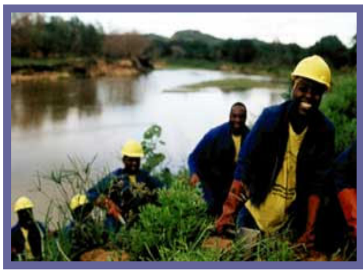
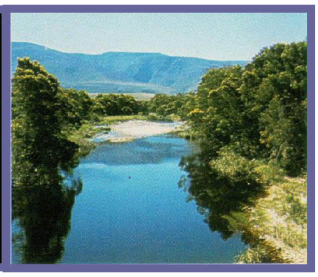
CSIR Report No: ENV-S-C 2004-108

An Assessment of Invasion Potential of Invasive Alien Plant Species in South Africa

Final Report



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INSTITUTE FOR PLANT CONSERVATION

CSIR ENVIRONMENTEK

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CHAPTER 1: INTRODUCTION

1.1 Background and Terms of Reference

The aim of this project was to identify invasive alien plant species that pose the biggest risk to South Africa, and develop scenarios of likely future spread to enable the Working for Water Programme to focus management on priority species and areas. To achieve this aim, five main tasks were identified and laid out in the Terms of Reference for this project (Box1.1). This report comprises the four papers that have been published or submitted for publication, each forming a chapter, brought together by this introduction and with a conclusions and recommendations for action and further research. Five tasks were specified in the original Terms of Reference for this project (see Box 1.1):

- Task 1: Provide a list of invasive alien plant species both in terms of species that have already become a problem (hereafter termed “major invaders”), and species already present in South Africa that could potentially become a problem in future (hereafter termed “emerging invaders”). See Box 1.2 for definitions of major and emerging invaders.

- Task 2: Provide a description of the determinants of distribution and mechanisms of spread, and the potential impacts of each of these species.

- Task 3: Rank these species in terms of their importance. The magnitude of potential impact will be the most important of each of these species.

- Task 4: Provide generic and mathematically explicit models that describe the rate of spread of the most important species as ranked above. Wherever possible, the models should be based on data on actual spread rates observed in South African ecosystems as a priority, and from other parts of the world.

- Task 5: Provide estimates of potential area that would be impacted by the most important species, and the time that it would take for each species to reach the full extent of its invasion potential.

Box 1.1: Terms of Reference of sub-contracted services

TOR 1

Provide a list of invasive alien plant (IAP) species both in terms of species that have already become a problem, and species already present in South Africa that could potentially become a problem in future.

Tasks:

i. Construct list of current and potential IAP species (hereafter referred to as "IAP list") using existing data sources (the best is Leslie Henderson's dataset (Henderson 2001), followed by Wells et al (1986) and Glenn (2002).
Responsible person(s): Theresa Mgidi (80%), Naomi Mdzeke (10%), David Le Maitre (10%)
ii. Draw up of a list of alien plant specialists to be contacted for information on potential IAP species, and contact each person.
Responsible person(s): Dave Richardson (90%), David Le Maitre (10%)
iii. Incorporate information derived from (ii) above on the IAP list.
Responsible person(s): Theresa Mgidi (90%), Naomi Mdzeke (10%)
iv. Interrogate Randall database to estimate weediness of each listed IAP species (use number of records).
Responsible person(s): Theresa Mgidi (50%), Lucille Schonegevel (50%)
v. Investigate feasibility of using bioclimatic profiles from the South African climatic workstations to locate similar areas elsewhere in the world. The IAP species at each of these other global locations could be used to crosscheck the species flagged as potential IAP species in South Africa.
Responsible person(s): Mathieu Rouget (10%), Lucille Schonegevel (50%), Theresa Mgidi (30%), Jeanne Nel (10%)
vi. Collate information on IAP list and prepare for expert workshop.
Responsible person(s): Naomi Mdzeke (20%), Theresa Mgidi (60%), Jeanne Nel (10%), Lucille Schonegevel (50%)
vii. Internal project team review the IAP list.
Responsible person(s): Dave Richardson (40%), David Le Maitre (30%), Brian van Wilgen (30%)
viii. Expert workshop:
    - Refine the IAP list.

    Responsible person(s): All and Brian van Wilgen
ix. Collate information from expert workshop and finalise IAP list.
Responsible person(s): Theresa Mgidi (70%), Dave Richardson (20%), David Le Maitre (10%)
x. Report on methods and results of TOR 1.
Responsible person(s): Theresa Mgidi (60%), Naomi Mdzeke (20%), Jeanne Nel (10%), Dave Richardson (10%)
xi. Internal TOR1-report review.
Responsible person(s): Brian van Wilgen (50%), Dave Richardson (50%)

TOR 2

Provide a description of the determinants of distribution and mechanisms of spread, and the potential impacts of each of these species.

Tasks:

i. Prepare a demonstration of existing databases and other available datasets for the project team.
Responsible person(s): Jeanne Nel (45%), Mathieu Rouget (35%), Naomi Mdzeke (10%), Lucille Schonegevel (10%)
ii. Explore the potential of the CLIMATE model for delineating complete environmental envelopes for all IAP species.
Responsible person(s): Mathieu Rouget (50%), Dave Richardson (10%), Lucille Schonegevel (30%), Jeanne Nel (10%)
iii. Project meeting:
    - Examine the potential of using Leslie Henderson's database.
    - Decide which other data could complement this database (e.g. Working for Water data).
    - Discuss the use of CLIMATE based on outputs of (iv) above.

Box 1.1 (continued)…

Responsible person(s): All

iv. Decide on environmental variables and produce environmental envelopes for IAP species with adequate data.
Responsible person(s): Mathieu Rouget (40%), Lucille Schonegevel (25%), Dave Richardson (10%), Jeanne Nel (25%)

v. For IAP species without adequate data (few or no records) run CLIMATE to ascertain coarse environmental envelope.
Responsible person(s):Lucille Schonegevel (50%), Jeanne Nel (30%), Mathieu Rouget (20%)

vi. Determine confidence levels used for both the AIP databases (use factors such as time since introduction, number of records, how well the species fits its environmental envelope).
Responsible person(s): Mathieu Rouget (80%), Dave Richardson (10%), Jeanne Nel (10%)

vii. Report on methods and results of TOR 2.
Responsible person(s): Jeanne Nel (50%), Mathieu Rouget (40%), Naomi Mdzeke (10%)

viii. Internal TOR2-report review.
Responsible person(s): Brian van Wilgen (50%), Dave Richardson (50%)

TOR 3
Rank these species in terms of their importance. The magnitude of potential impact will be the most important of each of these species.
Tasks:

i. Calculate the current impact of each IAP species, based on current range (e.g. how many quarter degree squares), abundance and ability of the species to transform a landscape (e.g. use an index of 1-3).
Responsible person(s): Jeanne Nel (40%), Lucille Schonegevel (30%), Mathieu Rouget (20%), Naomi Mdzeke (10%)

ii. Calculate the potential impact of each IAP species using the methodology in (i), but applying potential ranges and abundances.
Responsible person(s): Jeanne Nel (40%), Lucille Schonegevel (30%), Mathieu Rouget (20%), Naomi Mdzeke (10%)

iii. Preliminary ranking of IAP species based on its impact score.
Responsible person(s): Dave Richardson (40%), Jeanne Nel (25%), Mathieu Rouget (25%), Naomi Mdzeke (10%)

iv. Expert review via email
   - Review ranking of each IAP species.

Responsible person(s): Naomi Mdzeke (80%), Dave Richardson (20%)

v. Project meeting:
   - Refine ranking and methodology based on expert review.
   - Finalise the ranking.

Responsible person(s):All

vi. Report on methods and results of TOR 3.
Responsible person(s): Jeanne Nel (40%), Dave Richardson (20%), Mathieu Rouget (30%), Naomi Mdzeke (10%)

vii. Internal TOR3-report review.
Responsible person(s): Brian van Wilgen (50%), Dave Richardson (50%)

TOR 4
Provide generic and mathematically explicit models that describe the rate of spread of the most important species as ranked above. Wherever possible, the models should be based on data on actual spread rates observed in South African ecosystems as a priority, and from other parts of the world.
Tasks:

i. Identify information required for decision tree and prepare for project meeting to develop the decision tree.
Responsible person(s): Naomi Mdzeke (20%), Mathieu Rouget (20%), Jeanne Nel (30%), Lucille Schonegevel (30%)

ii. Project meeting:
   - Preliminary identification of important IAP species used for designing generic models (choose species with good data, that are representative of a cross-section of different types, have different invasive potential, have high impact scores etc).

Box 1.1 (continued)…

- Develop a decision tree approach for modelling spread and impacts of IAP species.

Responsible person(s): All and Brian van Wilgen

iii. Identify areas and IAP species of concern in the near future using the generic model developed in (iii).
Responsible person(s): Mathieu Rouget (60%), Jeanne Nel (40%)

iv. Report on methods and results of TOR 4.
Responsible person(s): Mathieu Rouget (60%), Jeanne Nel (40%)

v. Internal TOR4-report review.
Responsible person(s): Brian van Wilgen (25%), Dave Richardson (50%), David Le Maitre (25%)

TOR 5

Provide estimates of potential area that would be impacted by the most important species, and the time that it would take for each species to reach the full extent of its invasion potential.

Tasks:

i. Compile results from the models and provide estimates of potential area impacted.
Responsible person(s): Jeanne Nel (50%), Mathieu Rouget (40%), Naomi Mdzeke (10%)

ii. Supply categorical time scales for each species to reach the full extent of its invasion potential
Responsible person(s): Jeanne Nel (40%), Mathieu Rouget (30%), David Le Maitre (30%)

iii. Project meeting:
   - Review results to date.
   - Develop a Table of Contents for the final report, complete with responsible persons and due dates.

   Responsible person(s): All and Brian van Wilgen

iv. Report on methods and results of TOR 5
Responsible person(s): Jeanne Nel (40%), David Le Maitre (30%), Mathieu Rouget (20%), Naomi Mdzeke (10%)

v. Internal TOR5-report review.
Responsible person(s): Brian van Wilgen (50%), Dave Richardson (50%)

TOR 6

Provide a report detailing the results of the above-mentioned tasks. It is expected that this project will be completed within 18 months of the signature of the contract.

Task:

i. Final report collation and write-up.
Responsible person(s): Jeanne Nel (40%), Naomi Mdzeke (20%), Dave Richardson (20%), David Le maitre (20%)

ii. Final report review.
Responsible person(s): Brian van Wilgen (60%), Dave Richardson (40%)

Box 1.2: Defining Major and Emerging Invaders

Major invaders:
Invasive alien plants that are well-established, and which have already had a substantial impact on natural and semi-natural ecosystems of South Africa.

Emerging invaders:
Invasive alien plants that have already become naturalised in South African ecosystems, but which currently have less impact than major invaders; however these species have attributes and potentially suitable habitat that could lead to further impact in the future.

As the project progressed it became evident that the requirements of Tasks 2, 4 and 5 could not be fully met, largely because of the regional scale of the study (South Africa, Swaziland and Lesotho), the large number and wide variety of species which have invaded the country, and the lack of empirical data on spread rates of different species. The data needed to do the modelling required by Tasks 2 and 4 are only available for very few species and this level of modeling is not suited to large, climatically and ecologically heterogenous environments (Higgins et al. 2000; Rouget and Richardson 2003). Most of the data on the current distributions of the species was restricted to SAPIA records because Versfeld et al. (1998) survey only included 180 species and was very patchy in much of the country. The level of data needed to estimate current distributions was lacking except for a few species. The net result was that it would be difficult to estimate rates of spread and, thus, the time that would be required for these envelopes to become invaded with a reasonable degree of confidence. It also became clear that the information that is needed to answer the core question of which areas and species to prioritise would be covered by an analysis of the species traits and the areas they could invade. Estimating the time needed to invade these areas (Task 4) was a secondary issue. The emphasis therefore shifted to using information on climatic parameters and species occurrence data to provide predictions of the climatically suitable area for a suite of both the major and emerging invaders, and to identify which area most of those species would invade – thus meeting the requirements of Task 1, Task 3 and Task 5.

1.2 Project outputs and structure of this report

The complete suite of outcomes for this study are:

- Part 1: Report comprising text which summarizes our key findings in the form of four peer-reviewed publications.
- Part 2: Figures for each of the chapters in Part 1, numbered according to the chapters in which they appear.
- Part 3: Data CD comprising additional unpublished species maps in Powerpoint format, consisting of (i) maps of potential distributions for each of the major plant invaders modeled (PART3_Potential_Distributions_Major_Invaders_Nov04.ppt); (ii) maps of potential distributions for each of the emerging plant invaders modeled (PART3_Impacts_Nov04.ppt); and (iii) maps showing the total impacts on water, biodiversity and rangelands for the major and emerging invader plants (PART3_Potential_Distributions_Emerging_Invaders_Nov04.ppt).
- Part 4: GIS data and metadata.

This report (Part 1) comprises four peer-reviewed papers presented as separate chapters, and drawn together by an introduction, and conclusions and recommendations. It should be read in conjunction with Part 2, which contains the figures referred to in the text of each chapter. The peer-reviewed papers are as follows:

Chapter 2: A proposed classification of invasive plant species in South Africa: towards prioritizing species and areas for management action. South African Journal of Science 100: 53-64.
Nel, J.L., Richardson, D.M., Rouget, M., Mgidi, T., Mdzeke, N., Le Maitre, D.C., van Wilgen, B.W., Schonegevel, L., Henderson, L. & Neser, S. (2004)

> *This paper formed part of a special issue of the journal which was based on studies presented at the Working for Water Research Symposium in September 2003. This paper addressed Tasks 1 and 4 of the Terms of Reference. It involved the creation of a database summarising the attributes of 571 invaders from which a suite of 117 major and 84 emerging invaders was selected (Task 1). These species were ranked and prioritised through a series of expert workshops and the prioritised groups were identified (Task 3). A full list of the ranked major and emerging species is given in the appendices to this paper.*

Chapter 3: Mapping the potential ranges of major plant invaders in South Africa, Lesotho and Swaziland using climatic suitability. Diversity and Distributions 10: 475–484.
Rouget, M., Richardson, D.M., Nel, J, Le Maitre, D.C., Egoh, B. and Mgidi, T. N. (2004).

