A proposed classification of invasive alien plant species in South Africa: towards prioritizing species and areas for management action

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Many invasive alien plant species in South Africa are already well-established and cause substantial damage, while scores of others are at the early stages of invasion (only recently introduced and/or entering a phase of rapid population growth). Management programmes must target well-established invaders, but must also give appropriate attention to emerging problems. Protocols for objectively prioritizing species in the two groups for management action are lacking. To this end, we describe the objective derivation of two lists of invasive alien plants in South Africa, using available quantitative data and expert knowledge on current patterns of distribution and abundance, life-history traits, and (for emerging invaders) estimates of potential habitat. 'Major invaders' are those invasive alien species that are well-established, and which already have a substantial impact on natural and semi-natural ecosystems. 'Emerging invaders' currently have less influence, but have attributes and potentially suitable habitat that could result in increased range and consequences in the next few decades. We describe the derivation of lists that contain 117 major invaders (categorized into groups based on geographical range and abundance) and 84 emerging invaders (categorized into groups based on current propagule-pool size and potentially invasible habitat). The main lists, and groupings within them, provide a useful means for prioritizing species for a range of management interventions at national, regional and local scales.

Introduction

South Africa's natural ecosystems, like those in most parts of the world, are under threat from invasive alien plants.[1,2] The scale of the problem facing managers of invasive alien plants in South Africa is huge; about 10 million ha has been invaded to some extent.[3] Many invaders are already well-established, while scores of others are at early stages of invasion. Several are recent introductions, and/or have only recently entered a phase of rapid population growth. Problems associated with plant invasions are escalating rapidly. Limited resources dictate that choices must be made about where to focus control efforts, and which species to select for control. This paper presents a protocol for the objective derivation of lists of major and emerging invaders, and of several categories within these main groups. Classification of invaders to this end is needed to inform strategic planning at national and regional scales.

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Several attempts have been made to prioritize alien species based on their invasive potential in different parts of the world. Most attention has been given to screening species for their invasive potential *before* their introduction to a given region.[4–8] Less systematic attention has been directed at classifying invasive alien species already in a region to help formulate regional or national plans for managing invasions. Where this has been undertaken, studies generally apply expert knowledge to score criteria such as impact and invasiveness of species.[9,10] For example, a process for determining and ranking 'Weeds of National Significance' was developed for Australia[11] based on expert scoring of four criteria: invasiveness, impacts, potential for spread, and socio-economic and environmental values. The top twenty species thus ranked were selected to serve as a test case for improved coordination amongst affected parties in Australia. A similar study in South Africa[12] sought to prioritize invasive alien species based on their potential invasiveness, spatial characteristics, potential impacts, and conflicts of interest. Species were then ranked by summed scores of expert ratings to provide a means of prioritizing species for national action.

There are, however, several limitations with such ranking exercises. First, there is no objective criterion that determines when a score is sufficient to qualify a species for high-priority management action. Comparisons are also difficult between species that occur over a wide range of different habitats, with varying levels of abundance and impacts. For example, Robertson's paper[12] reported difficulty in ranking priority for species requiring management at the local scale against more widespread species (perhaps much less abundant) requiring control effort over large areas. Thorp and Lynch[11] suggested that, for most species, rankings in such exercises should be seen as approximate rather than absolute, and that it may be more appropriate to view groups of invasive alien species with some degree of similarity as 'clusters'. This study attempts to provide a means for 'clustering' invasive alien species in a way that takes account of current distribution patterns (range and abundance) for established invaders, and best estimates on potential range (based on current propagule availability and invasible habitat) for emerging invaders.

An opportunity to define more meaningful clusters of currently invasive alien species than has been done to date is provided by the Southern African Plant Invaders Atlas (SAPIA). The SAPIA database contains records for over 500 species of invasive alien plants in South Africa, Lesotho and Swaziland, with information on their distribution, abundance and habitat types.[13] In the study reported here, we present two lists of invasive alien plants, classified to group species based on similarities in their distribution, abundance and/or biological traits. The first list contains those species that have already had a substantial impact on natural and semi-natural ecosystems of South Africa. Impact is defined as the product of a species' range, abundance

and per capita effect.[14,15] Thus a species having a high value for any one of these three components will have a high impact, and species with high values for all three components have the highest impact. These species (hereafter termed 'major invaders') are likely to constitute the prime concern for managers, and projects aimed at their control should receive the largest proportion of available funding over the next few decades.

The second list contains those species that currently have a lower impact on natural or semi-natural ecosystems in South Africa (that is, a lower product of range, abundance and effect), but which appear to have the capacity to exercise greater influence in the future (based on an assessment of life-history attributes and potentially invasible habitat). These species (hereafter termed 'emerging invaders') are currently afforded lower priority in management. Some of these are likely to become more important in the future, and could become targets for pre-emptive action (such as biocontrol[16]); these species should be carefully monitored to ensure that they do not become major problems. Ultimately, we hope to use the lists to help select species for modelling their rates of spread, to determine where to focus management action in the future, and to facilitate improved scenario development for managing biological invasions.[17]

Methods

Database of invasive alien plants in South Africa

We compiled a database of invasive alien plants that have already been introduced to South Africa (for the purposes of this study, we have also included Lesotho and Swaziland). While recognizing that other alien plant species present in South Africa may begin to spread, or that new, highly invasive species may yet be introduced to the country, the species in this database are likely to account for the bulk of expenditure on management over the next few decades.

We used data from the SAPIA database as the primary source of information. This atlas comprises nearly 50 000 invasive alien plant records, incorporating records from roadside surveys conducted by Lesley Henderson (1979–1993) and the SAPIA project (1994–1998), as well records collected on an *ad hoc* basis from 1999 onwards.[13,18–20]

In instances where there is taxonomic uncertainty within a genus or identification of species is problematic in the field, the field sheets submitted for inclusion in the SAPIA database did not identify single species. In these instances, there may be records for individual species, records which simply name the genus, or records with the names of two close relatives within the genus. For the purposes of compiling our initial database, these species and species-groups were combined, except for the records for eucalypts and pines, which we treated separately (we decided not to combine the records for these species and species-groups because of the different effects and ranges of the individual species). This yielded a total of 552 taxa (species or species-groups) from the SAPIA database. We used information in the SAPIA database on spatial locality, which is provided for all records at the level of quarter-degree squares (15′ latitude × 15′ longitude, hereafter called grid-cells). We also used information on habitat and abundance. The 18 different habitat classes in the SAPIA database were grouped to identify riparian, landscape and human-modified habitats (see below), and the abundance classes were used to help classify major invaders.

A further 29 plant species found in the country were added to our database, based on published literature[21,22] and a consensus amongst alien-plant experts that these species have the potential of invading natural ecosystems in South Africa. No detailed information on distribution and abundance was available for these species in South Africa, partly because some are at an early stage of invasion.

