suitable properties for this intended purpose (which are mostly rhizomatous species).

(3) Working downstream to prevent the spread of propagules

Many wetlands are part of a drainage system and alien invasions would spread through the wetland from the upper to the lower sections. Therefore, removal of invasive aliens should start in the upper parts of any river catchment working downstream to prevent new infestations.[50] Before the removal of alien invaders is attempted in a wetland, and resources are spent on that particular wetland, an assessment needs to be made on the state of the catchment upstream of that wetland.

Table 3: A list of emerging invasive grasses in wetlands that may become more widespread in the near future

Grass species	Habitat invaded	Challenges	Management	References
Glyceria maxima (Hartm.) Holmb.	Wetlands, so far only recorded in Boston-Bulwer-Underberg area in KwaZulu-Natal	Spreads rapidly through thick rhizomes, clogging waterways, and possibly has toxic effects on livestock	Listed under NEMBA Category 1b. Control through fire or chemicals	Fish et al.[39], Visser et al.[27], Mugwedi[51]
Phalaris aquatica L. and *P. arundinacea* L.	Wetlands in cooler regions at high altitudes	Stands are shade-tolerant and competitive, even under drought conditions	When detected early, it can be removed physically. Herbicides that have been used are amitrole-T (3-amino-1,2,4-triazole ammonium thiocyanate), glyphosate (N-[phosphonomethyl]glycine) and dalapon (2,2-dichloro propionic acid). Recommended in conjunction with prescribed burning. Not yet listed under NEMBA and no risk analysis available.	Visser et al.[27], Lyons[52]
Coix lacryma-jobi L.	Coastal areas of KwaZulu-Natal, especially in wetlands associated with streams	Utilised culturally as a food crop and ornamentally in beads and necklaces. Forms dense populations that can block streams.	Not yet listed under NEMBA and no risk analysis available	Fish et al.[39]
Cortaderia selloana (Schult. & Schult.f.) Asch. & Graebn.	Widespread in South Africa in seasonally wet habitats	Originally established to control soil erosion and as an ornamental	Listed under NEMBA Category 1b. Seedlings and small plants can be removed by pulling and digging.	Fish et al.[39]
Alopecurus arundinaceus Poir.	Stable population exists in Wakkerstroom wetland in Mpumalanga	Possibly overlooked where it has found since the 1960s (according to misidentified herbarium specimen in John Bews herbarium)	Not yet listed under NEMBA and no risk analysis available	Fish et al.[39]

Table 4: Most important invasive floating aquatic plants

Species	Habitat invaded	Challenges	Management	References
Azolla filiculoides Lam.	Sometimes rivers, mostly on dams, throughout South Africa	Fast clonal reproduction on the water surface	Listed as Category 1 on NEMBA list. It can be subjected to biological control with the weevil *Stenopelmus rufinasus, Gyllenhal*.	Cook[53]
Salvinia molesta D.S. Mitchell	Dams and pools in warm regions, mostly in eutrophic conditions	Fast clonal reproduction on the water surface. No sexual reproduction in South Africa.	Listed as Category 1 on NEMBA list. Biological control by means of the weevil *Cyrtobagous singularis Hustache*.	Cook[53], Motitsoe et al.[54]
Pistia stratiotes L.	Dams and pools in warm regions of the country. Originally from tropical Africa. May be tolerant of slightly brackish water.	Berries produced that may be dispersed by birds	Listed as Category 1 on NEMBA list	Cook[53], Coetzee et al.[55]
Pontederia crassipes Mart.	Dams and rivers in warm regions of the country. Juvenile stage submerged.	It can occur in heavily polluted water where it can remove heavy metals and purify the water.	Listed as Category 1 on NEMBA list. Biological control is feasible with weevils of the genus *Neochetina*.	Opande et al.[56], Jafari[57], Martinez Jimenez and Gomez Balandra[58]

(4) Restoring hydrology of the wetland

The main focus of wetland restoration is the adjustment of hydrology of a wetland system so that flooding regime and hydroperiod are restored to the natural situation. In some cases, this aim intersects with the presence of invasive alien species in the wetland, for example when those alien species absorb excessive amounts of water or when invasion has followed a drying period of the wetland. Manipulating the hydrology of wetlands through rewetting, dispersion of flow or plugging erosion gullies should make the wetland more suitable for indigenous vegetation. However, the removal of the invasive aliens should help accelerate the natural recruitment process.