> *This paper used an analysis of key climatic parameters derived from a national atlas (Schulze et al. 1997) and species distributions from the SAPIA database (Henderson 1998, 2002) to define climatically suitable areas (envelopes) for 71 major invaders (Task 5). These envelopes were combined to identify the areas that were most vulnerable to invasions (Task 5). Maps showing the areas that could be invaded by each of the 71 species are provided electronically on the data CD as Part 3 of the report.*

Chapter 4: Alien plant invasions – incorporating emerging invaders in regional prioritization: a pragmatic approach for South Africa. In preparation, for submission to Environmental Management.

Mgidi, T.N., Le Maitre, D.C., Schonegevel, L., Nel, J., Rouget, M., and Richardson, D.M. in preparation.

This paper followed a similar approach to the one in Chapter 3 but, because emerging species (by definition) only occur in a few locations and environments, climate and species occurrence data from Australia and the USA was used to supplement the local records. A different procedure was also used to define the climate envelopes (suitable areas). Maps showing the areas that could be invaded by each of the 28 are provided electronically on the data CD as Part 3 of the report.

Chapter 5: Plant invasions in South Africa, Lesotho and Swaziland: assessing the potential impacts of major and emerging plant invader. In preparation, for publication in Global Change Biology.

Le Maitre, D.C., Mgidi, T.N., Schonegevel, L., Nel, J., Rouget, M., Richardson, D.M. and Midgley, C.

This study used a scoring system to assess impacts on biodiversity, rangelands and water resources (Task 3). The impact scores for biodiversity of each of the major species was combined with the data on its envelope, and the results were summed for all major species to predict the areas of the region where invasions could have the greatest impact on biodiversity (task 5). The same procedure was repeated for impacts on rangelands and water resources. The whole procedure was repeated for the emerging species (Tasks 3 and 5). Maps showing the total impacts on water, biodiversity and rangelands for the major and emerging invader plants are provided electronically on the data CD as Part 3 of the report.

1.3 References

Henderson, L. (1998). Southern African Plant Invaders Atlas (SAPIA). Appl. Plant Sci. 12: 31–32.

Henderson, L. (2002). Southern African Plant Invaders Atlas (SAPIA) with particular reference to invasive Australian species. Proc. 13th Australian Weeds Conference, Perth, September 2002.

Higgins, S.I., Richardson, D.M. and Cowling, R.M. 2000. Using a dynamic landscape model for planning the management of alien plant invasions. Ecological Applications 10: 1833–1848.

Rouget, M. & Richardson, D.M. 2003. Understanding patterns of plant invasion at different spatial scales: quantifying the roles of environment and propagule pressure. In Plant Invasions: Ecological threats and management solutions (ed. by L.E. Child, J.H. Brock, G. Brundu, K. Prach, P. Pyšek, P.M. Wade & M. Williamson), pp. 3-15. Backhuys Publishers, Leiden, The Netherlands.

Schulze, R.E., Maharaj, M., Lynch, S.D., Howe, B.J. & Melvil-Thomson, B. (1997) South African atlas of agrohydrology and -climatology. Water Research Commission, Pretoria.

Versfeld, D.B., Le Maitre, D.C. and Chapman, R.A. (1998). Alien Invading Plants and Water Resources in South Africa: A preliminary assessment. Report No. TT 99/98, Water Research Commission, Pretoria.

CHAPTER 2:
A PROPOSED CLASSIFICATION OF INVASIVE ALIEN PLANT SPECIES IN SOUTH AFRICA: TOWARDS PRIORITIZING SPECIES AND AREAS FOR MANAGEMENT ACTION

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Abstract

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 only 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 impact, but have attributes and potentially suitable habitat that could result in increased range and impacts in the next few decades. We describe the derivation of lists that contain 117 major invaders (categorised into groups based on geographical range and abundance) and 84 emerging invaders (categorised 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.

2.1 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 on 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.

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 socioeconomic and environmental values. The top twenty species thus ranked were selected to serve as a test case for improved coordination amongst stakeholders 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. Firstly, 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 (i.e., a lower product of range, abundance and effect), but which appear to have the capacity to have greater impact 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].

2.2 Methods

2.2.1 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 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 done 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 impacts 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 x 15' longitude, hereafter 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.

The database was reviewed by a team of seven alien-plant specialists, whose knowledge covered all major biome types, and consisted of 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 either owing to a consensus that 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. 2.1).

2.2.2 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 less than five records in the SAPIA database. Although some of these species could potentially have a major impact, they were not considered as major invaders owing to their current limited distribution. This filtering rule reduced the original list from 571 species to 290 species (Fig. 2.1).

Next, we classified species as landscape invaders, riparian 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 on species invading natural and semi-natural ecosystems, i.e., 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. 2.1).

We classified the remaining 248 species according to range and abundance, the cut-off values for each category being determined using cluster analysis (Table 2.1). 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 2.1). 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 (i.e. species which 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 (i.e. where habitat data of the SAPIA database seemed biased). This produced a final major invaders list of 117 species (Fig. 2.1).

2.2.3 Classification of emerging invaders

To construct the emerging invaders list, we first excluded all major invaders (i.e. 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 problematic 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 naturalised, 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 four, and Weedy congeners receiving a lower weighting of one to 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 2.2). 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. 2.1).

2.2.4 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].

2.3 Results

2.3.1 Database of invasive alien plants in South Africa

According to the distribution data recorded in the SAPIA database, almost 80% of the grid-cells within South Africa currently contain invasive alien species and almost 35% contain 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. 2.2). These correspond to areas with a high proportion of transformed land (such as agriculture, forestry and urbanization), high rainfall and a high population density.

2.3.2 Major invaders

We identified 117 major invaders (Appendix 2.1, Table 2.3) 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 2.3). 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., Working for Water Programme). 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 2.3). The distribution pattern of these 'very widespread/widespread-abundant' species (Fig. 2.3a) corresponds to the areas where high overall numbers of invasive alien plants are recorded (cf. Fig. 2.2). Most of the major invaders fall within the 'widespread-common' (39%) and 'localized-abundant' (31%) categories (Table 2.3, Fig. 2.3b). The highest numbers of species in the 'localized-abundant' category are restricted to Western Cape and Natal coasts, and the north-eastern Mpumalanga and Gauteng provinces (Fig. 2.3c).

2.3.3 Emerging invaders

We identified 84 emerging invaders (Appendix 2.2, Table 2.4), 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. 2.2). Almost 20% of the emerging species are classified as riparian species according to expert opinion (Table 2.4). 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 2.4), and almost 80% of species falling in these categories have been afforded legal status. These species are distributed along the eastern coast and north-eastern interior, but have not yet been recorded in the Northern Cape and Western Cape provinces (Fig. 2.4a and b). The majority 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 2.4). These categories show a slight difference in species distribution; distribution patterns of the 'moderate habitat-large propagule pool' category (Fig. 2.4c) 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. 2.4d). The emerging invaders that are estimated to have a small amount of invasible habitat available but a large current propagule pool size (Table 2.4 and Appendix 2.2) show a very similar distribution pattern to the species which fall into the 'moderate habitat-large propagule pool' category (Fig. 2.4c).

2.3.4 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 2.5): (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 (i.e. those categories shaded in Table 2.4). 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 2.1 and 2.2.

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

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* sp.), 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 2.5). 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*).

2.4 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 to 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 different implications for management; control efforts for species classified as 'widespread-common', e.g. Australian blackwood (*Acacia melanoxylon*) or jointed cactus (*Opuntia aurantiaca*), are best launched at a national scale, whereas the species within the 'localized-abundant' category, e.g. 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 amount of invasible habitat and a large propagule pool size should be investigated as priority species for research on biocontrol[16]; there should also be a major effort to eradicate the species within this category which are listed in legislation as 'category 1 species' (i.e. have no economic or social benefits), and an effort to limit the spread of those species listed in legislation as 'category 2 species' (i.e. species with commercial value). In contrast, emerging invaders with a small amount of invasible habitat and low propagule pressure may only require 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. 2.3a) follows a similar pattern to the distribution of areas where high numbers of major invaders are recorded (Fig. 2.2a). This suggests that these areas are at the most risk of being severely impacted by invasive alien plants because not only do they contain high numbers of invasive alien species, but the invasive alien species that do establish also have the ability to become abundant within these areas. This is in sharp contrast to the northern interior and north-western coast of the country, where both the number of major invaders and their associated abundance levels tend to be low (Figs. 2.2a and 3b).

Emerging invaders do not appear to be establishing in areas which were previously not invaded and exhibit similar distribution patterns to major invaders (see Figs. 2.2, 2.3 and 2.4). This suggests that some areas may be susceptible to invasion by alien plants because of certain climatic features, patterns of human settlement, or land use patterns that pre-dispose 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 little impact 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 for this study should also be used as a pro-active means of focusing biocontrol research in identifying agents that have the potential to keep these species under control, preventing them from having a major impact 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.

Utilising 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 using 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 reliable knowledge existed. 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. Firstly, 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. Secondly, 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.

2.5 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 a 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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Tables

Table 2.1: 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 less 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 less than 70 grid-cells)	Scarce (quantitative data were insufficient, and during expert review of the information the abundance was confirmed as scarce)

Table 2.2: 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)	

Table 2.3: The numbers of invasive alien plant species classified according to range and abundance. Major invader categories are shaded. Numbers in parentheses indicate number of species listed as declared weeds and invader plants by the Conservation of Agricultural Resources Act.

	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

Table 2.4: The numbers of invasive alien plant species classified according to potentially invasible habitat and current propagule pool size. Emerging invader categories are shaded. Numbers in parentheses indicate number of species listed as declared weeds and invader plants by the Conservation of Agricultural Resources Act.

	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

Table 2.5: 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

Legends for Figures

Fig. 2.1: 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.

Fig. 2.2: Distribution of (a) major invaders and (b) emerging invaders in South Africa.

Fig. 2.3: 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.

Fig. 2.4: 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.

Appendix 2.1: 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; '% 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	% 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

Range-abundance	Scientific name	Common name	Number of grid-cells	% abundant	Riparian or landscape	CARA category
Widespread-abundant	*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
	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

Range-abundance	Scientific name	Common name	Number of grid-cells	% abundant	Riparian or landscape	CARA category
Widespread-common	*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

Range-abundance	Scientific name	Common name	Number of grid-cells	% abundant	Riparian or landscape	CARA category
Localized-abundant	*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 2.2: Emerging invaders grouped according to categories of expert ratings. Scores for 'Impact', 'Weediness', Biocontrol' and 'Weedy relatives' are standardised 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
Moderate-large	*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

Habitat-propagule pool size	Scientific name	Common name	Impact	Weediness	Biocontrol	% Weedy relatives	Combined score	CARA category
	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
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	

Habitat-propagule pool size	Scientific name	Common name	Impact	Weediness	Biocontrol	% Weedy relatives	Combined score	CARA category
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	

CHAPTER 3: MAPPING THE POTENTIAL RANGES OF MAJOR PLANT INVADERS IN SOUTH AFRICA, LESOTHO AND SWAZILAND USING CLIMATIC SUITABILITY

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Abstract

Most national or regional initiatives aimed at managing biological invasions lack objective protocols for prioritising invasive species and areas based on likely future dimensions of spread. South Africa has one of the most ambitious national programmes for managing plant invasions in the world. There is, however, no protocol for assessing the likely future spread patterns needed to inform medium- to long-term planning. This paper presents an assessment of the climatic correlates of distribution of 71 important invasive alien plants, and an analysis of the implications of these findings for future invasions in different vegetation types in South Africa, Lesotho and Swaziland over the next few decades. We used a variant of climatic envelope models (CEMs) based on the Mahalanobis distance to derive climatic suitability surfaces for each species. CEMs were developed using the first three principal components derived from an analysis of seven climatic variables. Most species are currently confined to 10% or less of the region, but could potentially invade up to 40%. Depending on the species, between 2% and 79% of the region is climatically suitable for species to invade, and some areas were suitable for up to 45 plant invaders. Over one third of the modelled species have limited potential to substantially expand their distribution. About 20% of the vegetation types have low invasion potential where fewer than five species can invade, and about 10% have high invasion potential, being potentially suitable for more than 25 of the plant invaders. Our results suggest that management of the invasive plant species that are currently most widespread should focus on reducing densities, for example through biological control programmes, rather than controlling range expansions. We also identify areas of the region that may require additional management focus in the future.

Key words: Bioclimatic modelling, biological invasions, predictive models, spatial distribution, Mahalanobis distance, Working for Water programme.

3.1 Introduction

Biological invasions are a major threat to biodiversity and ecosystem functioning worldwide (Mack *et al*., 2001). Many important management initiatives have been initiated in different parts of the world, particularly in the last two decades. Such programmes target invasions in many different ways and focus at spatial scales ranging from global, through national and regional, to local (Wittenberg & Cock, 2001). This paper addresses the need for better information to inform national policy on the management of alien plant invasions in South Africa.

South Africa has been invaded by many species with well-documented ecological and economic impacts (Richardson *et al*., 1997; Versfeld *et al*., 1998; Le Maitre *et al*. 2000; Richardson & van Wilgen, 2004; van Wilgen, 2004). The country has a long history of research on, and management of, biological invasions, especially relating to invasive alien plants (Macdonald *et al*., 1986). A milestone in the management of alien plant invasions in South Africa was the initiation in 1995 of the national-scale Working for Water Programme (van Wilgen *et al*., 1996, 1998; van Wilgen, 2004). This programme has been widely lauded for its success in merging social, political, economic and environmental considerations (e.g. Hobbs, 2004). One of its biggest achievements has been the coordination of previously separate management initiatives (van Wilgen, 2004). Despite its successes on many fronts, many challenges still confront the programme (Macdonald, 2004). One of these is the need to prioritise areas and species to maximise the cost-effectiveness of control operations.

Systematic medium-term planning for a programme such as Working for Water that deals with many invasive species over a very large area demands an objective assessment of priorities for both species and areas. As a first step in this process, a classification of invasive alien plant species into major and emerging invaders for South Africa, Lesotho and Swaziland was recently proposed (Nel *et al*., 2004). This study highlighted the need for management to consider three categories of invaders: those species that are already widespread and abundant in the country, those that have only recently started to invade, and those that have not yet shown any sign of invasiveness or that are not yet present in the country but could pose a threat if introduced. Work is currently underway to improve our understanding of the extent of invasion (Versfeld *et al*., 1998) and dynamics (Robertson *et al*., 2003; Nel *et al*., 2004; Olckers, 2004; Robertson *et al*., 2004) of species in all these categories.