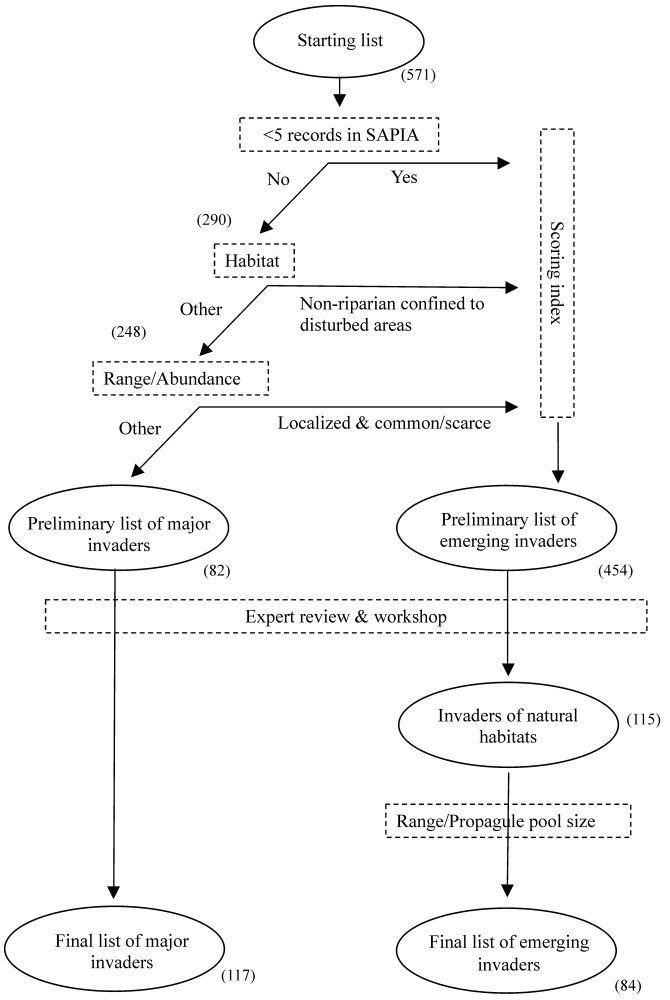

Fig. 1. Schematic representation of the approach used for constructing lists of major and emerging invaders in South Africa. Numbers in brackets are the number of species, or species-groups, after various filters had been applied to the database.

The database was reviewed by a team of seven alien-plant specialists, whose knowledge covered all major biome types, and represented approximately 175 years of collective relevant experience (ranging between 15 and 35 years per expert). These specialists also reviewed the lists of major and emerging invaders (see below). During the review, two species were added to the database, and 12 species were removed because a consensus was reached that either they were indigenous or that they did not yet occur in South Africa, Swaziland or Lesotho. This produced a final database of 571 species and species-groups, from which we identified major invaders and emerging invaders (Fig. 1).

Classification of major invaders

A preliminary list of major invaders was constructed by applying three filtering criteria to the SAPIA database: (i) the number of records, (ii) the type of habitat invaded, and (iii) the abundance and range of each species. First, we excluded any species having fewer than five records in the SAPIA database. Although some of these species could potentially have a major impact, they were not considered as significant invaders owing to their current limited distribution. This filtering rule reduced the original list from 571 species to 290 species (Fig. 1).

Next, we classified species as landscape invaders, riparian

Table 1. Thresholds used to define categories of abundance and range categories of likely major invaders in South Africa from information in the SAPIA database.

Range	Abundance
Very widespread (found in 350 or more grid-cells)	Abundant (the species was recorded in the SAPIA database as 'Very Abundant'/'Abundant' in 16% or more of the grid-cells where it is found)
Widespread (distributed over more than 70 grid-cells but fewer than 350 grid-cells)	Common (the species was recorded in the SAPIA database as 'Very Abundant'/'Abundant' in less than 16% of the grid-cells where it is found)
Localized (found in fewer than 70 grid-cells)	Scarce (quantitative data were insufficient, and during expert review of the information the abundance was confirmed as scarce)

invaders, or invaders of both landscape and riparian habitat. We did this using the 18 habitat categories in the SAPIA database,[13] which we grouped into riparian habitat (categories 'Watercourse' and 'Wetland'), and landscape habitat (all other categories). A species was classified as a riparian invader or a landscape invader if more than 75% of its records fell into the respective category. If neither the landscape nor riparian records exceeded 75% then the species was classified as an invader of both landscape and riparian habitats. We also distinguished species largely confined to human-modified habitat from those that invade natural and semi-natural habitats. Our interest in this study was in species invading natural and semi-natural ecosystems, that is, those that are still reasonably intact, having most of their biodiversity structure and functioning, and with primary driving forces operating within natural/evolutionary limits. A species was classified as being largely confined to human-modified habitat if more than 75% of its records fell into the following SAPIA database habitat categories: 'Road/Railside', 'Habitation', 'Plantation', 'Arable', 'Pastoral', 'Wasteland', and 'Transformed'. Using these categories, we applied the second filtering rule and excluded non-riparian species confined to human-modified habitat (riparian species confined to disturbed areas were included, based on the rationale that riparian habitats are naturally disturbed). This process reduced the list to 248 species (Fig. 1).

We classified the remaining 248 species according to range and abundance, the cut-off values for each category being determined using cluster analysis (Table 1). We performed two separate cluster analyses. The first, based on the number of grid-cells where the species was recorded, was used to determine the thresholds for range categories (very widespread, widespread, and localized). The second, based on the percentage of grid-cells where the species was recorded as 'abundant' or 'very abundant' in the SAPIA database, was used to determine the thresholds for abundance categories (abundant, common and scarce; see Table 1). Where more than one record with the same species and abundance code occurred within a grid-cell, it was counted as one record. The rationale for this was to eliminate any potential duplicate records for the same location. We excluded species from the range–abundance categories 'localized–scarce' and 'localized–common'. The list was thus reduced to 82 species, which we considered to be the preliminary list of major invaders, which was then submitted to expert review.

An expert workshop was held to review the range–abundance categories assigned to each species, according to the SAPIA database statistics. If there was general consensus amongst reviewers that some form of collection bias had resulted in an inaccurate classification, then species were moved to a more appropriate range–abundance category. If reviewers were in doubt as to which category a species belonged, then the species was left where it was, as dictated by the SAPIA database statistics on range and abundance. In this way, the range and/or abundance of 45 species in the 'localized–scarce' and 'localized–common' categories were elevated (that is, species that were initially excluded as major invaders were placed back on the major invaders list). A further 10 species were removed from the major invaders list because they are largely confined to human-modified habitats (that is, where habitat data of the SAPIA database seemed biased). This produced a final major invaders list of 117 species (Fig. 1).

Classification of emerging invaders

To construct the emerging invaders list, we first excluded all major invaders (namely, the 117 species above) from our original database of alien invasive plants in South Africa. This reduced the list to 454 species, which were then scored according to four criteria selected because of their strong association with factors that predict the potential invasiveness of plant species,[23] and the availability of quantitative data to support their subsequent scoring:

- Impact: the invasive status (listed in Henderson's guide to declared weeds and invaders[19]) was used to score impact in various categories[24], where 'Transformer' = 10, 'Potential transformer' = 5, 'Minor weed'/'Special effect weed'/'Poisonous'/'Irritant' = 1. Expert ratings were used to score the species added to the SAPIA database.
- Weediness: we used the global invasive status[25] to score weediness, based on the rationale that a plant showing signs of weediness elsewhere in the world has a higher chance of becoming problematic in South Africa.[23] Four of the 11 categories in Randall's compendium of weeds[25] were used to calculate a score for weediness, namely 'Sleeper weed', 'Noxious weed', 'Naturalized species' and 'Environmental weed'. The weediness score for each species was calculated by summing the number of times each species was listed within these four categories.
- Biocontrol: the status of species currently under biocontrol was scored based on available information,[26] and the potential of species for biocontrol in the future was scored using outputs from a recent expert workshop on biological control in South Africa. (Unpublished data from a workshop held in Thabameetse, South Africa, May 2002.) The categories[26] and scores thus derived were 'Complete' = 0 (species already under complete biocontrol are not likely to become a problem in the future, and are therefore unlikely to become emerging invaders), 'Substantial' = 1, 'Highly suitable' = 2; and 'Negligible'/'Unknown'/not listed = 5.
- Weedy relatives: this score gave the number of weedy species in the same genus worldwide,[25] expressed as a percentage of the total number of species per genus.[27] A recognized problem with this score is that the compendium of weeds[25] includes species that are introduced but not naturalized, and cultivated. To be accurate, records of congeneric species falling into these non-weedy categories should be excluded. Nevertheless, the score serves as a useful indicator of invasiveness.