Specific problems arising from some groups of invasive alien species

Lastly, we focus on two categories of invaders in wetlands and their removal: alien grasses and alien floating aquatics. Both groups are underrepresented in the National Wetlands Vegetation Database – the grasses because they are mostly recent invasions that are not yet very widely spread across the country, and the floating aquatic plants because they mostly invade farm dams and other artificial waterbodies that are underrepresented in the National Wetlands Vegetation Database. However, the practice of combating these alien species may inform ways in which other invasive species in wetlands, that have often not been considered, may be targeted as well.

Alien grasses

With alien grasses, it is very important to set up an early detection programme, as several grasses have been recorded in recent years that appear to cause problems on other continents. It has become clear that many grasses may remain undetected in wetlands just because many environmental practitioners are not familiar with them.[27] A number of recent finds of wetland invasive alien grasses in South Africa are listed in Table 3.

Alien floating aquatics

A second group of water plants that are often targeted for eradication are floating aquatic plants. There are four species that create problems in southern Africa. It is well established that floating aquatic plants create drastic changes to the underwater environment as they affect the light regime in the water column. The advantage of floating aquatic plants is that it is relatively easy to remove them mechanically, and, for most of them, there are biological control agents available in the form of weevils that graze on them. Submerged aquatic plants are much less of a problem in South Africa and most often only on a local scale, some examples being *Egeria densa* Planchon and *Myriophyllum aquaticum* (Velloso) Verdcourt. The four most troublesome floating aquatics are listed in Table 4.

Especially in the case of floating aquatic species, the removal of the aliens often triggers the recovery of the natural ecosystem. Consequently, the removal of invasive aliens should be regarded as an integral part of the restoration of natural ecosystems. This brings us back to the programmes for wetland restoration. Many of the wetland restoration works that have been carried out involve digging and may result in clear open areas that are subject to natural recruitment. If it is difficult and expensive to clear alien invasions in wetlands after they take place and it is difficult to control which plants enter a site, it may be a good idea to pre-empt alien invasion in wetlands by planting indigenous vegetation as a part of the restoration measures taken. Many of the species that enter a wetland after restoration are annuals and ruderal species, but eventually later-successional species may become more perennial aliens that are very difficult to remove.

In conclusion, alien invasion in wetland habitats is of particular concern and should be addressed as a distinct problem in ecosystem management. This has a bearing on both alien control programmes and wetland restoration programmes and if synergy between such programmes takes place, they will benefit the mandate of both. As South Africa faces an uncertain future with a water crisis looming, the alignment of these programmes is crucial if we want to obtain the goal of recovering the ecological functioning of wetlands, which are critical ecosystems that form an integral part of our ecological infrastructure.

Acknowledgements

We thank Ingrid Nänni, Sebataolo Rahlao, Umesh Bahadur, John Wilson and Farai Tererai for fruitful discussions that inspired the writing of this manuscript. The findings of the BSc Honours projects of Kimberley Moodley and Karmigan Naicker formed an important part of the conclusions that were discussed in the manuscript. We also thank the Water Research Commission (project K5/1980) for sponsoring the development of the National Wetlands Vegetation database that lies at the base of these findings.

Competing interests

We have no competing interests to declare.

Authors' contributions

E.J.J.S.: Conceptualisation, data collection, data analysis, writing – the initial draft, writing – revisions, project management. Ş.P.: Conceptualisation, writing – the initial draft, writing – revisions. A.C.M.: Writing – revisions. M.C.M.: Writing – revisions.