In this paper we present an approach for exploring the potential of important plant invaders to invade new areas in the region (South Africa, Lesotho and Swaziland). The analysis is based on a broad-brush assessment of climatic similarity between areas currently invaded and those not yet invaded. Many techniques have been proposed for understanding and modelling species-environment relationships (Franklin, 1995; Guisan and Zimmermann, 2000). Climate envelope models (CEMs), one type of predictive model, generate maps of potential species distribution using climatic characteristics where the species occurs. Major advantages of CEMs are their ability to cope with 'presence only' data, and their simplicity. Due to the relatively large number of plant invaders, a simple modelling technique, applicable to different taxa with a wide range of environmental requirements, was required, and CEMs were considered to be appropriate. The objectives of this study were to a) develop climatic envelopes for major plant invaders; b) map invasion potential for the whole country; and c) assess the invasion potential of the region's vegetation types.

3.2 Methods

3.2.1 Selecting invasive alien plant species

The Southern African Plant Invaders Atlas (SAPIA) is the best source of data on the distribution of invasive alien plants in South Africa, Lesotho and Swaziland. The SAPIA database contains records for over 500 species with information on their distribution, abundance, habitat preferences, and time of introduction (Henderson, 1998, 1999, 2001). Records are geo-referenced based on a quarter-degree grid system (hereafter quarter-degree squares or "QDS", 15' latitude x 15' longitude, representing roughly 25 x 27 km). Nel *et al.* (2004) used species distribution and abundance data from SAPIA to identify 126 major plant invaders - species recorded as either widespread, or localised but abundant. Our analyses focussed only on those major plant invaders with at least 50 records in SAPIA. Aquatic species were also excluded because their distribution is determined more by water availability than by climatic factors. The 71 major plant invaders selected for study are listed in Appendix 3.1.

3.2.2 Environmental modelling

Modelling the potential distribution of invasive species is always subject to uncertainties. For instance, the role of climate in controlling distribution is not the same for all species, and other factors such as disturbance regimes and biotic interactions may override climatic factors (Richardson & Bond, 1991; Hulme, 2003). Furthermore, the distribution of invasive species might not be in equilibrium with the environment because the geographic range of the species might still be expanding. Importantly, the majority of the species selected for study (Appendix 3.1) were introduced more than 100 years ago, allowing them time to sample a wide range of available habitats. An important assumption of our study is thus that the current distribution of the species in the region provides a good indication of their potential range in the region. We realise that potential distributions for some species (those for which human-aided dissemination has not afforded them opportunity to sample all potentially invasible habitats) may be underestimated. Similarly, for those species that have a scattered distribution over a large part of the region and/or where distribution is associated with human-induced disturbance more than inherent features of the environment, the potential distribution based on our assessments of climatic conditions is probably overestimated.

Despite these limitations, CEMs are very useful at a broad scale to develop a general picture of where species are most likely to invade, especially in this region with marked climatic gradients. For example, the mean annual rainfall exceeds 500 mm in the southern and eastern parts of the region but is less than 250 mm in the northwest and central interior (Schulze *et al.*, 1997). Likewise, growing conditions in the interior are strongly influenced by cold winters and a higher frequency of frost than in coastal areas. Previous studies have also shown that, at the scale of the whole region, climatic factors were the best environmental variables for predicting the distribution of two important invaders in South Africa (Rouget & Richardson, 2003).

The predictive ability of CEMs, however, is highly dependent on the choice of climatic factors. We investigated the use of a range of climatic variables developed by Schulze *et al.* (1997). Preliminary analyses suggested that the relative importance of climatic factors was species-specific, making it difficult to identify a few “generic” climatic variables, which could be applied for all our species. We therefore reduced the large number of possible explanatory variables to three components (principal component axes 1, 2 and 3) using Principal Component Analysis (PCA, Mardia *et al*., 1979). The first three components of the resulting PCA explained over 95% of the initial variation, based on the seven climatic variables with the greatest influence on plant species distribution (see Table 3.1; Fig 3.1). We then used these three climatic indices to derive the CEMs.

Most CEMs have used a rectilinear envelope based on minima and maxima of each climatic factor considered, which assign equal climatic suitability within the boundaries of the climatic envelope (Austin *et al*., 1990; Busby, 1991). In this study, we used a variant of CEMs based on an oblique ellipse model, which calculates the Mahalanobis distance to the ‘optimal’ climate conditions (Farber & Kadmon, 2003). Niche theory supports the use of such models because they assume the existence of optimal environmental conditions for a species and that any deviation from this optimum is associated with a lower climatic suitability. These models are an improvement on traditional CEMs in that a continuous range of climatic suitability values can be equated with probability of occurrence.

For each species, the following procedure was followed. We extracted the QDS records where the species occurs, and determined the climate characteristics of each QDS based on the three principal components. As climatic data were available at a finer resolution (1 minute) than the species distribution data (15 minutes), we used the mean value of the principal components for each of the 225 cells within the QDS. We followed the approach by Farber & Kadmon (2003) and calculated the mean vector (*m*) of the three principal components, which represents the ‘optimum’ climatic condition. We also calculated the covariance matrix (**C**) from a matrix whose rows represent the QDS where the species was recorded and whose columns represent the corresponding values of the three principal components. Next, each 1-minute cell was assigned a Mahalanobis distance using *m* and **C**, defined as:

$$d^2 = (\underline{x} - \underline{m})^T \mathbf{C}^{-1} (\underline{x} - \underline{m})$$

where $\underline{x}$ represents the set of climatic conditions in each 1-minute cell, and *d* is the Mahalanobis distance from which we derived a climatic suitability index (see below).

3.2.3 Mapping potential range

The Mahalanobis distance (*d*) ranges from 0 to infinity, with 0 representing the optimum condition (in our case, the optimum climatic condition). Cells with a Mahalanobis distance less than 2.5 were considered climatically suitable. Although Farber & Kadmon (2003) chose a higher cut-off (d = 4), preliminary analysis suggested that a cut-off of 2.5 provides the most accurate climatic envelopes. Expert assessment also found that envelopes including *d* values greater than 2.5 were unrealistic for species whose climatic envelopes were well understood. We rescaled the *d* values to obtain a climatic suitability index ranging from 0 to 100, where 0 represents any value of *d* greater than 5, 50 represents $d = 2.5$ and 100, $d = 0$. We assumed that alien plant species would have the potential of spreading in areas identified as the most climatically suitable (i.e. greater than 50).

For riparian species, we only modelled climatic suitability within those 1-minute cells containing sections of perennial or non-perennial rivers (24% of the region) based on the national 1: 500,000 scale river database. For each species, we calculated the percentage of the region's area that is climatically suitable for that species, as well as the increase in area relative to its current distribution. For riparian species, this was calculated in relation to the total area of riparian habitat. The current distribution of the 71 modelled species was compared to the potential range. Relative increase was calculated as the difference between potential and current range, divided by the current range. Finally, we summarised invasion potential by calculating the total number of plant invaders that could potentially occur in each 1-minute cell based on climatic suitability, and the average climatic suitability for those species.

Unfortunately, no other independent data set was available for testing model predictions of the 71 species. For each species, we generated a random QDS set of pseudo-absences (with sample size equivalent to the number of QDS where the species was recorded present). We used pseudo-absence and presence records to calculate presence accuracy (% of QDS, where the species occurs, correctly classified by the CEM), absence accuracy (% of QDS, where the species is supposed absent, correctly classified by the CEM), and the Kappa statistic. Kappa statistic evaluates the predictive model accuracy relative to the accuracy that might have resulted by chance (Cohen, 1960; Fielding & Bell, 1997). It ranges from –1 (complete disagreement) to 1 (perfect agreement) with 0 indicating random agreement. Model accuracy (i.e. high Kappa value) should be greater for species at equilibrium with the environment. We assumed that species introduced long time ago would have reached pseudo-equilibrium and analysed the Kappa values in relation to the introduction date of the species.

3.2.4 Prioritising vegetation types

We used the vegetation map of South Africa, Lesotho and Swaziland (Mucina & Rutherford, 2005) to assess invasion potential of the nine biomes and the 441 vegetation types defined for the region. Vegetation types are ecological units, which reflect similarities in climate and soils, and in processes, for example, disturbance regimes such as fires (Mucina & Rutherford, 2005). This suggests that we can treat them as homogenous units in terms of their susceptibility to invasion by different species. For each alien plant species, we selected areas of highest climatic suitability (i.e. greater than 50). We then calculated the median number of potential plant invaders per 1-minute cell for each biome and vegetation type. The average climatic suitability per 1-minute cell was summarised for each vegetation type. Based on natural breaks in the frequency distribution of the median number of potential plant invaders per vegetation type, we identified four categories which describe the invasion potential of vegetation types in the region.

3.3 Results

3.3.1 Potential distribution

Climate envelope models (CEMs) appear very suitable for providing a broad picture of the potential spread of major plant invaders in the region. The Kappa statistic was 0.6 on average for all species and greater than 0.5 for 52 species (Appendix 3.1). On average, 80% of the QDS where each species currently occurs were identified as climatically suitable for that species (Appendix 3.1). The climatic envelopes for three species selected as representative of different types of distribution in the region also match their current distribution reasonably well (Fig. 3.2).

Major plant invaders currently occupy between 1% (*Casuarina equisetifolia*) and 43% (*Opuntia ficus-indica*) of the QDS in the region. The CEMs show that, depending on the species, between 2% (*Casuarina equisetifolia*) and 79% (*Arundo donax*) of the region is potentially suitable for species to invade. Most of the species are currently confined to 10% or less of the region, but could potentially invade up to 40%. Based on climatic suitability, only 14 species have the potential to invade more than 50% of the country (Appendix 3.1). Of these, five species only invade landscapes (i.e. non-riparian areas), but all of these were either cacti (*Opuntia* spp.) or sisals (*Agave* spp.), which can invade large areas of the arid and semi-arid interior. Three of the 14 species are strictly riparian invaders (*Arundo donax, Eucalyptus camaldulensis, Nicotiana glauca,*), and six invade both landscape and riparian habitats. Our results suggest that more than a third of the major plant invaders have limited potential to substantially increase their range (where the potential distribution is at best twice that of the current extent). The proportional increase in potential distribution exceeds 1000% for seven species (Appendix 3.1). There was a negative relationship between current distribution and model accuracy (based on Kappa statistic). Model accuracy tended to be higher for species with small distribution than for widespread species (Fig. 3.3a). However, there was no relationship between time since introduction and model accuracy (Fig. 3.3b).

CEMs predicted that some parts of the region were climatically suitable for up to 45 major plant invaders (Fig. 3.4a). Over half of the region is suitable for between one and 15 major plant invaders, and only 2% of the region was predicted to be climatically unsuitable for invasion by any of the major plant invaders. The eastern coastal plain and the north-eastern interior are climatically suitable for most of the currently invading species (Fig. 3.4a). However, average climate suitability varies within these areas. For example, although fewer species can invade the Agulhas Plain at the southern-most tip of the region, the average climatic suitability for those species is much higher than for parts of the Eastern Cape where more species could invade (Fig. 3.4b). The low potential number of invaders and average climatic suitability of the escarpment, Drakensberg and mountains of the Western Cape (Figs. 3.4a and b) appears to be primarily due to frequent frosts and low mean temperatures of the coldest month (second principal component, Fig. 3.1b, Table 3.1) rather than rainfall or otherwise favourable growing conditions.

3.3.2 Invasion potential of biomes and vegetation types

Vegetation types and biomes differ markedly in their potential for invasion by the suite of major plant invaders explored in this study. Relatively few alien plant species can invade the desert and succulent karoo biomes, whereas more than 15 species could potentially invade the Albany thicket, forest and grassland biomes (Table 3.2). The maximum potential number of major plant invaders is relatively similar in all biomes, except for the desert and succulent karoo, which are suitable for fewer species. The average climatic suitability is however fairly similar among biomes (Table 3.2).

The average climate suitability and the number of potential plant invaders per vegetation type are positively correlated (Fig. 3.5). In other words, areas of high climatic suitability are also suitable for many species. There is a direct relationship between climatic suitability and the number of potential invaders up to an average climatic suitability of around 65%. Thereafter, there seems to be very little relationship, indicating that climatic factors are important, but only below certain threshold values. Figure 6 shows the invasion potential for each vegetation type, classified into four categories based on the potential number of plant invaders. Just over 20% of the region's vegetation types are characterised by very low invasion potential where less than 5 species could invade (Fig. 3.6); most of this area falls within the desert and succulent karoo biomes. The second group, characterised by low invasion potential (5-15 potential plant invaders), comprises mainly fynbos, succulent karoo and savanna types, the third group (5-25 potential plant invaders) mainly fynbos and grassland types, and the fourth group (more than 25 potential plant invaders), comprising about 10% of vegetation types (44). Vegetation types in group 4 occur mainly on the eastern coastal plains (such as Midlands mistbelt grasslands) and in the northern part of the country (mostly savanna types).

3.4 Discussion

3.4.1 Modelling approach

The variant of CEM used in this study allowed us to express potential distribution as continuous gradients at a 1-minute spatial resolution rather than discrete values for quarter-degree squares. Although downscaling the resolution of data can introduce more uncertainty (Araujo *et al.*, 2004), this facilitated an analysis of invasion potential of biomes and vegetation types. Such an analysis could not be done using the QDS data from SAPIA, since many QDS contain more than one biome or vegetation type.

The major limitation for modelling invasive species is the assumption that species are at equilibrium with the environment. Although, most of the species modelled here have a sufficiently long history in the region to have sampled most of the environmental conditions, their distribution is probably not yet at equilibrium. Furthermore, current model accuracy techniques (such as Kappa) might not be appropriate for modelling invasive species. Low model accuracy (i.e. low Kappa values) could mean either that the climatic envelope does not capture the environmental determinants of the species distribution, or that the climate envelope is correct and the species has huge potential for spreading into suitable environment.