Scores for these four criteria were standardized and weighted, with Impact, Weediness and Biocontrol receiving equal weighting of 4, and Weedy congeners receiving a lower weighting of 1 to

Table 2. Definitions used by alien plant experts to categorize the potentially invasible habitat and current propagule size of likely emerging invaders in South Africa.

Potential invasible habitat	Current propagule pool size
Large (likely to become dominant over large areas, i.e. a generalist)	Large (large plantation/crop plant; or widespread single plants)
Moderate (dominant in localized areas, i.e. a specialist)	Moderate (size is between large and small)
Small (not likely to dominate)	Small (isolated plants; few individuals)
Riparian (riparian/wetland species)	

account for the lower level of confidence in this factor. The weighted criteria were summed to obtain a combined score for each species. The combined score was used only as a first, coarse filter approach to focus attention at expert workshops on the species most likely to become problematic. Expert opinion overruled ranking results in some instances. All species with a combined score of 60 or more (just over 100 species) were chosen for collective expert review by the same experts who reviewed the major invaders list. The combined score cut-off of 60 was arbitrarily selected on the basis of what was manageable for the collective workshop, and species with a combined score of less than 60 were also reviewed by the same experts, but individually. For the individual reviews, experts were asked to elevate any species that had a combined score lower than 60, but which they felt were receiving too low a score. These species were included with those species with combined scores of 60 or more. The remaining species with scores less than 60 were excluded, reducing the list to 167 species.

Those species that are largely confined to human-modified habitats and have not shown the ability to invade natural or semi-natural ecosystems were identified by expert reviewers, and excluded. Our rationale was that species invading natural and semi-natural habitats will have the most impact on native biodiversity and ecosystem processes; the influence of alien plants in human-modified environments is generally less than that of the human impact itself. This reduced the list to 115 species.

We classified the remaining 115 species according to the amount of invasible habitat available for each species and their current propagule pool size. Experts estimated invasible habitat and current propagule pool size in various categories (Table 2). We excluded species from the categories where the combined invasible habitat and propagule pool was 'moderate habitat–small propagule pool', 'riparian habitat–small propagule pool', 'small habitat–moderate propagule pool', 'small habitat–small propagule pool'. The list was thus reduced to 84 species, which we considered to be the final list of emerging invaders (Fig. 1).

Comparisons with other national invasive alien plant management lists

We compared our lists of major and emerging invaders with four other national lists of invasive alien plant species:

1) The regulations pertaining to the Conservation of Agricultural Resources (Act 43 of 1983). These regulations provide legislation that lists different categories of 199 weeds and invasive alien species, and prescribes the actions which landowners are obliged to take to control these species.
2) A proposed prioritization system[12] that lists and ranks 61 priority invasive alien plant species for management in South Africa.
3) A ranking of the top 25 invasive alien plant species in South Africa, based on their estimated mean annual water use.[28]
4) A list of 84 important environmental weeds in southern African biomes.[2] This list was compiled by combining the 'transformer' species in South Africa's 'catalogue of problem plants'[21] with the invaders recorded as 'widespread' in a survey of South African nature reserves.[29]

Results

Database of invasive alien plants in South Africa

According to the distribution information recorded in the SAPIA database, almost 80% of the grid-cells within South Africa currently contain invasive alien species and almost 35% support 10 or more species. This excludes the additional 29 species in our invasive alien plant database for which we did not have distribution data. The areas containing more than 10 species per grid-cell occur mainly along the southern and eastern coasts of South Africa, along the eastern escarpment of Natal and Mpumalanga, and around the eastern Free State and Gauteng provinces (Fig. 2). These correspond to areas with a high proportion of transformed land (such as agriculture, forestry and urbanization), high rainfall and a high population density.

Major invaders

We identified 117 major invaders (Appendix 1, Table 3) and just over 80% of these have also been listed by the regulations under the Conservation of Agricultural Resources Act. Black wattle (*Acacia mearnsii*), white and grey poplars (*Populus alba/canescens*) and mesquite (*Prosopis glandulosa* var. *torreyana/velutina*) are the three species/species-groups falling within the 'very widespread–abundant' category (Table 3). More funds have been apportioned to controlling black wattle by the Working for Water programme than all other invasive alien plants together (C. Marais, pers. comm.). Twenty-five species of major invaders (21%) are defined as 'very widespread/widespread–abundant', all of which are listed in the regulations of the Conservation of Agricultural Resources Act (Table 3). The distribution pattern of these 'very widespread/widespread–abundant' species (Fig. 3a) corresponds to the areas where high overall numbers of invasive alien plants are recorded (*cf.* Fig. 2). Most of the major invaders fall within the 'widespread–common' (39%) and 'localized–abundant' (31%) categories (Table 3, Fig. 3b). The highest numbers of species in the 'localized–abundant' category are restricted to Western Cape and Natal coasts, and northeastern Mpumalanga and Gauteng (Fig. 3c).

Emerging invaders

We identified 84 emerging invaders (Appendix 2, Table 4), and almost 60% of these have been listed by the regulations under the Conservation of Agricultural Resources Act. Emerging invaders account for approximately 2500 records, or 5%, of the SAPIA database, and those species added from other sources[21,22] and expert knowledge, do not have any detailed spatial information. The limited spatial information that is available shows that these species currently occupy roughly the same areas where high numbers of major invaders were recorded (Fig. 2). Almost 20% of the emerging species are classified as riparian species according to expert opinion (Table 4). A further 17% are

estimated to have the potential of expanding over a large part of the country if unmanaged (categories 'large habitat–large propagule pool', 'large habitat–moderate propagule pool' and 'large habitat–small propagule pool' in Table 4), and almost 80% of species falling in these categories have been afforded legal status. These species are distributed along the eastern coast and northeastern interior, but have not yet been recorded in the Northern Cape and Western Cape (Fig. 4a, b). Most of the emerging invaders (61%) are estimated to have a moderate amount of invasible habitat available within South Africa (categories 'moderate habitat–large propagule pool' and 'moderate habitat–moderate propagule pool' in Table 4). These categories show a slight difference in species distribution; distribution patterns of the 'moderate habitat–large propagule pool' category (Fig. 4c) are similar to the 'localized–abundant' category of major weeds, whilst distribution patterns for the 'moderate habitat-moderate propagule pool' category show a lower incidence of fynbos invaders (Fig. 4d). The emerging invaders that are estimated to have a small amount of invasible habitat available but a large current propagule pool size (Table 4 and Appendix 2) show a very similar distribution pattern to the species which fall into the 'moderate habitat–large propagule pool' category (Fig. 4c).

Comparisons with other national invasive alien plant management lists

Of the 199 species listed in the regulations of the Conservation of Agricultural Resources Act, 50 (25%) are not in our lists of major and emerging invaders. None of these species qualified as major invaders, and were subsequently excluded from our list of emerging invaders owing to three filtering rules (Table 5): (i) the species scored less than 60 for their combined score and was not subsequently elevated based on expert review; (ii) the species is largely confined to human-modified habitat; or (iii) the habitat–propagule pool size did not fall within the required emerging invader categories (that is, those categories shaded in Table 4). Exclusions from the legal regulations mainly include those species that were proposed for listing under the Conservation of Agricultural Resources Act, but required further investigation before they could be included. These species are marked 'proposed' in Appendices 1 and 2.