References

1. Van Wilgen BW, Forsyth GG, Le Maitre DC, Wannenburgh A, Kotzé JDF, van den Berg E, Henderson L. An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. Biol Conserv. 2012;148:28–38. https://doi.org/10.1016/j.biocon.2011.12.035
2. Hassan R, Mahlathi S. Evaluating the environmental and social net-worth of controlling alien plant invasions in the Inkomati catchment, South Africa. Water SA. 2020;46:54–65. https://doi.org/10.17159/wsa/2020.v46.i1.7881
3. Galatowitsch S, Richardson DM. Riparian scrub recovery after clearing of alien invasive trees in headwater streams of the Western Cape, South Africa. Biol Conserv. 2005;122:509–521. https://doi.org/10.1016/j.biocon.2004.09.008
4. Meek CS, Richardson DM, Mucina L. A river runs through it: Land-use and composition of vegetation along a riparian corridor in the Cape Floristic Region, South Africa. Biol Conserv. 2010;143:156–164. https://doi.org/10.1016/j.biocon.2009.09.021
5. Holmes PM, Richardson DM, Esler KJ, Witkowski ETF, Fourie S. A decision-making framework for restoring riparian zones degraded by invasive alien plants in South Africa: Review article. S Afr J Sci. 2005;101:553–564.
6. Holmes PM, Esler KJ, Richardson DM, Witkowski ETF. Guidelines for improved management of riparian zones invaded by alien plants in South Africa. S Afr J Bot. 2008;74:538–552. https://doi.org/10.1016/j.sajb.2008.01.182
7. Finlayson CM, Van der Valk AG. Wetland classification and inventory: A summary. Vegetatio. 1995;118:185–192. https://doi.org/10.1007/BF00045199
8. Schlesinger WH, Bernhardt ES. Biogeochemistry: An analysis of global change. Waltham: Academic Press; 2013.
9. Bacher S, Blackburn TM, Essl F, Genovesi P, Heikkilä J, Jeschke JM, et al. Socio-economic impact classification of alien taxa (SEICAT). Methods Ecol Evol. 2018;9:159–168. https://doi.org/10.1111/2041-210X.12844
10. Moor H, Rydin H, Hylander K, Nilsson MB, Lindborg R, Norberg J. Towards a trait-based ecology of wetland vegetation. J Ecol. 2017;105:1623–1635. https://doi.org/10.1111/1365-2745.12734
11. Kumschick S, Bacher S, Dawson W, Heikkilä J, Sendek A, Pluess T, et al. A conceptual framework for prioritization of invasive alien species for management according to their impact. NeoBiota. 2012;15:69–100. https://doi.org/10.3897/neobiota.15.3323
12. Veitch CR, Clout MN. Turning the tide: The eradication of invasive species: Proceedings of the International Conference on Eradication of Island Invasives; 2001 February 19–23; Auckland, New Zealand. Gland: IUCN; 2002.
13. Pyšek P, Richardson DM, Rejmánek M, Webster GL, Williamson M, Kirschner J. Alien plants in checklists and floras: Towards better communication between taxonomists and ecologists. Taxon. 2004;53:131–143. https://doi.org/10.2307/4135498
14. Henderson L. Alien weeds and invasive plants. Pretoria: Plant Protection Research Institute; 2001.
15. Sieben EJJ, Mtshali H, Janks M. National Wetland Vegetation Database: Classification and analysis of wetland vegetation types for conservation planning and monitoring. Pretoria: Water Research Commission; 2014.
16. Nel JL, Richardson DM, Rouget M, Mgidi TN, Mdzeke N, Le Maitre DC, et al. A proposed classification of invasive alien plant species in South Africa: Towards prioritizing species and areas for management action: Working for water. S Afr J Sci. 2004;100:53–64.
17. Moshobane MC, Mukundamago M, Adu-Acheampong S, Shackleton R. Development of alien and invasive taxa lists for regulation of biological invasions in South Africa. Bothalia. 2019;49:1–12. https://doi.org/10.4102/abc.v49i1.2361
18. Weidenhamer JD, Callaway RM. Direct and indirect effects of invasive plants on soil chemistry and ecosystem function. J Chem Ecol. 2010;36:59–69. https://doi.org/10.1007/s10886-009-9735-0
19. Vilà M, Espinar JL, Hejda M, Hulme PE, Jarošík V, Maron JL, et al. Ecological impacts of invasive alien plants: A meta-analysis of their effects on species, communities and ecosystems. Ecol Lett. 2011;14:702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x

20. Corbin JD, D'Antonio CM. Gone but not forgotten? Invasive plants' legacies on community and ecosystem properties. Invasive Plant Sci Manag. 2012;5:117–124. https://doi.org/10.1614/IPSM-D-11-00005.1

21. Grime JP. Benefits of plant diversity to ecosystems: Immediate, filter and founder effects. J Ecol. 1998;86:902–910. https://doi.org/10.1046/j.1365-2745.1998.00306.x

22. Richardson DM, Rejmánek M. Trees and shrubs as invasive alien species – A global review. Divers Distrib. 2011;17:788–809. https://doi.org/10.1111/j.1472-4642.2011.00782.x

23. Van Kleunen M, Dawson W, Maurel N. Characteristics of successful alien plants. Mol Ecol. 2015;24:1954–1968. https://doi.org/10.1111/mec.13013