Three main factors are likely to affect the accuracy of our results. Most importantly, CEMs assume the current distribution of the species provides a good indication of their potential range. Where this is not the case, potential range will be over- or underestimated. Potential range is likely to be overestimated for species occurring in few scattered locations throughout the entire region, but underestimated for species currently occurring in a small, clumped range. Secondly, spatial bias in the SAPIA database (see Nel *et al*., 2004 for discussion) may have led to underestimation of the current and potential distribution of species that are less conspicuous and/or that are under-represented in the database for other reasons (e.g. difficult to identify to species level). Lastly, the process of averaging the climatic suitability values (based on the principal component scores) of the 225 1-minute cells per QDS assumes that the mean values represent the location where the species occurs. The likelihood of there being a significant error in this assumption depends on the variability of the climatic factors in the QDS, and will be greater in areas of complex topography. At the broad scale at which this analysis is intended to inform management and planning, we do not believe that any of these factors have a substantial effect on the overall accuracy or usefulness of the results. More detailed assessments will, however, be necessary for local decision-making.

3.4.2 Potential spread of major and emerging plant invaders

Our study focused on the major plant invaders identified by Nel *et al*. (2004), because they are the invasive species most likely to be problematic in the medium-term, and management of these species will use most of the available resources. There was also sufficient data on current distribution of major plant invaders within the region for us to have reasonable confidence in the potential distributions we generated. Clearly, emerging invaders (not covered in this study) must also receive attention in long-term planning, as it is well known that control options are most cost effective at the early stages of invasion (Hobbs & Humphries, 1995; Myers *et al.*, 2000; Olckers, 2004). Prioritisation for these species requires a different approach to that adopted in this study.

Results show that some of the regions' worst perceived invaders (Le Maitre *et al*., 2000; Robertson *et al*., 2003), such as *Acacia mearnsii*, *A. saligna*, *Chromolaena odorata*, *Lantana camara*, and *Opuntia ficus-indica*, have much less potential to substantially increase their ranges than many other species (Appendix 3.1). This suggests that that management of these species should focus on preventing increased density within their current range, thus averting escalating impacts. The species that have the greatest potential to increase are not those that have previously been identified by experts as important invaders (Robertson *et al*., 2004). Only three species (*Eucalyptus camaldulensis*, *Pinus elliottii* and *P. halepensis*) out of the ten with the greatest potential increase occur on the expert-generated list of Robertson *et al*. (2004), and none of these were in their top ten. As these species could potentially have major impacts in the near future, more work is needed on their distribution and determinants of spread (including climatic requirements).

3.4.3 Spatial pattern and invasion potential of vegetation types

The map of potential number of major plant invaders in the region (Fig. 3.4a) is generally similar to the current distribution patterns (Nel *et al*., 2004), although the Free State and North West provinces of South Africa could potentially be invaded by many more species than currently occur in these areas. The potential number of invaders in the mountains of the Western Cape (Fig. 3.4a) is also surprisingly low, given the current numbers of major plant invaders. Mountain fynbos is one of the most severely impacted habitats in the region (Richardson *et al*., 1997), but has only been heavily invaded by a small number of tree and shrub species that are preadapted to the nutrient-poor soils and fire regime (Richardson & Cowling, 1992). These habitats are not suitable for invasion by most of the species in Appendix 3.1.

Invasion potential differs substantially among vegetation types. The fynbos lowlands, and parts of the grassland, savanna and thicket biomes are highly suitable (climatically) for invasion by a wide range of species (Figs. 3.4a and b). From a watershed perspective, the susceptibility of the grasslands to further invasions, particularly by woody species, is of concern because watersheds in this region have relatively high water yields and woody plant invasions can significantly reduce runoff (Le Maitre *et al*., 2000). Only a few areas appear to be suitable for more than 25 species. These areas do not always coincide with areas where management programmes are focussing their efforts. For example, about a third of the expenditure of the Working for Water Programme has been in the fynbos areas of the Western and Eastern Cape provinces (Marais *et al*., 2004), which have a lower invasion potential (i.e. are potentially suitable for fewer major invasive species). As discussed above, this area is severely affected by a few ecosystem-transforming invasive species (Richardson *et al*., 1997) and substantial management intervention is clearly justified. We have identified areas that are highly suitable for invasion by a wide range of species. Clearly, the potential number of invaders and average climatic suitability are not the only, or even the most important, indicator of the impacts invading species can have. Impact is defined as the product of a species' range, abundance and per capita effect (Parker *et al*., 1999; Richardson & van Wilgen, 2004). Finer-scale prioritisation will need to include an assessment of the impact.

In conclusion, most of the major invaders have limited potential to expand their distribution (at least under current climatic conditions), and management should seek to control density rather than to prevent range expansions. This strongly supports the use of biological control which is very effective at maintaining invaders at low densities (Olckers, 2004). Our analyses have also identified parts of the region where management of range expansions could be important, notably in the Transkei region of the Eastern Cape, in northern KwaZulu-Natal, and the bushveld areas of Gauteng and the Northern Province (Fig. 3.6).

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Tables

Table 3.1: Results of principal component analysis. More than 95% of the variation of the original seven climatic variables was explained by three climatic components. The correlation between climatic variables and principal components is indicated and the two most correlated variables are shown in bold for each component. Climatic data are from Schulze *et al*. (1997).

Climatic variables	1st component	2nd component	3rd component
Growth days per year	**0.53**	0.07	0.25
Minimum soil water stress	**-0.49**	-0.04	0.22
Frost duration	-0.11	**-0.60**	0.25
Growth temperature	-0.22	0.42	**0.64**
Mean temperature of the hottest month	-0.40	0.39	0.10
Mean temperature of the coldest month	0.17	**0.55**	-0.38
Mean annual precipitation	0.48	0.08	**0.51**

Table 3.2: Invasion potential summarised in major biomes and habitats (*sensu* Mucina & Rutherford, 2004). The median number, as well as the range, of plant invaders for which the climatic conditions are suitable is indicated (no. invaders).

Biome/Habitats	no. invaders
Biomes	
Albany Thicket	19 (1-31)
Desert	2 (0-15)
Forest	17 (0-42)
Fynbos	11 (0-36)
Grassland	20 (0-45)
Nama-Karoo	10 (0-34)
Savanna	15 (0-44)
Succulent Karoo	5 (0-26)
Wetland habitats	10 (0-42)

Legends for Figures

Figure 3.1: Climatic indices used to derive climatic envelope models. These were derived from Principal Component Analysis using seven climatic variables (see Table 3.3.1) and explained more than 95% of the initial variance. The first component (a) is mostly associated with growth days and minimum soil water stress; the second component (b) with frost duration and mean temperature of the coldest month, and the third component (c) with growth temperature and mean annual precipitation.

Figure 3.2: Species presence observations and climatic suitability derived from climatic envelope models for three characteristic species in South Africa, Lesotho and Swaziland: a) *Acacia mearnsii*, a very widespread and abundant invader; b) *Opuntia stricta*, a widespread and common invader; and c) *Hakea drupacea*, a localised and abundant invader.

Figure 3.3: (a) Relationship between current geographic range and model accuracy (Kappa statistics) based on climatic envelopes models for 71 major plant invaders in South Africa, Lesotho and Swaziland. Kappa statistics range from 0 (random agreement) to 1 (perfect agreement. Current distribution was derived from the SAPIA databases based on the QDS where the species was recorded (expressed as a % of the region). (b) Relationship between time since introduction and model accuracy (Kappa statistic). Numbers indicate a few representative species: (1) *Schinus terebinthifolius*; (2) *Arundo donax*; (3) *Psidium guajava*; and (4) *Opuntia ficus-indica*.

Figure 3.4: Potential number of major plant invaders and their average climatic suitability based on climatic envelope models.

Figure 3.5: Relationships between average climatic suitability and potential number of major plant invaders for 441 vegetation types of South Africa, Lesotho and Swaziland. Predictions were based on climatic envelope models. Four categories (labelled 1 to 4 on the figure) were identified based on natural breaks in the frequency distribution of the median number of potential invaders per vegetation type.

Figure 3.6: Invasion potential of vegetation types based on the potential number of major plant invaders. Four categories were identified: 1) < 5 potential invaders; 2) 6-15 potential invaders; 3) 16-25 potential invaders; and 4) > 25 potential invaders. South African provincial boundaries, and Lesotho and Swaziland borders are indicated: WC = Western Cape; NC = Northern Cape; EC = Eastern Cape; KZN = KwaZulu-Natal; MP = Mpumalanga; LI = Limpopo; GP = Gauteng; NW = North West; FS = Free State; LES = Lesotho; and SW = Swaziland.

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Appendix 3.1: Characteristics of major plant invaders modelled using climatic envelope models (CEMs). Categories follow Nel *et al*. (2004). Current distribution was derived from the SAPIA databases based on the QDS (expressed as a % of South Africa, Lesotho and Swaziland) where the species was recorded. The area climatically suitable was derived from CEMs using three principal components of a climatic analysis of the region. The increase was calculated as the difference between potential and current range, divided by the current range. Accuracy was calculated using a) the Kappa statistic, b) the % of QDS where the species occurs which were found to be climatically suitable (presence accuracy), c) the % of QDS where the species does not occur which were not found to be climatically suitable (absence accuracy). The Kappa statistic evaluate the model accuracy relative to the accuracy that might have resulted by chance. It ranges from –1 (complete disagreement) to 1 (perfect agreement) with 0 indicating random agreement.

Species name	Distribution/abundance category	Riparian or landscape	Current distribution (%)	Area climatically suitable (%)	Increase	Kappa statistic	presence accuracy (%)	Absence accuracy (%)
Acacia baileyana	widespread-scarce	Both	4.3	25.8	5.0	0.48	80.2	68.0
Acacia cyclops	widespread-abundant	Both	8.3	10.1	0.2	0.77	80.7	96.1
Acacia dealbata	widespread-abundant	Riparian	14.1	28.4	1.0	0.62	85.1	89.6
Acacia decurrens	widespread-common	Both	5.0	14.6	1.9	0.63	71.8	90.9
Acacia longifolia	widespread-abundant	Both	4.7	11.5	1.4	0.72	72.9	88.8
Acacia mearnsii	very widespread-abundant	Both	21.4	27.2	0.3	0.56	83.0	88.1
Acacia melanoxylon	widespread-common	Both	6.9	15.7	1.3	0.72	67.4	97.3
Acacia pycnantha	localised-abundant	Landscape	1.7	2.5	0.5	0.30	71.4	41.1
Acacia saligna	widespread-abundant	Both	7.9	8.1	0.0	0.58	74.2	75.1
Achyranthes aspera	widespread-common	Both	3.8	60.3	14.9	0.61	88.3	70.4
Agave americana	very widespread-common	Landscape	21.5	67.3	2.1	0.73	90.0	95.4
Ageratum conyzoides	widespread-abundant	Riparian	2.3	11.0	3.8	0.83	72.9	99.3
Araujia sericifera	widespread-common	Both	1.8	28.1	14.6	0.58	83.3	89.7
Arundo donax	very widespread-common	Riparian	20.7	78.4	2.8	0.76	87.2	96.3
Atriplex lindleyi	widespread-abundant	Landscape	8.1	34.4	3.2	0.35	90.2	54.0
Atriplex nummularia	widespread-common	Both	8.6	36.6	3.3	0.60	86	80.2
Bidens formosa	widespread-common	Riparian	2.6	16.6	5.4	0.72	77.1	88.5
Caesalpinia decapetala	widespread-abundant	Both	6.4	9.2	0.4	0.61	77.9	92.0

Species name	Distribution/abundance category	Riparian or landscape	Current distribution (%)	Area climatically suitable (%)	Increase	Kappa statistic	presence accuracy (%)	Absence accuracy (%)
Cardiospermum grandiflorum	localised-abundant	Riparian	2.5	22.5	8	0.59	84.1	87.0
Casuarina equisetifolia	widespread-common	Both	1.2	1.5	0.3	0.43	83.3	59.9
Cereus jamacaru	widespread-common	Landscape	6.3	32.6	4.2	0.21	80.0	34.8
Cestrum laevigatum	widespread-abundant	Both	3.6	11.7	2.3	0.71	68.0	86.3
Chromolaena odorata	widespread-abundant	Both	4.8	6.5	0.4	0.56	80.0	98.1
Cuscuta campestris	widespread-common	Both	4.1	50.4	11.3	0.58	81.7	93.5
Echinopsis spachiana	localised-abundant	Landscape	2.8	34.6	11.4	0.54	84.2	68.5
Eucalyptus camaldulensis	widespread-common	Riparian	6.8	66.1	8.7	0.74	88.5	95.6
Eucalyptus lehmannii	localised-abundant	Landscape	2.0	3.6	0.8	0.66	80.5	82.1
Hakea drupacea	localised-abundant	Landscape	1.4	2.8	1.0	0.51	71.4	69.3
Hakea sericea	widespread-common	Landscape	3.9	6.4	0.6	0.57	74.4	96.6
Ipomoea indica/purpurea	widespread-common	Both	3.7	20.9	4.6	0.58	79.7	90.3
Jacaranda mimosifolia	widespread-common	Both	10.0	18.5	0.9	0.36	83.4	50.0
Lantana camara	widespread-abundant	Both	13.0	15.3	0.2	0.69	69.1	97.8
Leptospermum laevigatum	localised-abundant	Landscape	1.9	4.3	1.3	0.72	76.3	93.8
Macfadyena unguis-cati	localised-abundant	Both	1.3	14	9.8	0.79	73.1	91.4
Melia azedarach	very widespread-common	Both	27.7	52.6	0.9	0.68	83.4	89.3
Morus alba	widespread-common	Riparian	7.1	36.8	4.2	0.55	88.4	89.9
Nicotiana glauca	very widespread-common	Both	19.7	71.5	2.6	0.45	85.6	65.0
Opuntia aurantiaca	widespread-common	Landscape	3.0	44.7	13.9	0.40	83.6	49.5
Opuntia ficus-indica	very widespread-common	Landscape	42.9	73.5	0.7	0.69	85.6	98.5
Opuntia imbricata	widespread-common	Landscape	6.5	52	7.0	0.33	86.3	43.2
Opuntia monacantha	widespread-common	Both	2.4	14.1	4.9	0.63	85.4	73.0
Opuntia robusta	widespread-common	Landscape	11.2	52.9	3.7	0.53	87.1	72.2
Opuntia stricta	widespread-common	Landscape	5.4	49.5	8.2	0.54	86.8	69.5
Paraserianthes lophantha	localised-abundant	Both	2.7	2.6	0.0	0.78	57.4	97.4
Pinus elliottii	localised-abundant	Landscape	1.7	28.4	15.7	0.68	88.2	98.0
Pinus halepensis	widespread-common	Landscape	4.2	45.7	9.9	0.72	84.7	96.8
Pinus patula	widespread-common	Both	4.5	9.9	1.2	0.74	64.7	96.9