Of the 61 species ranked and prioritized by Robertson *et al.*,[12] 51 are listed on our list of major invaders, and three are listed as emerging invaders. Seven species listed in Robertson *et al.*[12] do not occur on our lists (Table 5); six were removed because they are confined largely to human-modified habitat, and one was removed because it did not fall within the required emerging invader category. These species also received a low ranking (less

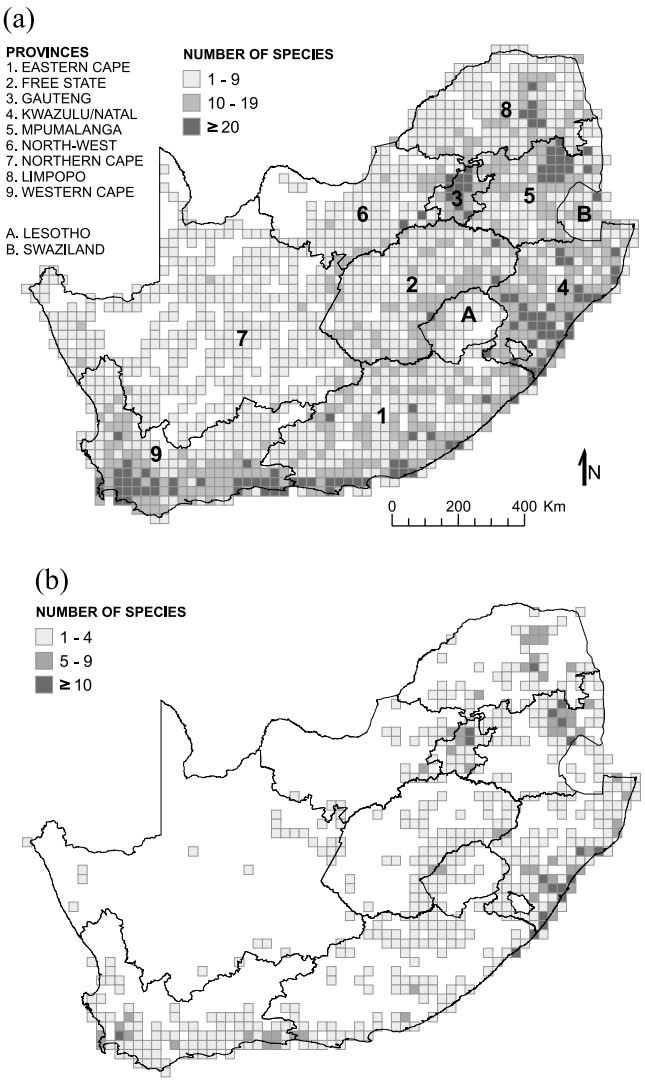

Fig. 2. Distribution of (**a**) major invaders and (**b**) emerging invaders in South Africa.

Table 3. The numbers of invasive alien plant species classified according to range and abundance. Major invader categories are shaded.

	Abundance			
Range	Abundant	Common	Scarce	Total
Very widespread	3 (3)*	8 (6)	0	11
Widespread	22 (22)	46 (34)	2 (1)	70
Localized	36 (29)	60	81	177
Total	61	114	83	258

*Numbers in brackets indicate number of species listed as declared weeds and invader plants by the Conservation of Agricultural Resources Act.

Table 4. The numbers of invasive alien plant species classified according to potentially invasible habitat and current propagule pool size. Emerging invader categories are shaded.

	Potential invasible habitat				
Current propagule pool size	Large	Moderate	Riparian	Small	Total
Large	4 (3)*	22 (17)	7 (4)	3 (1)	36
Moderate	7 (5)	29 (15)	9 (2)	11	56
Small	3 (3)	8	4	8	23
Total	14	59	20	22	115

*Numbers in brackets indicate number of species listed as declared weeds and invader plants by the Conservation of Agricultural Resources Act.

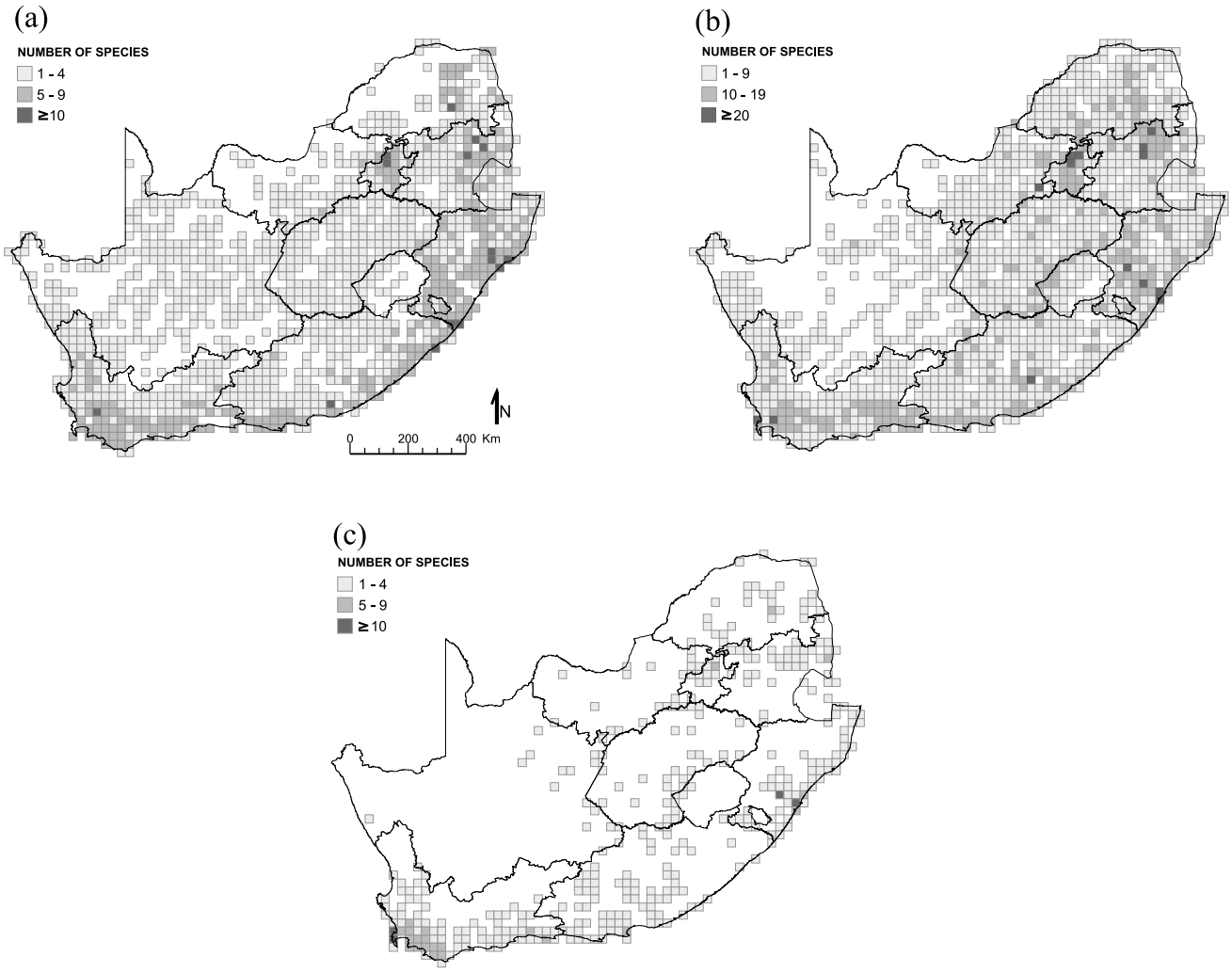

Fig. 3. Distribution of the number of major invader species per grid-cell for three range–abundance categories: (**a**) 'widespread–abundant', (**b**) 'widespread–common', and (**c**) 'localized–abundant'. Categories 'very widespread–abundant', 'very widespread–common' and 'widespread–scarce' were grouped respectively with 'widespread–abundant', 'widespread–common' and 'widespread–common', owing to their similar distribution patterns and/or small number of occupied grid-cells.

than 32) by the prioritization system of Robertson *et al.*[12]

All 25 species on the list of invasive alien plant species ranked according to their estimated mean annual water use[28] appear on our lists, and all are classified as major invaders except for English oak (*Quercus* species), which is classified as an emerging invader.