24. Van Kleunen M, Dawson W, Schlaepfer D, Jeschke JM, Fischer M. Are invaders different? A conceptual framework of comparative approaches for assessing determinants of invasiveness. Ecol Lett. 2010;13:947–958. https://doi.org/10.1111/j.1461-0248.2010.01503.x

25. Song Y-B, Yu F-H, Keser LH, Dawson W, Fischer M, Dong M, et al. United we stand, divided we fall: A meta-analysis of experiments on clonal integration and its relationship to invasiveness. Oecologia. 2013;171:317–327. https://doi.org/10.1007/s00442-012-2430-9

26. Sieben EJJ, Le Roux PC. Functional traits, spatial patterns and species associations: What is their combined role in the assembly of wetland plant communities? Plant Ecol. 2017;218:433–445. https://doi.org/10.1007/s11258-017-0701-6

27. Visser V, Wilson JRU, Canavan K, Canavan S, Fish L, Maitre DL, et al. Grasses as invasive plants in South Africa revisited: Patterns, pathways and management. Bothalia. 2017;47:1–29. https://doi.org/10.4102/abc.v47i2.2169

28. Gaertner M, Biggs R, te Beest M, Hui C, Molofsky J, Richardson DM. Invasive plants as drivers of regime shifts: Identifying high-priority invaders that alter feedback relationships. Divers Distrib. 2014;20:733–744. https://doi.org/10.1111/ddi.12182

29. Nkuna KV, Visser V, Wilson JRU, Kumschick S. Global environmental and socio-economic impacts of selected alien grasses as a basis for ranking threats to South Africa. Neobiota. 2018;41:19–65. https://doi.org/10.3897/neobiota.41.26599

30. Robertson RT. The three waves of globalization: A history of a developing global consciousness. London: Zed Books; 2003.

31. Weeda EJ. The role of archaeophytes and neophytes in the Dutch coastal dunes. J Coast Conserv. 2010;14:75–79. https://doi.org/10.1007/s11852-009-0079-2

32. Aronson J, Aronson TB, Patzelt A, Knees SG, Lewis GP, Lupton D, et al. Paleorelicts or archaeophytes: Enigmatic trees in the Middle East. J Arid Environ. 2017;137:69–82. https://doi.org/10.1016/j.jaridenv.2016.11.001

33. Stohlgren TJ, Pyšek P, Kartesz J, Nishino M, Pauchard A, Winter M, et al. Widespread plant species: Natives versus aliens in our changing world. Biol Invasions. 2011;13:1931–1944. https://doi.org/10.1007/s10530-011-0024-9

34. Le Roux JJ, Strasberg D, Rouget M, Morden CW, Koordom M, Richardson DM. Relatedness defies biogeography: The tale of two island endemics (*Acacia heterophylla* and *A. koa*). The New Phytol. 2014;204:230–242. https://doi.org/10.1111/nph.12900

35. Sorte FAL, Pysek P. Extra-regional residence time as a correlate of plant invasiveness: European archaeophytes in North America. Ecology. 2009;90:2589–2597. https://doi.org/10.1890/08-1528.1

36. McLean P, Gallien L, Wilson JRU, Gaertner M, Richardson DM. Small urban centres as launching sites for plant invasions in natural areas: Insights from South Africa. Biol Invasions. 2017;19:3541–3555. https://doi.org/10.1007/s10530-017-1600-4

37. Liebhold A, Bascompte J. The Allee effect, stochastic dynamics and the eradication of alien species. Ecol Lett. 2003;6:133–140. https://doi.org/10.1046/j.1461-0248.2003.00405.x

38. Lake JC, Leishman MR. Invasion success of exotic plants in natural ecosystems: The role of disturbance, plant attributes and freedom from herbivores. Biol Conserv. 2004;117:215–226. https://doi.org/10.1016/S0006-3207(03)00294-5

39. Fish L, Mashau AC, Moeaha MJ, Nembudani MT. Identification guide to southern African grasses. An identification manual with keys, descriptions and distributions. Strelitzia. Vol. 36. Pretoria: South African National Biodiversity Institute; 2015.

40. South African Department of Environment, Forestry and Fisheries. National Environmental Management: Biodiversity Act No. 10 of 2004: Alien and Invasive Species Lists. Government Gazette. 2020;43726:31–104.