Species name	Distribution/abundance category	Riparian or landscape	Current distribution (%)	Area climatically suitable (%)	Increase	Kappa statistic	presence accuracy (%)	Absence accuracy (%)
Pinus pinaster	widespread-abundant	Landscape	4.3	6.7	0.6	0.43	72.1	58.7
Pinus radiata	widespread-common	Landscape	3.5	11.3	2.2	0.25	76.1	39.6
Populus alba/canescens	widespread-abundant	Riparian	10.2	33.4	2.3	0.41	80.5	54.1
Populus nigra	very widespread-abundant	Riparian	4.9	31.3	5.4	0.43	85.6	55.5
Populus x canescens	widespread-scarce	Riparian	20.4	60.6	2.0	0.41	89.2	54.0
Prosopis glandulosa	very widespread-common	Both	20.5	32.9	0.6	0.62	85.7	73.0
Psidium guajava	widespread-abundant	Both	8.3	9.8	0.2	0.42	78.3	57.9
Pyracantha angustifolia	widespread-common	Both	7.1	24.8	2.5	0.69	83.9	96.9
Ricinus communis	very widespread-common	Riparian	25.9	37.7	0.5	0.68	75.4	91.3
Robinia pseudoacacia	widespread-common	Both	5.5	35.5	5.5	0.74	81.8	88.9
Rubus cuneifolius	widespread-abundant	Both	3.7	6.7	0.8	0.66	61.3	92.9
Rubus fruticosus	widespread-abundant	Both	4.4	13.3	2.0	0.09	68.5	26.8
Salix babylonica	very widespread-common	Riparian	26.1	46.6	0.8	0.63	78.9	89.9
Salix fragilis	widespread-abundant	Riparian	4.1	22.9	4.6	0.67	86.7	82.7
Schinus molle	widespread-common	Both	11.5	57.4	4.0	0.27	85.8	38.1
Schinus terebinthifolius	localised-abundant	Both	1.6	3.1	0.9	0.62	73.3	72.8
Senna didymobotrya	widespread-common	Both	7.1	10.1	0.4	0.60	78.4	79.0
Senna occidentalis	widespread-common	Both	2.8	11	2.9	0.47	87.5	57.9
Sesbania punicea	widespread-common	Riparian	17.8	53.1	2	0.61	85.2	76.1
Solanum mauritianum	widespread-abundant	Both	13.3	18.9	0.4	0.58	79.2	82.7
Solanum seaforthianum	widespread-common	Both	1.6	11.2	6.0	0.60	64.5	73.6
Solanum sisymbriifolium	widespread-common	Both	2.0	37.3	17.7	0.73	80.0	86.3
Verbena bonariensis	widespread-common	Riparian	3.2	23.9	6.5	0.49	72.4	63.2
Xanthium strumarium	widespread-common	Both	7.5	54.4	6.3	0.55	90.7	83.3

CHAPTER 4: ALIEN PLANT INVASIONS – INCORPORATING EMERGING INVADERS IN REGIONAL PRIORITIZATION: A PRAGMATIC APPROACH FOR SOUTH AFRICA

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Abstract

Plant invasions are known world-wide to be a serious threat to natural and semi-natural ecosystems. However, most research on such invasions is focussed on the management of plant invaders that have already become a problem. A climate matching procedure was used to define areas of South Africa, Lesotho and Swaziland that could be invaded by 28 plant species that had been classified as emerging invaders. Information on the location of species populations in the study area was combined with information on where they occurred in parts of Australia and the United States of America. Climatic data was obtained for weather stations near these locations and used to define the climatically suitable area for each of the 28 species in the study area. This analysis of the current and potential distribution of a selection of South Africa's emerging plant invaders identified the species with the potential to be the most problematic in the future without timely intervention, as well the areas which are most vulnerable to invasion by these species. There was no relationship between the extent of the climatically suitable area the different species and an expert ranking of their invasion potential, emphasising the uncertainties inherent in making assessments based on very little information. The results also highlight the importance of early warning systems and risk assessment of newly introduced alien plants in South Africa, and emphasise the importance of dealing with alien plant invaders in the early stages of invasion i.e. emerging plant invaders. The modelling process followed to derive the climatic envelopes that represent each of the selected species' potential distribution is the first of its

kind in South Africa. Previous exercises have involved modelling one or a few species at a time compared with the 28 assessed here. The methods used in this analysis establish a protocol for future modelling exercises to assess the spread potential of other emerging invaders.

Keywords:

Emerging plant invaders, climatic envelope, potential distribution

4.1 Introduction

Most studies on the management of biological invasions are focused on dealing with already established infestations or stopping introductions of high-risk species (Le Maitre et al., 2000, 2002; Nel et al., 2004). This study focuses on a different part of the alien plant invasion continuum, namely species already identified as invaders but which are in their early stages of invasion (Hobbs & Humphrey, 1995).

Once an alien plant species becomes invasive it becomes increasingly difficult to eradicate with an acceptable expectation of success (Hobbs and Humphries 1995; Myers et al. 2000; Rejmánek, in press). Emerging or re-emerging invaders are of increasing international concern because of the potentially devastating effects they can have on the economy, the environment, and society (Community Indicators, 2002). Early warning systems (which include regular and urgent reporting by monitoring systems and public awareness initiatives) and rigorous eradication and containment procedures must therefore be put in place and maintained if South Africa is to successfully prevent and manage ‘new’ and ‘emerging’ alien plant invasions. In South Africa, initiatives such as the Working for Water Programme are recognised for their innovative approach to addressing the management of mainly major invasive alien plants (van Wilgen et al., 2002). However, most of the current initiatives are reactive measures of managing those alien plants that are already invasive, often with large adventive ranges. More pro-active approaches are needed to maximise the success of management efforts in the control of both already well-established invaders and, more importantly, emerging invasive alien plants and the areas which they are most likely to affect. Such a preventative approach requires that these newly invading alien plant species and areas to be identified, prioritised, and then managed.

About 750 invasive alien tree species and 8 000 invasive alien shrubby and herbaceous species have been introduced into South Africa (Henderson, 1998; 1999) for a range of purposes (as crop species, for fodder, for timber and firewood, as tannin production, as garden ornamentals, for stabilizing sand dunes and as barrier and hedge plants). Many of these alien species have become naturalized, and some of these naturalized species have become invasive (Richardson et al., 1997). Invasive alien plants are a significant problem in South Africa, affecting almost 10 million hectares (8.28%) of the region, and spreading rapidly (Versfeld et al., 1998; Le Maitre et al. 2000).

Nel et al. (2004) identified 84 species of emerging plant invaders of South Africa, Swaziland and Lesotho based on their potential to spread. It is critical to incorporate these species into alien plant monitoring programmes, to give early-warning of rapid spread and increased impacts (Wittenberg and Cock, 2001). South African researchers have also demonstrated that biological control is most effective during the earliest stages of invasion; thus focussing biological control efforts on emerging invaders could be used as a pro-active means of directing biological control research (Macdonald et al., 1986; Olckers, 2004). Understanding the potential distribution ranges of emerging invaders in South Africa will enable identification of the emerging invaders which have high explosion-potential within South Africa, and allow management to focus action and monitoring efforts on the areas which have highest vulnerability to invasion.

Studies that have been done to predict the potential distribution of invading species generally have focussed on few species whose attributes and ecological requirements are well-known (Sutherst et al., 1991; Pheloung, 1996; Kriticos and Randall, 2001). Some of these approaches include consideration of the likely dispersal probabilities and pathways, and the suitability of the new environment for the plant (Kriticos and Randall, 2001). This study required a more pragmatic approach suitable for a national scale (with diverse environmental conditions), involving a range of species and with only very basic information on these species. It has long been recognised that the distribution patterns of plants are constrained primarily by climate (Woodward, 1987; Huntley et al., 1995; Rouget and Richardson, 2003) and this has underpinned many attempts to predict the potential distribution of species.

This study provides a protocol for predicting the potential distribution of emerging invasive alien plant species using distribution records from other countries or regions to augment existing records within the country of concern. This enables: (i) the prediction of areas where emerging invasive alien plant species are likely to become a problem, to provide an opportunity for early action (e.g. for biocontrol); (ii) the determination of whether the areas in South Africa, Lesotho and Swaziland (hereafter called the region) that are climatically suitable for invasion by new plant invaders are new areas or areas that are, or were previously, invaded by the major alien plant invaders identified by Rouget et al. (2004); and (iii) testing whether the extent of the climatically suitable envelope of each of the selected emerging plant invaders is consistent with the expert rating of emerging plant invaders as defined by Nel et al. (2004).

4.2 Methods

4.2.1 Selection of species

Twenty-eight out of 84 emerging invasive alien plant species were selected from Nel et al. (2004) for modelling using the CLIMATE model. These species were chosen on the basis of three criteria:

(i) First, we chose species which were listed independently by more than two out of six alien plant experts as the most important emerging invaders. This gave us a list of 11 plant species (Table 4.1).

(ii) The combined score of Nel et al. (2004) - which scored the emerging plant invaders according to impact, weediness, potential for biocontrol and proportion of weedy relatives within the genus - was used to choose the next suite of species. Emerging plant invaders with a combined score of 80 or more were chosen next (Table 4.1), providing an additional thirteen species. Emerging aquatic weeds were excluded because they are not suitable for climatic modelling.

(iii) Finally, we made sure that we had chosen at least one representative from each emerging invader category assigned by Nel et al. (2004) according to potentially invasible habitat and current propagule pool size. *Grevillea robusta* and *Quercus robur* were selected as representatives of the otherwise absent category for species with a small habitat and large propagule pool.

4.2.2 Assembling global distribution records for selected species

Most of the emerging plant invaders in South Africa, by definition, currently occur over a limited range. Thus, location data from South Africa alone is insufficient for deriving reliable potential distributions using climatic envelope models, such as those developed for South Africa's major plant invaders (Rouget et. al., 2004). We therefore assembled additional species locations from elsewhere in the world to supplement input data into our climatic envelope model.

To provide guidance on other regions of the world with similar climates, the CLIMATE model (Pheloung, 1996) was run using weather station datasets for South Africa as input locations. Australia, USA, South America and parts of Europe showed the greatest climatic similarities to South Africa (Figure 4.2). Experts from each of these countries were consulted and an internet search was conducted to collect occurrence data and geographic locations for the selected 28 emerging plant invaders. Two databases were available for Australia, the Australian Virtual Herbarium and the Queensland Herbarium databases. The former database does not distinguish between cultivated and naturally occurring records, and since it contains many records from botanical gardens that would obscure the climatic envelope modelling, we decided not to use it. The following data sets were used:

- Queensland Herbarium database: this flags cultivated records, and contains several records from elsewhere in Australia as well as a few records from South East Asia and other parts of the world.

- USA Plants database: lists 15 of the 28 species and supplies occurrence data at a county level. The USA Plants database only records naturalised or native populations, so the issue of cultivated specimens was not of concern in this database. Several States did not have county level information; the data from these States were therefore at a scale too coarse for our analyses and were excluded.

- Southern African Plant Invaders Atlas (SAPIA) database: provides occurrence data at the level of quarter-degree squares (15' latitude x 15' longitude, QDS) for species within southern Africa.

We were unable to access data from South America. The Flora Europaea database which we were able to search only included one of the species we had selected; however, the full Flora Europaea database was not available, and we therefore do not know whether it includes more of the species.

4.2.3 Selection of a suitable model

The CLIMATE model was chosen to model potential envelopes of the 28 selected species, as it is appropriate for the global scale at which we needed to model the species' distribution data. CLIMATE was developed from concepts contained in the Bioclim Prediction System (Nix, 1986) and CLIMEX (Sutherst et al. 1999). The meteorological data is laid out in CLIMATE within a "world database" (a worldwide collection of locations) and the "airports database" (an additional set of meteorological data taken from the World WeatherDisc produced by WeatherDisc Associates, Inc). We used both these datasets for these analyses as the "world database" was more comprehensive in Australia, and the "airports database" improved the data resolution in the USA.

CLIMATE uses 16 climate variables based on temperature and rainfall data (Table 4.2), from a set of geographical locations where a species is known to occur, to construct a climatic profile. A set of locations matching this profile within South Africa is then produced. The 16 parameters are identical to those defined in the BioClim Prediction System (Nix, 1986). The climatic parameters have been selected to identify overall differences in temperature and rainfall, as well as the seasonal patterns in rainfall and their relationship to temperature (e.g. winter versus summer rainfall). The parameters are used to generate a climatic profile for each species which is suitable for a percentile, statistical or Euclidean distance analysis. Some statistical methods can produce erroneous predictions if the inputs are from highly diverse climates. In such cases, averaging can generate an intermediate profile which is not representative of the extremes.

The cumulative matching method, using the closest Euclidian match option, was chosen in this study to avoid this type of error. In this method each of the weather station data set points where the species occurs is compared to each one of the selected weather stations in the area that could be invaded. The data are normalised using the standard deviation of the entire meteorological database. For each of the 16 climate parameters, the difference between the value of the input point and the corresponding value of the output point is calculated. The Euclidean distance is the sum of the squares of these differences. Where a comparison gives a reasonable degree of match, the matching weather station is output to a file. Matches are then rated based on the Euclidean distance and rescaled to the range: 0-100, where 0 = a complete match and 100 = no match. We chose to output the matches in four categories: very high (0-20), high (20-30), medium (30-40) and low (40–50).

4.2.4 Matching weather station locations and species occurrences

Nearly all the Queensland Herbarium data records had latitude and longitude information and where they did not, we used the place name to obtain the geographic location. The nearby weather stations were selected as input for the CLIMATE model (Table 4.3). These weather stations were typically less than 20 km away from the species collection locality in question, but in some cases stations up to 50 km away had to be selected.

The county level occurrences of the USA Plants database were used to select all the weather stations that fell within counties where the species occurred (Table 4.3). Most counties on the east coast are less than 50 km across while those on the west coast are often 100km across. The width of the west coast counties are of concern as this can increase the range in climate factors due to changes in elevation and orographic gradients. This means that the climate at the selected weather station may not be a good match to the species collection locality even though they are in the same county.