Of the 84 important environmental weeds in southern Africa recorded by Richardson *et al.*,[2] 24 species do not occur on our lists, the majority of which were excluded because they are confined largely to human-modified habitat (Table 5). Of the species that are common on both lists, 60 are classified as major invaders and three are classified as emerging invaders, namely the sugar gum (*Eucalyptus cladocalyx*), passion fruit (*Passiflora edulis*), and pereskia (*Pereskia aculeata*).

Discussion

The identification and classification of invaders presented here will ultimately be used to prioritize species on which to focus management and to identify those species which require further study and/or close monitoring. Classification is a necessary means of prioritizing species at a national level, because it circumvents the problem of prioritization across multiple spatial scales,[12] which make it difficult to compare the importance of species that occupy different ranges and habitats, with different levels of impact and abundance ('comparing apples with oranges'). This classification system therefore provides a means of implementing scale-appropriate management strategies. For example, the scale of the 'widespread–common' and 'localized–abundant' categories of major invaders have differ-

Table 5. Numbers of species appearing in legislation (Conservation of Agricultural Resources Act), or on other national lists of invasive alien plants[2,12], but which do not occur on our lists of major or emerging invaders, and reasons for their removal from our lists.

Reason for removal	Number of species not listed in legislation	Number of species not in Robertson *et al.*[12]	Number of species not in Richardson *et al.*[2]
Combined score <60	20	0	6
Largely confined to human-modified habitat	15	6	14
Range/propagule size filtering	14	1	2
Does not occur in South Africa, Lesotho or Swaziland	1	0	2
Total	50	7	24

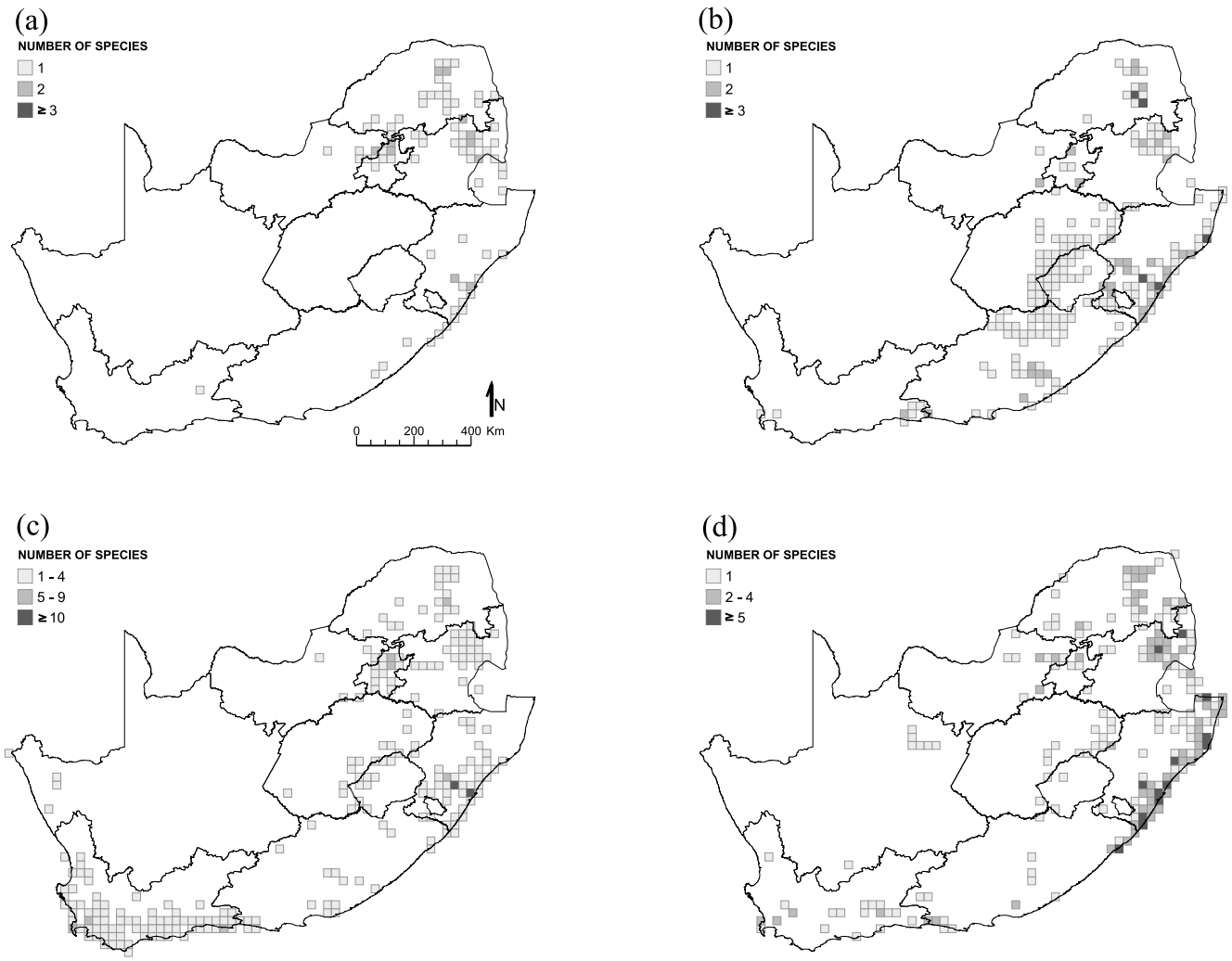

Fig. 4. Distribution of the number of emerging invader species per grid-cell for four categories of potentially invasible habitat and propagule pool size: (**a**) 'large habitat–large propagule pool', (**b**) 'large habitat–moderate propagule pool' (**c**) 'moderate habitat–large propagule pool', and (**d**) 'moderate habitat–moderate propagule pool'. Categories 'large habitat–small propagule pool' and 'small habitat–large propagule pool' were grouped with 'large habitat–moderate propagule pool' and 'moderate habitat–large propagule pool' respectively, owing to their similar distribution patterns and/or small number of occupied grid-cells.

ent implications for management; control efforts for species classified as 'widespread–common', for example, Australian blackwood (*Acacia melanoxylon*) or jointed cactus (*Opuntia aurantiaca*) are best launched at a national scale, whereas the species within the 'localized–abundant' category, such as rock hakea (*Hakea gibbosa*), will require habitat-specific control operations, at the regional or provincial scale. The categories will also help to define specific management guidelines. For example, emerging invaders with a large area of invasible habitat and a substantial propagule pool size should be investigated as priority species for research on biocontrol;[16] there should also be a sustained effort to eradicate the species within this category that are listed in legislation as 'category 1 species' (that is, have no economic or social benefits), and an attempt to limit the spread of those species listed in legislation as 'category 2 species' (those with commercial value). In contrast, emerging invaders with a small amount of invasible habitat and low propagule pressure may require only removal from sensitive sites, and basic monitoring of known populations can be designed to detect any changes in their invasion patterns.

Applying ranking systems[11,12] within each of the categories defined in this study would, therefore, circumvent scale issues, and further prioritize species within each of the categories presented by this study.

We have classified 117 species as well-established, major invaders. The distribution of the species which are 'widespread–abundant' (Fig. 3a) follows a similar pattern to the distribution of areas where high numbers of major invaders are recorded (Fig. 2a). This suggests that these areas are at the most risk of being severely affected by invasive alien plants because not only do they contain large numbers of invasive alien species, but the invasive alien species that do establish themselves also have the ability to become abundant within these areas. This is in sharp contrast to the northern interior and northwestern coast of the country, where both the number of major invaders and their associated abundance levels tend to be low (Figs 2a and 3b).