41. Donald DB, Cessna AJ, Farenhorst A. Concentrations of herbicides in wetlands on organic and minimum-tillage farms. J Env Qual. 2018;47:1554-1565. https://doi.org/10.2134/ jeq2018.03.0100

42. Bereswill R, Streloke M, Schulz R. Risk mitigation measures for diffuse pesticide entry into aquatic ecosystems: Proposal of a guide to identify appropriate measures on a catchment scale. Integr Environ Assess Manag. 2014;10:286–298. https://doi.org/10.1002/ieam.1517

43. Elliott JA, Cessna AJ. Transport of two sulfonylurea herbicides in runoff from border dyke irrigation. J Soil Water Conserv. 2010;65:298–303. https://doi.org/10.2489/jswc.65.5.298

44. Cessna AJ, McConkey BG, Elliott JA. Herbicide transport in surface runoff from conventional and zero-tillage fields. J Environ Qual. 2013;42:782–793. https://doi.org/10.2134/ jeq2012.0304

45. Henry GM, Yelverton FH, Burton MG. Dallisgrass (*Paspalum dilatatum*) control with foramsulfuron in Bermudagrass turf. Weed Technol. 2007;21:759–762. https://doi.org/10.1614/WT-06-163.1

46. Elmore M, Brosnan J, Mueller T, Horvath B, Kopsell D, Breeden G. Seasonal application timings affect dallisgrass (*Paspalum dilatatum*) control in tall fescue. Weed Technol. 2013;27(3):557–564. https://doi.org/10.1614/wt-d-13-00007.1

47. Johnston CR, Henry GM. Dallisgrass (*Paspalum dilatatum*) control with thiencarbazone-methyl, foramsulfuron, and halosulfuron-methyl in bermudagrass turf. Hortic Sci. 2016;51:754–756. https://doi.org/10.21273/HORTSCI.51.6.754

48. Sieben EJJ, Kotze DC, Noffke M. Erosion control in wetlands. Veld & Flora. 2007;93(2):106–107.

49. Banerjee R, Goswami P, Lavania S, Mukherjee A, Lavania UC. Vetiver grass is a potential candidate for phytoremediation of iron ore mine spill dumps. Ecol Eng. 2019;132:120–136. https://doi.org/10.1016/j.ecoleng.2018.10.012

50. Foxcroft, LC, Rouget M, Richardson DM. Risk assessment of riparian plant invasions into protected areas. Conserv Biol. 2007;21:412–421. https://doi.org/10.1111/j.1523-1739.2007.00673.x

51. Mugwedi LF. Invasion ecology of *Glyceria maxima* in KZN rivers and wetlands [MSc dissertation]. Johannesburg: University of the Witwatersrand; 2012.

52. Lyons KE. Element stewardship abstract for *Phalaris arundinacea*. The nature conservancy [webpage on the Internet]. c1998 [2021 Feb 18]. Available from: http://tncweeds.ucdavis.edu/esadocs/documnts/phalaru.html

53. Cook CDK. Aquatic and wetland plants of southern Africa. Leiden: Backhuys Publishers; 2005.

54. Motitsoe SN, Coetzee JA, Hill JM, Hill MP. Biological control of *Salvinia molesta* D.S. Mitchell drives aquatic ecosystem recovery. Diversity. 2020;12:204. https://doi.org/10.3390/d12050204

55. Coetzee JA, Langa SDF, Motitsoe SN, Hill MP. Biological control of water lettuce, *Pistia stratiotes* L., facilitates macroinvertebrate biodiversity recovery: A mesocosm study. Hydrobiologia. 2020;847:3917–3929. https://doi.org/10.1007/s10750-020-04369-w

56. Opande GO, Onyango JC, Wagai SO. Lake Victoria: The water hyacinth (*Eichhornia crassipes* [Mart.] Solms), its socio-economic effects, control measures and resurgence in the Winam gulf. Limnologica. 2004;34:105-109. https://doi.org/10.1016/S0075-9511(04)80028-8

57. Jafari N. Ecological and socio-economic utilization of water hyacinth (*Eichhornia crassipes* Mart Solms). J Appl Sci Environ Manag. 2010;14:43-49. https://doi.org/10.4314/jasem.v14i2.57834

58. Martinez Jimenez M, Gomez Balandra MA. Integrated control of *Eichhornia crassipes* by using insects and plant pathogens in Mexico. Crop Protect. 2007;26:1234–1238. https://doi.org/10.1016/j.cropro.2006.10.028