Most records in the SAPIA database are at the scale of a QDS (grid cells of 15' latitude x 15' longitude; QDS), and nearby weather stations were selected as input for the CLIMATE model (Table 4.3). As with the Australian data these weather stations were typically less than 20 km away from the QDS in question, but in some cases stations up to 50 km away had to be selected.

4.2.5 Creating climate envelopes for South Africa

As the USA and Australian datasets were at different scales, we decided to model them separately. The South African data was also kept separate to serve as a comparison. For each species, we first produced separate climatic profiles based on location data from Australia, USA and South Africa to test the effect of the different spatial scales at which the location data are recorded. In most cases the number of records for the separate climatic envelopes is too low and the data collection bias too high to provide a statistically reliable climate envelope (Table 4.3). Therefore, we combined the separate outputs to get more confidence in the derived envelopes.

The output from the CLIMATE model for each emerging plant invader was a set of weather station locations in South Africa which matched the values of the 16 climate parameters for that plant species with a predetermined degree of accuracy (very high, high, medium and low; Figure 4.1 & Table 4.3). Climatic envelope surfaces at a resolution of 1x1 grid cells were derived for each species as follows:

(i) Sixteen climatic surfaces describing the climatic parameters used by CLIMATE (Table 4.2) were derived using the monthly temperature and rainfall data of the South African Atlas of Agrohydrology and Climatology (Schulze et al. 1997), which provides data at a resolution of 1’ latitude x 1’ longitude grid-cells. The climatic surfaces were smoothed with a focal mean function, using a 3x3 neighbourhood filter to calculate the mean climatic conditions in that vicinity of the weather station, and to minimise the impact of inaccuracies in the location of weather stations. The accuracy of the match between the Atlas and CLIMATE values for each of the stations was analysed by comparing both the relationship between the Atlas and CLIMATE values for each station and the correlation between the values in the two data sets. The analysis showed that 15 correlations were significantly positively correlated ($P < 0.001$), but that there was no relationship with the CV of the monthly rainfall. Since some preliminary analyses had shown that the CLIMATE model is particularly sensitive to exclusion of any of the 16 climatic parameters. Thus, we did not exclude CV of the monthly rainfall from CLIMATE, but excluded it from the climate envelope surface generation.

(ii) Weather station locations in the very high accuracy category of match were selected and converted to a raster-based GIS surface at the same resolution as that of the South African Atlas of Agrohydrology and Climatology (a value of 1 was given to the grid-cell where each weather station was located and 0 for the remaining cells).

(iii) The range of values of each of the 16 climatic surfaces derived from the Atlas data was calculated and used to build a climatic profile for each species. Grid cells whose values fell within the range for each of the climatic parameters were selected and assigned a value of 1; those outside the range were assigned a value of 0. Multiplying the resulting 16 climatic surfaces provided a single climatic envelope which represented the area where the envelopes for all 16 parameters overlapped (Figure 4.1 & Table 4.3).

The 28 climatic envelope surfaces were then added together to create a final combined envelope for all the species (Figure 4.1).

4.3 Results

4.3.1 Invasion potential

Potential extent of distribution of the 28 emerging plant invaders

Most of South Africa has the potential to be invaded by at least one of the 28 emerging plant invaders (Figure 4.4a). About 26% of the natural environments in the region (roughly x% of the total area) could be invaded by 1-5 emerging plant invaders, 31% by 6-15, and 24% (dark grey) by 16 or more species. Only 19% was not potentially invadable and most of this area was situated in the arid north-western interior, Limpopo River valley and in the subalpine regions of Lesotho. The worst affected area with 20 or more species covers most of the grasslands of the highveld and an area below the eastern escarpment The least affected area, with only one or two species, is situated in the arid western interior and west coast and most of the Western Cape is only suited to invasions by up to 5 species.

Potential distribution of the 28 emerging plant invaders

The extent of the potential invasions varies substantially between the different species (Table 4.2). Three are predicted to invade no more than 10% of the region, 10 could invade 10-25%, 11 between 25 and 50%, and four species to invade more than 50%. The species with the most extensive indvadable area include three tree species (*Acacia podalyriifolia, Gleditsia triacanthos, Grevillea robusta*) and a grass species (*Cortaderia selloana*). *Acacia podalyriifolia* has a very wide potential distribution (64% of the region, Figure 4.3(a)) and its absence from the western interior and the Limpopo River valley and lowveld seem to be determined mainly by the low rainfall and relatively high temperatures in these areas. *Lythrum salicaria* has a much more limited potential distribution (7% of the region) and seems to be confined to the moderate climates (high rainfall, moderate temperatures) that characterise the east coast and parts of the southern and western coastal lowlands (Figure 4.3b). Like *A. podalyriifolia*, *Pereskia aculeata* could invade much of the eastern past of the region (Figure 4.3(c)), suggesting that this species, which is already known to be difficult to control, has the potential to become very widespread. *Ulex europeus* could become a major grassland invader (Figure 4.3(d)) and also is known to be difficult to control.
Comparing the current distribution to the derived climatic envelopes

The approach of predicting potential distributions of biota using climatic envelope models is based on the assumption that species distributions are primarily determined by their local climate. The current distribution range fell within the region that was shown to be climatically suitable for future invasions and generally was much smaller than the potential area for each species (Table 4.3). The current distributions ranged from 0.1% of the region (*Acacia paradoxa*, *Celtis sinensis*, *Cestrum parqui*, *Lythrum salicaria*, *Psidium guineense*) to 6.2% of the region with a mean of 1.4%. The potential distributions ranged from less than 1% (*Psidium guineense*) to 64% (*Acacia podalyriifolia*) with a mean of 30%. Most of the species had current distributions of 3% or less of the region and only two species had current distributions of more than 3% (*Gleditsia triacanthos* and *Rosa rubiginosa*).

A general trend of increasing potential distribution with increasing current distribution is evident from the comparison of current to potential distribution ($R^2 = 0.77$, $P < 0.01$) (Figure 4.5). There is a substantial scatter for species with current distributions of less than 1% of the region but less for those above 2%. For example, *Cestrum parqui* (currently <1%) could potentially invade up to 35% of the region and *Spartium junceum* (1%) could invade 45%. Both *C. parqui* and *Celtis sinensis* (envelope extent 15%) had only one SAPIA record but they were from locations where the climatic conditions (for the 16 selected parameters) represent a wide area. The Australian data only added three matched weather stations and there were no species occurrence records for these species from the USA. The case for *S. junceum* was different; although there were only 20 SAPIA records these were spread across the region, resulting in an extensive climatically suitable area for invasion.

4.3.2 Contribution of weather station data towards invasion potential

An analysis of the contributions of the different countries (SA, Australia and USA) to the "very high" and "high" weather station category matches (Euclidean distance scores of 0-30) for each of the twenty-eight species, showed some interesting patterns of invasion potential. The USA weather station input data points (at county level) did not add any new potential distribution location points to those predicted using the South African SAPIA input data. Rather than adding new points, the USA data strengthened the potential distribution prediction from the South African input data for the Western Cape and occasionally parts of the Northern Cape.

The Australian weather station data input added new potential distribution location points in eleven of the twenty-eight species, with these points often either being located in the Eastern Cape and/or Northern KwaZulu Natal (particularly along the coast). The contribution from the South African weather station data towards predicting the potential distribution of the selected emerging plant invaders was the most prominent, highlighting the eastern part (Gauteng, Mpumalanga, Limpopo, inland KwaZulu Natal and Eastern Cape, and the boundaries of the Northwest Province) of the region as vulnerable to future invasions by emerging plant invaders.

An analysis of the overall contributions from weather station data from the different sources (Table 4.3) shows that the extent of the potentially invadable areas is strongly correlated with both the number of SAPIA records (R^2=0.77, P<0.01) and regional weather station records used (R^2=0.88, P<0.01). The correlations between envelope size and the number of weather stations from both Australia and the USA are all weak and non-significant. The same is true for the number of occurrence records for the species in Australia and the USA. The correlations were also weak and non-significant for the total number of weather stations used. An analysis of the cores given to the species (Table 4.1) also found that they were not correlated with the extent of the potentially invadable areas. These findings emphasise the point made above that few of the foreign weather stations were well matched to local conditions. They also highlight the critical importance of local distribution records, however few, in predicting the climatically suitable areas of a region for a particular species.

4.4 Discussion

4.4.1 Limitations imposed by the lack of species occurrence data

Although the climatic conditions in South Africa showed strong matches with large areas of Australia, USA, South America and the Mediterranean Basin, we were only able to obtain adequate species distribution data for Queensland and parts of the USA. We only had access to a portion of the Flora Europaea database which only had information on one species. The lack of species occurrence data has undoubtedly had an impact on process of identifying and matching species and climate records, but it is not possible to determine whether or not the resulting climate envelope would have been more extensive, and whether or not this effect would have differed for different species. These uncertainties must be borne in mind when interpreting these results.

4.4.2 Steps leading to over- or under-estimating envelopes

The occurrence data that were obtained almost certainly does not represent the complete climatic range of that species. The use of a subset rather than the full range will result in an unknown degree of underestimation of the climatic envelope. For the USA data, the selection of all the weather stations in a county is likely to capture a wider climatic range than would be the case if the actual locations of the species were available. This would lead to an overestimation of the climatic envelope.

In the case of the Australian and South African data sets, where nearby weather stations had to be selected to represent the occurrence data, overestimation of the envelope would occur if the weather station was situated in more extreme climatic conditions than the input point. Conversely, underestimation might occur if the weather station was situated in more moderate climatic conditions. This is often the case because weather stations are situated in towns or cities which are generally in the valleys rather than in the nearby mountain areas where the species was recorded.

The net impact of these uncertainties on the predicted extent of the potentially climatically suitable areas cannot be estimated but it must be borne in mind when interpreting these results. The overriding importance of species occurrence data in the region of interest emphasises the importance of selecting the local weather stations that match these locations as carefully and rigorously as possible.

4.4.3 Expert rated habitat potential vs climatic envelopes

A comparison of the expert rating of the extent of the potentially invadable habitat (Nel et al 2004) with the predicted climatically suitable proportion of the region for the same species shows that the predictions did not match up (Figure 4.6). The category of a small potential range showed the greatest mean range but only involved two species (*Quercus robur* and *Grevillea robusta*) compared with the 12 species with a moderate and eleven species with a large potentially invadable habitat (Table 4.3). The range of values in both the moderate and large potential habitat size groups is wide, from <1 to more than 50% with medians of 23 and 28, respectively. This indicates that the expert ratings for the remaining 56 emerging species (Nel et al. 2004) may not be a useful guide to the extent of the potentially invadable area.

A comparison of the combined potential distributions of these 28 species shows that they correspond in a general way with the distributions of the number of species per quarter degree square for all 81 emerging species (Nel et al. 2004, Figure 4.4a and b), But this study shows that much greater area of the region will be invaded by most of the species than is indicated by species occurrence records even though this study examined fewer species.

The important differences are the greater and more extensive impacts on the highveld, and in a region parallel to and below the eastern escarpment, which are predicted by this study.

The SAPIA data show greater concentrations of invaders in the more densely inhabited areas, particularly on the east coast and in the forestry and agricultural areas of Mpumalanga and Limpopo Province. This study also differs from the SAPIA data (Figure 4.4b) in that it predicts a relatively low degree of invasion along the east coast. This is surprising given that the sub-tropical climates in this area support invasions by a wide range of highly aggressive species. It is likely that the results of this study may have been more influenced by the climatic preferences of the set of 28 species that was included in this analysis so that these findings are not a good indication of the potential vulnerability of those environments to invasions.

4.4.4 Concern about particular species

The Australian species *Acacia elata* occurs in several locations in South Africa with most occurrences being in the Western Cape and a few in Gauteng, Mpumalanga and KwaZulu Natal. Given this range of environments, it was surprising that the three weather stations identified from Australian distribution records did not even find weak matches. A closer inspection showed that the climates of the Australian weather stations in the CLIMATE database (Bellingen, Wollongong, Yarras) are characterised by relatively high rainfall (>1400 mm per year), all year rainfall and a moderate climate (mean annual temperature >17°C). There are no close analogues of this climate in South Africa, particularly with such high rainfall.

Cytisus scoparius is a major invader in California, and other areas of the USA, but the 104 records of this species in the USA data generated only weak matches for this species in South Africa. We examined the CLIMATE data for the Californian weather stations to determine why this was so. The main difference seems to be that the seven Californian stations were all characterised by little or no summer rainfall (driest month and driest quarter) whilst the weather stations on South Africa’s west coast have substantial proportion of summer rainfall. One of the Californian stations is situated on the Monterey Peninsula, one of the sources of *Pinus radiata* which successfully invades fynbos (Richardson, 1998). This suggests that there may still be a substantial risk that *Cytisus scoparius* could invade fynbos.

4.4.5 Importance of early warning systems

With increasing globalization it is likely that the volumes and speed of trade, travel and tourism to South Africa will continue to increase, at least in the short and medium terms (Le Maitre et al., 2004). It is thus likely that the rate of arrival of invasive alien plant species will also increase in the immediate future. It is predicted that with global climate change indigenous ecosystems will become increasingly maladapted to the novel climates occurring in their natural ranges (Rutherford et al., 1999). This is likely to result in indigenous ecosystems becoming increasingly susceptible to invasions by alien plant species that arrive pre-adapted to these novel climates from elsewhere in the world where such climatic conditions have occurred previously (Macdonald, 1992; Dukes and Mooney, 1999).

Another factor that will facilitate alien plant invasion is the extent to which natural ecosystems will be transformed by humans. Studies throughout the world have shown that land transformations, such as clearing for agriculture and forestry plantations, favour a whole host of invasive alien plant species (Hobbs, 2000; With, 2002). Land cover monitoring studies have shown that large proportions of South Africa's natural ecosystems are already transformed, particularly in the wetter coastal and highveld regions (these areas already hold the most invasive alien plant species) (Fairbanks et al. 2000). The extent and rate of land transformation is likely to increase in the coming decades (Tainton et al., 1989; Macdonald, 1989; Soulé, 1991; Dale et al., 1994; Sala et al., 2000). Further, ecosystem modifications as a result of human-induced changes in factors such as the fire regime or grazing are also known to facilitate alien invasions (Hobbs and Huenneke, 1992; Macdonald 1992; D'Antonio, 2000). It is highly likely that in the decades ahead mounting human pressures will increase the extent to which South Africa's remaining natural ecosystems are modified. All of the above trends support the view that in the future the challenges posed by invasive alien plant species will increase markedly over what we are currently experiencing. This emphasizes the need to rapidly and markedly improve the ability to prevent new and manage existing invasions.