Emerging invaders do not appear to be establishing in areas which were previously not invaded and exhibit distribution patterns similar to major invaders (see Figs 2, 3 and 4). This suggests that some areas may be susceptible to invasion by alien plants because of certain climatic conditions, patterns of human settlement, or land-use patterns that predispose them to invasion by alien plants. Past invasions by 'major invader' species are also likely to be facilitating invasions of many of the 'emerging invader' species. Emerging invaders are often overlooked because they currently have few consequences compared to major invaders. However, they have the potential to cause severe impacts in the future if not kept in check. We have identified 84 species of emerging invaders. It is critical to incorporate these species into alien plant monitoring programmes.

South African researchers have also demonstrated that biocontrol is most effective during the earliest stages of invasion.[26] The emerging invaders identified in this study should be used as a pro-active means of focusing biocontrol research to identify agents that have the potential to keep these species under control, preventing them from having a major influence on natural and semi-natural ecosystems.

The relatively close correspondence between the results of this analysis and the species lists compiled and ranked using other data sources and criteria, demonstrates that there is general agreement on which are the most important species. The differences appear to be species which are grouped in the SAPIA database, or which are confined largely to human-modified habitat, but some are not easily explained. A more detailed assessment of the anomalies is needed but is beyond the scope of this paper.

Using quantitative data from the SAPIA database and other sources to guide experts in making decisions regarding the classification of invasive alien plants has the advantage of reducing the inevitable subjectivity of expert knowledge alone. In turn, experts were given the opportunity of collectively reviewing the quantitative data provided by the SAPIA database, and updating data gaps wherever there was reliable knowledge. A primary source of collection bias within the SAPIA database, which affected the classification of major invaders, was species visibility. Some of the less visible, undergrowth invasive alien plants, which in reality are quite widespread or common, were initially excluded from the major invaders list because their range and/or abundance was underestimated in the SAPIA database. Experts identified where this form of collection bias was evident and reached consensus on a more appropriate classification for these species during review.

There are two limitations of the data from the SAPIA database which affected our study, and could not be rectified. First, treating all species and species groups of pines as well as eucalypts separately (when they have been recorded by SAPIA sometimes as separate species and at other times combined into species groups) may have led to underestimating the extent of infestation of some individual species. Second, although the mapping programme has attempted to survey every grid-cell, the database is likely to contain a certain degree of collection bias towards areas which are easily accessible by road, or around the areas where active SAPIA contributors live and work. Future modelling exercises to examine potential distributions of species using data from the SAPIA database will help to correct this bias.

Conclusions

A national strategy to manage invasive alien plants will need to consider a broad range of management actions simultaneously. For example, it should aim to eradicate invasive alien plants that are confined to small areas or just beginning to become invasive; it should consider targeting emerging invaders for biocontrol;[16] and it should seek to prioritize areas on which to focus management of the most widespread species. Our classification system provides a starting point on which these priorities can be formulated. In addition, predictive modelling is planned to explore the potential distribution ranges for the major and emerging invaders. This, in turn, will aid further prioritization through the identification of invaders that probably have achieved their full potential range in the country, and those which still have significant available habitat into which they can spread, as well as areas which are particularly vulnerable to invasions. This will help us to predict species and areas where current and future management will be most cost-effective.

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Appendix 1. Major invaders grouped according to categories. 'No. grid-cells' is the number of grid-cells where the species has been recorded in the Southern African Plant Invaders Atlas (SAPIA) database; '% grid-cells abundant' is the percentage of grid-cells in South Africa where the species is recorded as very abundant or abundant in the SAPIA database (note: where more than one record with the same species and abundance code occurred within a grid-cell, it was counted as one record); 'Riparian or landscape' is the classification given to a species if more than 75% of its records in the SAPIA database fell into the respective category (if neither the landscape nor riparian records exceeded 75% then the species was classified as 'both'); and 'CARA category' lists the species regulated by the Conservation of Agricultural Resources Act (Act 43 of 1983), where 1 refers to Category 1 prohibited weeds that must be controlled in all situations; 2 includes Category 2 plants with commercial value that may be planted in demarcated areas subject to a permit, provided that steps are taken to control spread; 3 includes Category 3 ornamental plants that may no longer be planted or traded, but may remain in place provided a permit is obtained and steps taken to control their spread; and 'proposed' includes those species that were proposed for listing under the Conservation of Agricultural Resources Act, but require further investigation before they can be included.

Range–abundance	Scientific name	Common name	Number of grid-cells	% Grid-cells abundant	Riparian or landscape	CARA category
Very widespread–abundant	*Acacia mearnsii*	Black wattle	432	28	Both	2
	Populus alba/canescens	White and grey poplars	557	20	Riparian	2
	Prosopis glandulosa var. *torreyana/velutina*	Honey mesquite/prosopis	453	15	Both	2
Very widespread–common	*Agave americana*	American agave	433	1	Landscape	Proposed
	Arundo donax	Giant reed	377	14	Riparian	1
	Eucalyptus spp.	Gum trees	506	4	Both	
	Melia azedarach	Seringa	558	7	Both	3
	Nicotiana glauca	Wild tobacco	396	3	Both	1
	Opuntia ficus-indica	Sweet prickly pear	863	4	Landscape	1
	Ricinus communis	Castor-oil plant	471	7	Riparian	2
	Salix babylonica	Weeping willow	475	12	Riparian	2
Widespread–abundant	*Acacia cyclops*	Red eye	167	29	Both	2
	Acacia dealbata	Silver wattle	256	24	Riparian	1/2
	Acacia longifolia	Long-leaved wattle	95	24	Both	1
	Acacia saligna	Port Jackson willow	160	28	Both	2
	Ageratina adenophora	Crofton weed	11	19	Riparian	1
	Ageratum conyzoides/houstonianum	Invading ageratum	74	26	Riparian	1
	Argemone mexicana	Yellow-flowered Mexican poppy	29	18	Riparian	1
	Atriplex lindleyi ssp. *inflata*	Sponge-fruit saltbush	164	43	Landscape	3
	Azolla filiculoides	Red water fern	206	36	Riparian	1
	Caesalpinia decapetala	Mauritius thorn	128	19	Both	1
	Campuloclinium macrocephalum	Pompom weed	17	25	Both	1
	Cardiospermum grandiflorum/halicacabum	Balloon vines	63	22	Both	1
	Cestrum aurantiacum/laevigatum	Inkberry	80	24	Both	1
	Chromolaena odorata	Triffid weed	96	36	Both	1
	Eichhornia crassipes	Water hyacinth	95	22	Riparian	1
	Lantana camara	Lantana	261	27	Both	1
	Pinus pinaster	Cluster pine	86	26	Landscape	2
	Psidium guajava	Guava	167	17	Both	2
	Rubus cuneifolius	American bramble	75	34	Both	1
	Rubus fruticosus	European blackberry	89	20	Both	2
	Salix fragilis	Crack willow	75	22	Riparian	2
	Solanum mauritianum	Bugweed	268	21	Both	1
Widespread–common	*Acacia decurrens*	Green wattle	101	21	Both	2
	Acacia melanoxylon	Australian blackwood	138	15	Both	2
	Achyranthes aspera	Burweed	77	4	Both	1
	Ailanthus altissima	Tree-of-heaven	32	5	Both	3
	Anredera cordifolia	Bridal wreath	24	8	Both	1
	Araujia sericifera	Moth catcher	36	2	Both	1
	Atriplex nummularia ssp. *nummularia*	Old-man saltbush	173	7	Both	2
	Bidens formosa	Cosmos	48	11	Riparian	
	Cardiospermum halicacabum	Heart pea	30	0	Riparian	
	Casuarina equisetifolia	Horsetail tree	24	3	Both	2
	Cereus jamacaru	Queen of the night	127	9	Landscape	1
	Conyza bonariensis	Flax-leaf fleabane	5	0	Riparian	
	Crotalaria agatiflora subsp. *imperialis*	Bird flower	18	0	Both	Proposed
	Cuscuta campestris	Common dodder	82	1	Both	1
	Datura spp.(*D. ferox*/*D. inoxia*/*D. stramonium*)	Thorn apples	84	1	Riparian	1
	Echium plantagineum/vulgare	Patterson's curse/blue echium	44	14	Both	1
	Eucalyptus camaldulensis	Red river gum	123	15	Riparian	2
	Hakea sericea	Silky hakea	78	12	Landscape	1
	Ipomoea alba	Moonflower	23	3	Riparian	1
	Ipomoea indica/purpurea	Morning glories	98	8	Both	1 (*I. indica*) 3 (*I. purpurea*)
	Jacaranda mimosifolia	Jacaranda	201	6	Both	3
	Mirabilis jalapa	Four-o'clock	7	0	Landscape	Proposed

Continued on p. 62

Appendix 1 (*continued*)

Range–abundance	Scientific name	Common name	Number of grid-cells	% Grid-cells abundant	Riparian or landscape	CARA category
Widespread–common	*Morus alba*	White or common mulberry	130	4	Riparian	3
	Opuntia aurantiaca	Jointed cactus	61	5	Landscape	1
	Opuntia imbricata	Imbricate cactus	131	10	Landscape	1
	Opuntia monacantha	Cochineal prickly pear	48	1	Both	1
	Opuntia robusta	Blue-leaf cactus	225	1	Landscape	
	Opuntia stricta	Australian pest pear	108	10	Landscape	1
	Pinus halepensis	Aleppo pine	85	3	Landscape	2
	Pinus patula	Patula pine	90	12	Both	2
	Pinus radiata	Radiata pine	71	12	Landscape	2
	Pinus spp.	Pine trees	126	9	Landscape	
	Pyracantha angustifolia	Yellow firethorn	143	1	Both	3
	Robinia pseudoacacia	Black locust	110	9	Both	2
	Schinus molle	Pepper tree	232	1	Both	Proposed
	Senna didymobotrya	Peanut butter cassia	142	13	Both	3
	Senna occidentalis	Wild coffee	56	8	Both	
	Sesbania punicea	Red sesbania	325	13	Riparian	1
	Solanum seaforthianum	Potato creeper	33	7	Both	1
	Solanum sisymbriifolium	Dense-thorned bitter apple	40	6	Both	1
	Sorghum halepense	Johnson grass	44	4	Riparian	2
	Tamarix spp. (*T. chinensis*/*T. ramosissima*)	Tamarisk	92	4	Riparian	1/3
	Verbena bonariensis	Purple top	58	5	Riparian	
	Verbena tenuisecta	Fine-leaved verbena	14	4	Riparian	
	Xanthium strumarium	Large cocklebur	151	12	Both	1
	Zinnia peruviana	Redstar zinnia	4	0	Both	
Widespread–scarce	*Acacia baileyana*	Bailey's wattle	87	0	Both	3
	Populus nigra var. *italica*	Lombardy poplar	90	0	Riparian	Proposed
Localized–abundant	*Acacia pycnantha*	Golden wattle	35	25	Landscape	1
	Albizia lebbeck	Lebbeck tree	5	33	no data	1
	Azolla pinnata var. imbricata	Mosquito fern	3	25	Riparian	
	Colocasia esculenta	Elephant's ear	10	21	Riparian	
	Echinopsis spachiana	Torch cactus	57	3	Landscape	1
	Eucalyptus lehmannii	Spider gum	41	13	Landscape	1/2
	Flaveria bidentis	Smelter's bush	19	26	Riparian	
	Hakea drupacea	Sweet hakea	28	7	Landscape	1
	Hakea gibbosa	Rock hakea	18	11	Landscape	1
	Harrisia martinii	Moon cactus	21	43	Both	1
	Hedychium coccineum	Red ginger lily	3	20	Riparian	1
	Hedychium flavescens	Yellow ginger lily	5	40	Both	1
	Hedychium spp.	Ginger lilies	7	25	Riparian	1
	Helianthus annuus	Sunflower	5	17	no data	
	Leptospermum laevigatum	Australian mrytle	38	30	Landscape	1
	Ligustrum vulgare	Common privet	3	20	Riparian	3
	Lilium formosanum	Formosa lily	16	21	Landscape	3
	Litsea glutinosa	Indian laurel	8	44	Both	1
	Macfadyena unguis-cati	Cat's claw creeper	27	27	Both	1
	Melilotus alba	White sweet clover	15	40	Riparian	
	Metrosideros excelsa	New Zealand bottlebrush	2	25	Riparian	3
	Myriophyllum aquaticum	Parrot's feather	48	19	Riparian	1
	Nassella trichotoma	Nassella tussock	12	21	Landscape	1
	Nerium oleander	Oleander	24	6	Riparian	1
	Opuntia fulgida	Chainfruit-cholla/rosea cactus	11	17	Landscape	1
	Opuntia lindheimeri/*Opuntia engelmannii* var. *linderheimeri*	Small round-leaved prickly pear	11	21	Landscape	1
	Paraserianthes lophantha	Stinkbean	54	10	Both	1
	Parthenium hysterophorus	Parthenium weed	24	37	Riparian	1
	Paspalum dilatatum	Common Paspalum	6	33	Riparian	
	Pennisetum villosum	Feathertop	22	21	Landscape	1
	Pinus elliottii	Slash pine	34	15	Landscape	2
	Pistia stratiotes	Water lettuce	27	17	Riparian	1
	Pittosporum undulatum	Australian cheesewood	3	0	Both	1
	Rumex usambarensis	Rumex	4	20	Landscape	
	Salvinia molesta	Salvinia	33	20	Riparian	1
	Schinus terebinthifolius	Brazilian pepper tree	32	16	Both	1

Appendix 2. Emerging invaders grouped according to categories. Scores for 'Impact', 'Weediness', Biocontrol' and 'Weedy relatives' are standardized by dividing the maximum score for that criterion and multiplying by 10 (see text for details on how scores were assigned to these criteria). Scores for these four criteria were weighted, with 'Impact', 'Weediness' and Biocontrol' receiving an equal weighting of four, and 'Weedy relatives' receiving a lower weighting of one (see text). The weighted criteria were summed to obtain the 'Combined score' for each species. 'CARA category' lists the species regulated by the Conservation of Agricultural Resources Act (Act 43 of 1983), where 1 refers to Category 1 prohibited weeds that must be controlled in all situations; 2 includes Category 2 plants with commercial value that may be planted in demarcated areas subject to a permit, provided that steps are taken to control spread; 3 includes Category 3 ornamental plants that may no longer be planted or traded, but may remain in place provided a permit is obtained and steps taken to control their spread; and 'proposed' includes those species that were proposed for listing under the Conservation of Agricultural Resources Act, but require further investigation before they can be included.