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Tables

Table 4.1: Emerging plant invaders from Nel et al. (2004) selected for climatic modelling of their potential distributions. "Category" refers to the size (small, medium large, riparian) of potentially invasible habitat and current propagule pool size (small, medium, large) as assigned by Nel et al. (2004). "Combined score" refers to the score assigned to each species by Nel et al. (2004) on the basis of their impact, weediness, potential for biocontrol and number of weedy relatives. Species selected for modelling were those which were rated by more than two out of six alien plant experts as important emerging plant invaders; species with a combined score ≥ 80, and species chosen to achieve full category representation as per Nel et al. (2004).

Scientific name	**Common name**	**Category**	**Score**	**Reason for selection**
Acacia elata	Pepper tree wattle	M-L	69	Expert rated
Acacia paradoxa	Kangaroo wattle	L-S	69	Expert rated
Acacia podalyriifolia	Pearl acacia	M-L	67	Expert rated
Celtis sinensis	Japanese Hackberry	L-M	45	Expert rated
Cestrum parqui	Chilean cestrum	M-M	91	Score = 90
Cinnamomum camphora	Camphor tree	M-L	90	Score = 90
Cortaderia jubata	Pampas grass	R-L	75	Expert rated
Cortaderia selloana	Pampas grass	R-L	81	Score 80-89
Cytisus scoparius	Scotch broom	L-M	86	Score 80-89
Gleditsia triacanthos	Honey/Sweet locust	M-M	68	Expert rated
Grevillea robusta	Australian silky oak	S-L	67	Category representation
Hedychium coronarium	White ginger lily	M-L	87	Score 80-89
Hedychium gardnerianum	Kahili ginger lily	M-L	92	Score = 90
Ligustrum sinense	Chinese privet	M-L	80	Score 80-89
Lonicera japonica	Japanese honeysuckle	M-L	83	Score 80-89
Lythrum salicaria	Purple loosestrife	M-M	88	Score 80-90
Mimosa pigra	Giant sensitive plant	R-M	76	Expert rated
Nephrolepis exaltata	Sword fern	M-L	84	Score 80-89
Pennisetum purpureum	Elephant grass, Napier grass	L-M	95	Score = 90
Pereskia aculeata	Barbados gooseberry	L-M	87	Expert rated
Pinus taeda	Loblolly pine	L-L	87	Score 80-89
Psidium guineense	Brazilian guava	M-L	84	Score 80-90
Quercus robur	English oak	S-L	67	Category representation
Rosa rubiginosa	Eglantine, Sweetbriar	L-M	96	Score = 90
Spartium junceum	Spanish broom	M-L	82	Expert rated
Tecoma stans	Yellow bells	L-L	69	Expert rated
Tipuana tipu	Tipu tree	L-L	73	Expert rated
Ulex europeus	European gorse	L-M	80	Score 80-89

Table 4.2: The 16 climate parameters by Schulze et al. (1997) used as input data into the CLIMATE model to compare and match climates based on weather station data. For more information see the methods.

Temperature parameters (°C)	**Rainfall parameters (mm)**
Mean annual temperature	Average annual rainfall
Minimum temperature of coolest month	Rainfall of wettest month
Maximum temperature of warmest month	Rainfall of driest month
Average temperature range	CV monthly rainfall
Mean temperature of coolest quarter	Rainfall of wettest quarter
Mean temperature of warmest quarter	Rainfall of driest quarter
Mean temperature of wettest quarter	Rainfall of coolest quarter
Mean temperature driest quarter	Rainfall of warmest quarter

Table 4.3: Expert rankings, habitat invaded and information on the data on the number of records and weather stations that was used to predict the climatically suitable area for each species with the CLIMATE model. The extent of the climatically suitable envelope is also shown. QDS = Quarter degree square i.e. 0.25° of longitude x 0.25° of latitude.

Scientific Name	Expert ranked categories	Habitat invaded	SAPIA records (number QDS)	Number of regional weather stations	Australian distribution data (number QDS)	Number of Australian weather stations	USA distribution data (number QDS)	Number of USA weather stations	Extent of climatic envelope (% of region)
Acacia elata	ML	Landscape	35	19	3	3	0	0	50
Acacia paradoxa	LS	Landscape	1	3	56	39	1	12	1
Acacia podalyriifolia	ML	Landscape	57	34	32	32	0	0	64
Celtis sinensis	LM	Landscape	1	1	41	12	0	0	15
Cestrum parqui	MM	Landscape	1	2	68	27	0	0	35
Cinnamomum camphora	ML	Landscape	10	11	50	0	6	108	21
Cortaderia jubata	RL	Riparian	7	5	1	0	0	0	20
Cortaderia selloana	RL	Riparian	55	30	8	6	2	48	56
Cytisus scoparius	LM	Riparian	10	8	11	7	12	104	23
Gleditsia triacanthos	LM	Riparian	111	34	27	27	22	342	57
Grevillea robusta	SL	Landscape	53	26	25	0	3	59	51
Hedychium coronarium	ML	Riparian	14	9	4	4	1	45	32
Hedychium gardnerianum	ML	Riparian	12	10	7	5	0	0	12
Ligustrum sinense	ML	Riparian	8	7	53	17	11	170	18
Lonicera japonica	ML	Riparian	5	6	31	14	21	420	26
Lythrum salicaria	MM	Riparian	1	3	41	24	21	278	7
Mimosa pigra	RM	Riparian	7	5	16	2	0	0	21
Nephrolepis exaltata	ML	Landscape	13	7	3	2	1	95	17
Pennisetum purpureum	LM	Riparian	40	21	41	23	1	111	40
Pereskia aculeataa	LM	Landscape	44	24	7	5	1	23	41
Pinus taeda	LL	Landscape	7	8	5	5	9	162	22
Psidium guineense	MS	Landscape	2	2	21	13	0	0	<1
Quercus robur	SL	Riparian	50	27	3	4	4	25	36
Rosa rubiginosa	LM	Landscape	119	29	45	18	20	187	50
Spartium junceum	ML	Landscape	20	16	3	4	1	103	45
Tecoma stans	LL	Landscape	58	21	40	22	1	51	38
Tipuana tipu	LL	Riparian	24	13	13	9	0	0	28
Ulex europeus	LM	Riparian	9	5	10	6	4	79	24

Legends for Figures

Figure 4.1: Schematic representation of the process that was followed in deriving climatic envelopes for the selected emerging plant invaders**.**

Figure 4.2: The regions of the world where the climates are most closely matched with the climates in the region based on outputs from the CLIMATE model. This dataset was used to identify the areas of the world that were searched for information and distribution records for the 28 emerging species. The data were also used in the process of deriving climatic envelopes for the selected emerging plant invaders.

Figure 4.3: Potential (a) and current (b) distribution of all twenty-eight emerging plant invaders. The information on the current distributions was derived by Nel et al. (2004) from the SAPIA database (Henderson 1998).

Figure 4.4: The current and potential distributions of a selection of the twenty-eight emerging plant invaders. (a) *Acacia podalyriifolia* is an example of a species that has a very wide potential distribution and (b) *Lythrum salicaria* an example of a species with a very limited potential distribution but is among the world's 100 worst invaders (Lowe et al. 2001), (c) *Pereskia aculeata* is already considered a very problematic emerging invader in SA and (d) *Ulex europeus* is also among the 100 worst invaders.

Figure 4.5: Relationship between the current and potential ranges of emerging species. The current range is expressed as the percentage of the Quarter Degree Squares (0.25° x 0.25°) in the region that have been invaded (data from the SAPIA database, Henderson 1998), and the potential range as the percentage of the total number of 1' x 1' grid points in the region which are climatically suitable for the species to invade.

Figure 4.6: Comparison of the expert rating of the potentially invadable habitat of emerging species and the predicted climatically suitable area (% of the region). Error bars show the standard deviation.

CHAPTER 5: PLANT INVASIONS IN SOUTH AFRICA, LESOTHO AND SWAZILAND: ASSESSING THE POTENTIAL IMPACTS OF MAJOR AND EMERGING PLANT INVADERS

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Abstract

The study assesses the potential impacts of a suite of 71 major and 28 emerging plant invaders on biodiversity, water resources and the productivity of natural rangelands (bushveld, grassland, shrublands) in South Africa, Lesotho and Swaziland. The scores for these impacts were based on a survey of the literature and including the following factors: per capita impact estimated for attributes such as size and growth form as an index of potential transpiration, ability to transform natural communities and toxicity to livestock, multiplied by their natural ability to form dense stands to give a per population impact. The population scores were multiplied with estimates of the extent of their climatically suitable range to give a total impact score. The geographic distribution of the impacts in the region was also assessed using data sets from previous studies which predicted the distribution of the climatically suitable areas for each species. Analyses of the scores of individual species for population impacts on water resources showed them to be generally similar to previous investigations, but previously underrated species emerged as having important impacts on biodiversity and rangelands because they can transform natural communities or are toxic to livestock. The total impact scores were markedly affected by the extent of the climatically suitable area. Some *Opuntia* species scored highly because they can invade most of the arid and semi-arid interior as well as higher rainfall areas. *Prosopis glandulosa,* which invades the arid interior, also achieved a high score. Riparian invaders such as *Arundo donax, Acacia* and *Populus* species can invade a large proportion of the river systems in the region. The distribution of the population impacts of the major species on biodiversity and water resources differed substantially from those on rangelands, but the rangeland impacts differed little from those based on the number of species alone. This was not

so for the emerging species where the predicted impacts on rangelands, biodiversity and water resources differed little from those based on species number, except for the Western Cape coastal lowlands where the impacts on water were somewhat higher. Species numbers alone will only give a reasonable estimate of the potential impacts when most of the predicted distributions or impact scores, or both, are similar. The main reason for the smaller differences in some cases (major species impacts on rangelands, emerging species impacts) appears to be that many species had similar scores and there were extensive overlaps in the climatically suitable areas for the different species. The eastern regions that will be affected include the high water-yielding catchments and important centres of plant endemism and richness. This information can be used by decision makers to set priorities for which areas should get the most investment and for developing control strategies for individual species.

5.1 Introduction

The Working for Water Programme has become internationally known for its innovative approach to invasive alien plant control which combines a national scale clearing programme with social development through job creation. During the past seven years the programme has invested US$265 million in the clearing of alien plant invasions and rehabilitation of cleared areas (Anon 2002). One of the areas where the programme has been weak is in developing a clear rationale for the selection of certain species and areas for channelling its investment (Laros et al. 2003). This is not simply a problem for the programme, many countries are busy developing or testing strategies for prioritising investment in controlling alien species invasions. There have been numerous studies of the risks posed by invading species. Some have focused on invasion ecology and used biological attributes of the invaders or of the environment being invaded to assess the potential for invasions (Tucker and Richardson 1995; Reichard and Hamilton 1997; Pheloung et al. 1999; Lockwood et al. 2001; Rejmánek et al. 2004; Robertson et al. 2003). Others have focussed more on assessing the climatic potential for invasions by matching key climatic parameters to identify regions with suitable climates for the species (Panetta and Dodd 1987; Sutherst et al. 1999; Kriticos and Randall 2001; Rouget et al. 2004). None of these studies have attempted to assess the impacts of those invasions. A knowledge of where species are likely to invade is useful, but quantitative information on the magnitude of the impacts on different resources or environments is needed to answer the “So what?” question. Parker et al. (1999) set this out in their simple and general model for assessing the potential impacts of invading species:

Impact = Range x Abundance x Per Capita Impact

The product of Abundance and Per Capita Impact can be seen as measure of the per unit invaded area or per population impact. When multiplied by the range it becomes the total impact score. For convenience these three scores are referred to as the capita impact, population impact and total impact scores.

Although the model developed by Parker et al. (1999) is conceptually simple, the lack of data makes it difficult to apply in practice. Information on the potential range may be available but information on the abundance and capita impact is more problematic. Many studies have provided qualitative descriptions of the impacts of invading species on communities and ecosystems (usually as population impact) but few studies have quantified the abundance or capita impact or examined the underlying processes and mechanisms in detail (Levine et al. 2003; Richardson and Van Wilgen 2004). The mechanisms and processes which lead to the impacts are often complex and the outcomes can be difficult to predict (Brooks et al. 2004), even in relatively well understood agricultural systems (Vilà et al. 2004). Neubert and Parker (2004) have argued that rate of spread is also an important parameter for estimating impact but estimating rates of spread at a national scale for modelling is problematic (Rouget and Richardson 2003) so we have not included this parameter in our assessments.

This paper is based on the outputs from three analyses of plant invaders in South Africa: one categorising introduced species into major and emerging species (Nel et al. 2004) and two predicting the areas which could be invaded by the major (Rouget et al. 2004) and the emerging species (Mgidi et al. in prep). Both these papers used climate-based approaches which assume that climatic factors override other factors such as disturbance regimes and biotic interactions such as interspecific competition (Richardson & Bond, 1991; Hulme, 2003). This is clearly not always the case, but climatic factors appear to give the best correlations with invasive plant species distributions at a national scale in South Africa (Rouget and Richardson 2003).

There are many invading plant species in southern Africa (Henderson 2001; Nel et al. 2004) and they have a wide range of impacts on natural ecosystems (Richardson et al. 1997; Richardson and Van Wilgen 2004). In this study we have focussed on the potential population and total impacts of a sub-set of 71 major and 28 emerging invaders on:

- Water resources: South Africa is a dry country and invasions, especially by tree species are known to have a significant impact on water resources (Le Maitre et al. 1996, 2000; Dye and Jarmain 2004; Görgens and van Wilgen 2004).
- Biodiversity: southern Africa has a number of biomes and high plant and animal species diversity (Cowling and Hilton Taylor 1997; Le Roux 2002) with many centres of plant species richness and endemism (Van Wyk and Smith 2001). Some of these have already been given formal international recognition as natural World Heritage Sites. Invading plant species are known to have major impacts on the biodiversity of natural communities, although there have been few detailed studies (Richardson and Van Wilgen 2004) so biodiversity impacts were considered to be an important aspect for analysis.
- Productivity of natural rangelands: large areas of South Africa are not suited to cultivated crops and extensive use is made of natural rangelands (savanna, grassland and Karoo shrublands) for commercial and subsistence farming of livestock (Tainton 1999). In addition, there is a growing game farming industry which is dependent on natural rangelands. Invasive species which reduce the productivity of these areas could have significant socio-economic impacts.