Habitat–propagule pool size	Scientific name	Common name	Impact	Weediness	Biocontrol	% Weedy relatives	Combined score	CARA category
Large–large	*Bromus diandrus*	Ripgut brome	0	2	10	5	53	
	Pinus taeda	Loblolly pine	10	1	10	4	87	2
	Tecoma stans	Yellow bells	5	1	10	3	69	1
	Tipuana tipu	Tipu tree	5	1	10	10	73	3
Large–moderate	*Celtis sinensis*/ *Celtis occidentalis*/ *Celtis australis*	Chinese nettle tree/ Common hackberry/ European hackberry	0	1	10	1	45	Proposed
	Cytisus scoparius	Scotch broom	5	5	10	4	86	1
	Pennisetum purpureum	Elephant grass	10	3	10	2	95	Proposed
	Pereskia aculeata	Pereskia	10	1	10	2	87	1
	Rosa rubiginosa	Eglantine	10	3	10	3	96	1
	Toona ciliata	Toon tree	5	1	10	2	64	3
	Ulex europaeus	European gorse	5	5	10	1	80	1
Large–small	*Acacia paradoxa*	Kangaroo thorn	5	2	10	3	69	1
	Pueraria lobata	Kudzu vine	5	3	10	5	76	1
	Triplaris americana	Triplaris	5	0	10	1	62	1
Moderate–large	*Acacia elata*	Peppertree wattle	5	2	10	3	69	3
	Acacia podalyriifolia	Pearl acacia	5	1	10	3	67	3
	Ardisia crenata	Coralberry tree	5	1	10	0	66	1
	Cinnamomum camphora	Camphor tree	10	2	10	0	90	1/3
	Cotoneaster franchetii	Orange cotoneaster	5	2	10	1	69	3
	Cotoneaster pannosus	Silver-leaf cotoneaster	5	2	10	1	69	3
	Eucalyptus cladocalyx	Sugar gum	5	1	10	2	68	2
	Eucalyptus saligna	Saligna gum	5	1	10	2	66	
	Eugenia uniflora	Surinam cherry	5	2	10	0	68	1
	Hedychium coronarium	White ginger lily	10	2	10	1	87	1
	Hedychium gardnerianum	Kahili ginger lily	10	3	10	1	92	1
	Ligustrum japonicum	Japanese wax-leaved privet	5	1	10	3	66	3
	Ligustrum lucidum	Chinese wax-leaved privet	5	4	10	3	78	3
	Ligustrum ovalifolium	Californian privet	5	1	10	3	68	3
	Ligustrum sinense	Chinese privet	5	4	10	3	80	3
	Lonicera japonica	Japanese honeysuckle	5	6	10	1	83	Proposed
	Myoporum serratum	Manatoka	5	0	10	2	62	
	Myoporum tenuifolium ssp. *montanum*	Manatoka	5	0	10	2	63	3
	Nephrolepis exaltata	Sword fern	10	0	10	3	84	3
	Pyracantha coccinea	Red firethorn	5	0	10	8	69	
	Spartium junceum	Spanish broom	5	3	10	10	82	1
	Syzygium paniculatum	Australian water pear	5	0	10	0	61	
Moderate–moderate	*Albizia procera*	False lebbeck	5	1	10	2	64	1
	Alhagi maurorum	Camelthorn bush	5	2	10	10	79	1
	Anacardium occidentale	Cashew nut	5	1	10	1	63	
	Callistemon rigidus	Sitt-leavedbottlebrush	0	1	10	1	45	Proposed
	Catharanthus roseus	Madagascar periwinkle	0	2	10	3	51	
	Cestrum parqui	Chilean cestrum	10	3	10	1	91	1
	Cynodon nlemfuensis	East African couch	5	2	10	10	76	
	Cytisus monspessulanus	Montpellier broom	5	0	10	4	66	1
	Duranta erecta	Forget-me-not	0	1	10	1	44	Proposed
	Eriobotrya japonica	Loquat	0	2	10	0	50	3
	Ficus carica	Fig	0	2	10	0	50	
	Gleditsia triacanthos	Honey locust	5	2	10	1	68	2
	Leucaena leucocephala	Leucaena	5	3	4	3	52	1
	Mangifera indica	Mango	0	1	10	0	46	
	Montanoa hibiscifolia	Tree daisy	0	1	10	1	44	1
	Passiflora edulis	Passion fruit	0	2	10	1	50	
	Passiflora subpeltata	Granadina	0	1	10	1	46	1
	Physalis peruviana	Cape gooseberry	0	2	10	5	54	
	Phytolacca octandra	Forest inkberry	0	2	10	6	55	
	Pyracantha crenulata	Himalayan firethorn	5	1	10	8	73	3

Continued on p. 64

Appendix 2 (*continued*)

Habitat–propagule pool size	Scientific name	Common name	Impact	Weediness	Biocontrol	% Weedy relatives	Combined score	CARA category
Moderate–moderate	*Senna bicapsularis*	Rambling cassia	5	0	10	1	62	3
	Senna pendula var. *glabrata*	Rambling cassia	5	2	10	1	68	3
	Sesbania bispinosa var. *bispinosa*	Spiny sesbania	0	0	10	4	45	
	Sophora japonica	Japanese pagoda tree	0	0	10	2	42	
	Syzygium cumini	Jambolan	5	1	10	0	66	3
	Syzygium jambos	Rose apple	5	1	10	0	66	3
	Tithonia diversifolia	Mexican sunflower	0	1	10	3	48	1
	Ulmus parvifolia	Chinese elm	0	0	10	5	46	
	Verbena brasiliensis	Slender wild verbena	0	1	10	2	45	
Riparian–large	*Canna indica*	Indian shot	5	2	10	10	79	1
	Canna x *generalis*	Garden canna	5	1	10	10	72	
	Casuarina cunninghamiana	Beefwood	5	1	10	4	69	2
	Cortaderia jubata	Purple Pampas	5	3	10	2	75	1
	Cortaderia selloana	Pampas grass	5	5	10	2	81	1
	Oenothera biennis	Evening primrose	5	1	10	4	67	
	Populus deltoides	Match poplar						Proposed
Riparian–moderate	*Eucalyptus microtheca*	Coolabah	0	0	10	2	42	
	Mimosa pigra	Giant sensitive plant	5	4	10	1	76	3
	Myriophyllum spicatum	Spiked water-milfoil	5	4	10	3	80	1
	Oenothera glazioviana	Evening primrose	5	2	10	4	72	
	Oenothera indecora	Evening primrose	5	1	10	4	68	
	Oenothera jamesii	Giant evening primrose	5	0	10	4	64	
	Oenothera laciniata	Cutleaf evening primrose	5	1	10	4	67	
	Oenothera tetraptera	White evening primrose	5	0	10	4	66	
	Parkinsonia aculeata	Jerusalem thorn	5	1	10	0	66	
Small–large	*Alpinia zerumbet*	Shell ginger	5	0	10	0	62	
	Grevillea robusta	Australian silky oak	5	2	10	0	67	3
	Quercus robur	English oak	5	1	10	1	67	

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

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Biological control against incipient, or emerging, weeds (plants in an early stage of invasion) has not been widely practised in many countries, largely because limited budgets tend to be directed at invasions that have already reached detrimental levels. Because of restricted funds and few opportunities for exploration abroad in the past, South African practitioners of biological control have made the most of their survey trips by collecting as many potentially useful control agents, from as many target plants, as they could. Exploration for agents against high-priority weeds thus allowed simultaneous collection of natural enemies of low-priority weeds in the same region. These opportunistic programmes have been beneficial for South Africa in the management of invasive alien plants. In 2003, the Working for Water programme allocated funds for biological control programmes against five emerging weed species. This investment has, for the first time, given formal recognition to the rationale of targeting incipient weeds and bodes well for the future of biological weed control in South Africa. This paper reviews cases where emerging weeds were targeted for biological control in this country, the successes that were achieved, and the prospects for enhancing this approach in the future.

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Introduction

Biological control of invasive alien plants was begun in South Africa some 90 years ago and has an impressive record.[1] In recent years, much of the progress achieved here has been facilitated by the Working for Water programme. This enterprise, together with other factors that have influenced the success of weed biological control in South Africa, are comprehensively reviewed elsewhere in this issue.[2]

One of the important features of the biological control of weeds in South Africa has been the realization that the targeting of incipient weeds (that is, plants in an early stage of invasion) considerably enhances the prospects for success.[3] However, the targeting of emerging weeds has generally not been widely practised internationally, largely because biological control is often used as a last resort, when conventional methods of