The impact scores presented in this paper are not based on actual measured impacts so the values must be treated as relative and not absolute. Thus a score of eight does not necessarily mean twice the potential impact of a score of four but it does still indicate a greater impact.

5.2 Methods

Information relating to the impacts of 99 plant species, 71 identified as major invaders and 28 as emerging invaders (Table 5.1; Nel et al. 2004), was gathered from scientific publications, books on invaders and internet database resources, including Wells et al. (1986), Bromilow (1995), Randall (2002), Henderson (2001) and Nel et al. (2004). Invaders of cultivated lands were excluded because the focus of the study was on species which invaded natural or near natural ecosystems. Species nomenclature follows the SAPIA database (Henderson 1998) and Henderson (2001) unless indicated otherwise.

Data on the potential impacts on water resources and biodiversity were relatively easy to find but there was little information on the impacts on the productivity of rangelands. In many cases there was information on only one species in a group of invaders with a similar growth form and size (e.g. opuntias). If the characteristic was not species specific, then all the other species in the same group were given the same score for that characteristic.

5.2.1 Rating of impacts

One of the key issues in estimating impacts is to determine whether they are additive or multiplicative. For example, Parker et al's (1999) model assumes that the individual contributions of the area invaded, abundance and per capita effect are all multiplicative but this is not necessarily so. Although there probably are many cases where the individual attributes are multiplicative, the data needed to substantiate this are lacking. In the end we adopted a conservative approach and assumed that the characteristics contributing to the capita impact scores are additive.

Impacts on water resources were estimated from the following characteristics:

- Potential transpiration rates: In South African climates the bulk of the water evaporated from vegetation is in the form of transpiration (Dye 1996). A simple but reasonable estimate of transpiration is given by the growth form and size of plants (Le Maitre et al. 1996; Calder 1999). Tall trees, other trees and shrubs, along with aquatic plants, were assumed to transpire the greatest amounts of water. Tall trees were assigned a score of four and other trees, shrubs and aquatic plants were given a score of three. Grasses, reeds and herbs were assigned a score of two. Climbers and scramblers were assigned the lowest score of one, with the exception of *Lantana* and *Chromolaena* which were given a score of three because of their ability to reach a high biomass.
- Impact on groundwater – species which were recorded as being able to deplete groundwater in areas they invaded were assigned a score of one and the rest were given a score of zero. In many areas of the region groundwater is the main or only water source for particular ecosystems or for meeting human needs (DWAF 2004), so this characteristic was considered important.
- Habitat invaded – species were classified as invaders of riparian or dryland habitats or both habitats. In general, invaders of dryland areas are not able to transpire more water than is available in the soil which, in the long-term, is equal to the net rainfall (Le Maitre and Görgens 2003; Dye and Jarmain 2004; Görgens and van Wilgen 2004). Riparian invaders potentially have access to additional water from both lateral inflow and in the

stream or river itself. They can, therefore, transpire greater amounts of water than the same species in the adjacent dryland areas. Dryland invaders were assigned a score of one, riparian invaders a score of two and species invading both habitats were assigned a score of three.

- Potential natural abundance and dominance – species which were recorded as being able to form dense stands were assigned a score of two and the others were given a score of one. The species ability to form dense stands is considered less important in determining its total impact on water resources than the potential transpiration per individual because closed stands tend to transpire less per plant (Jarvis 1985; Whitehead 1986).

The population impact score for each species on water resources was the sum of its capita impact scores for transpiration, groundwater and habitat invaded, multiplied by the potential abundance score.

Impacts on biodiversity were rated using the following attributes:

- Type of invader – this score was based on the ratings given in the SAPIA database (Henderson 1998) which were based on a classification developed by Wells et al. (1986). Species which were classified as transformers were assumed to have the greatest impact on biodiversity and were assigned a score of three. Invaders were assigned a score of two and weeds were assigned a score of one.
- Habitat invaded – species were classified as invading dryland or riparian habitats or both. Riparian habitats are generally not necessarily rich in species compared with the adjacent non-riparian habitats but they are particularly susceptible to invasions (Planty-Tabacchi et al. 1996; Stohlgren et al. 2002) and often become totally dominated by riparian invaders. Therefore dryland invaders were given a score of one and riparian invaders a score of two. Species invading both dryland and riparian habitats were considered to have the greatest impacts and were assigned a score of three.
- Potential natural abundance and dominance – invasive species which are known to be able to form dense stands will be able to have a significant impact on the biodiversity of the ecosystems they invade. Where there was information indicating that a species can form dense stands it was given a score of two and the other species were given a score of one. This attribute is one of those that makes a species a transformer, but it was considered sufficiently important to rate it separately as suggested by Parker et al. (1999).

The population impact for each species on biodiversity was the sum of the capita impact scores for the type of invader and habitat invaded, multiplied by the potential natural abundance.

Impacts on pastoral agriculture were based on the following characteristics:

- Toxicity – plants which were recorded as being poisonous to livestock were given a score of three. Plants known to have allelopathic effects were assigned a score of two because this may give them a competitive advantage over useful or valuable rangeland species. All the other species were given a score of zero.
- Invades rangelands – Species recorded as invading natural rangelands were assigned a score of two and the rest were given a score of one. A default score of one rather zero was used because zero would be equivalent to assuming that the species has no effect and this is believed to be unlikely.

- Potential natural abundance and dominance – invasive species which can form dense stands will be able to have a significant impact on the rangelands they invade. A score of two was given to species known to form dense stands and one to the rest as was done for the other impacts.

The population impact score for rangeland was the sum of the capita impacts on toxicity and rangeland invasion potential multiplied by the potential abundance score.

A number of species are known to have a number of benefits when they invade pastures, for example, some can provide fodder or fuel wood for rural communities (Anon 2002; Turpie 2004). The benefits proved to be too complex to include in the assessment at this stage and were left out of the final score. There was little or no data for many species which resulted in many being given a final score of one for impacts on rangeland.

The final output was a spreadsheet giving a summary of the population impact scores for each species and each aspect that was affected: water, biodiversity and rangeland. These population impact scores incorporate both the abundance and per capita components of the impacts as described by Parker et al. (1999). The scores for each species were also multiplied by the percentage of the region (South Africa, Lesotho and Swaziland) which fell within the climatically suitable area to get an idea of their potential total impact. Data on the climatically percentage of the region were taken from Rouget et al. (2004) for the major species and from Mgidi et al. (in prep) for the emerging species. The total impact score, therefore, incorporates the range, abundance and per capita components of the (total) impact as proposed by Parker et al. (1999). The total impact scores for each species were then rescaled to a range of 0-10 to make them more comparable and to assist in interpretation.

5.2.2 Geographic distribution of the population impacts

Rouget et al. (2004) and Mgidi et al. (in prep) predicted the geographic distribution of the areas predicted to be climatically suitable for each of the major and emerging species, respectively. The predictions were derived using climatic data which were available for South Africa, Lesotho and Swaziland on an *ArcInfo*® grid (or raster) data set with an interval of 1’ of longitude x 1’ of latitude prepared by Schulze et al. (1997). The predicted distributions were represented using this grid with a value of one for points where the species climate regime was suitable and zero for points where the climate regime was unsuitable. The population impact scores for each species were multiplied with the grid point values using the Raster Calculator in *ArcMap*® to give a weighted grid for each of the major and emerging species. The resulting grids were summed to produce two grids, one showing the cumulative impact on biodiversity, water and productivity of the major species, and one for the emerging species. The cumulative impact scores for each of the impacts (biodiversity, water, rangeland) differed so they were converted to a common scale with a range from zero to ten to make them easier to compare and interpret.

5.3 Results

There were sufficient data for scoring the impacts on biodiversity and water resources so the potential population and total impacts of the major and emerging species on these aspects can be assessed with some confidence. The lack of data on the impacts of species on rangelands, particularly the emerging species, was a definite limitation and these results must be viewed as conservative and preliminary. A more detailed assessment with inputs from rangeland agriculturalists is needed to get a proper assessment.

5.3.1 Population impacts (abundance x capita)

The scores for the population impacts of the major species on biodiversity ranged from two to 12 with most species scoring four to six and a mean of 6.0 (Figure 5.1). There were eight species with an impact score of 12, including: *Chromolaena odorata, Lantana camara, Prosopis glandulosa* and five *Acacia* species (*A. saligna, A. cyclops, A. longifolia, A. melanoxylon and A. mearnsii*). The emerging species scores for biodiversity impact varied from two to 10 with most in the range from two to four (Figure 5.2) and a mean of 4.0. *Lythrum salicaria* received a score of 10, *Acacia elata* a score of nine, *Mimosa pigra* and *Pinus taeda* a score of eight and *Ligustrum sinense* and *Lonicera japonica* a score of six.

The scores for the major species' impacts on water ranged from two to 16 with most species scoring four to six and two species, *Acacia mearnsii* and *Prosopis glandulosa,* getting a score of 16 (Figure 5.1). Five species were given a score of 14, including *Acacia melanoxylon*, *Populus alba, P canescens* and *Eucalyptus camaldulensis*. The mean score was 7.9. The emerging species' scores were lower than the major species, probably because there is a smaller proportion of the relatively high scoring tall tree species than among the major species (Table 5.1). The score ranged from two to 12 with a mean of 5.4 and 11 species had a score of four (Figure 5.2). *Acacia elata* scored 12, *Mimosa pigra* and *Lythrum salicaria* scored 10, *Ligustrum sinense, Ulex europaeus* and *Cytisus scoparius* scored eight.

The major species' scores for impacts on rangelands were concentrated around one and two, with 31 species scoring the default of one, and a few high scores (Figure 5.1). The mean score was 2.5. *Opuntia stricta* and *Ageratum conyzoides* scored 6, *Opuntia ficus-indica, Chromolaena odorata* and *Lantana camara* scored 8 and *Robinia pseudoacacia* scored 10. The latter two species scores were higher because they are both toxic to livestock and invade rangelands and *Robinia* also has allelopathic properties. *Prosopis glandulosa* is unpalatable but not known to be toxic, so its score was four. The emerging species scores ranged from one to four with a mean of 1.8. Fourteen species had a score of one because of a lack of data on impacts. The top scorers on four were *Pennisetum purpureus, Cytisus scoparius, Ulex europaeus* and *Mimosa pigra*, all of which invade natural rangelands and are unpalatable but apparently not toxic.

5.3.2 Total impact scores: population x climatically suitable proportion of the region

The multiplication of the population impacts (abundance x capita) with the climatically suitable range (percentage of the total area of South Africa, Lesotho and Swaziland) had a significant impact on the ranking of the species and also influenced the distribution of the scores. Only the scaled total impact scores are discussed here.

The scaled scores for total biodiversity impacts for the major species were skewed towards the lower values, which is to be expected given the proportion of low population impact scores (Figure 5.1) and that more than 50% of the species had a climatically suitable area of less than

25% of the region (Table 5.2). The scores for the major species ranged from 0.14-10 (Figure 5.3) with a mean of 2.78. The top scorers were: *Populus nigra* with 10 and *Arundo donax* with nine, *Xanthium strumarium* and *Prosopis glandulosa* with eight and *Atriplex nummularia* with seven. *Lantana camara* and *Opuntia ficus-indica* had the next highest scores. Only *Prosopis* was among the top five on the population scores, illustrating the impact of the size of the climatically suitable areas of the region. For example, *Opuntia ficus-indica* (dryland) and *Arundo donax* (riparian) have 74 and 76%, respectively, of the region classified as climatically suitable. In contrast, only 33% of the region is classified as climatically suitable for *Prosopis*. For emerging species, the scaled scores were more evenly distributed than those of the major species (Figure 5.4) and ranged from 0.07 to 10. More than 50% of the emerging species had climatically suitable areas of more than 50% of the region (Table 5.2). Only three species scored five or more and the mean score was 2.67. The top species include *Acacia elata* (10), *Gleditsia triacanthos* (6), *Acacia podalyriifolia* (4), *Pinus taeda* (4), *Mimosa pigra* and *Pereskia aculeata* (4).

Major species' scaled impact scores for water resources ranged from 0.19 to 10 with a mean of 2.23. *Eucalyptus camaldulensis* was the top scorer with 10 because it has both a high per capita impact for water use and about 65% of the region is regarded as climatically suitable for it to invade. The next highest score was for *Arundo donax* with eight. Also among the top five were *Populus nigra* with 63% of the region and *Prosopis glandulosa.* The scaled water resource impact scores for emerging species ranged from 0.07 to 10 with a mean of 2.67 and only two species had a score of five or more. The top scorer was *Acacia elata*, followed by *Gleditsia triacanthos, Acacia podalyriifolia* and *Grevillea robusta*.

The scaled major species impact scores for rangelands show a strong bias toward the lower values with a mean of 1.23 and 55 species with a score of less than two (Figure 5.2). The top scorer was *Opuntia ficus-indica* followed by *Nicotiana glauca* (toxic to livestock), *Robinia pseudoacacia*, *Opuntia stricta* and *Opuntia imbricata*. *Prosopis glandulosa* was among the top 10 but *Lantana camara* was 12th with a relatively low score (2.0), largely because only 15% of the region is classified as climatically suitable for it to invade. The emerging species generally got higher scaled total impact scores (mean 4.67) and the scores were more evenly distributed (Figure 5.4). The top score went to *Acacia elata* (10), followed by *Ulex europaeus* (9.6), *Pennisetum purpureum* (9.2), *Cytisus scoparius* (9), *Mimosa pigra* (8) and *Pereskia aculeata* (8).

5.3.3 Geographic distribution of the impacts

The geographic distribution of the population impacts of the major species on biodiversity and water are very similar but differ from the species numbers and rangeland impacts (Figures 5.5 and 5.6). Impacts on rangelands are greater in the interior and impacts on biodiversity and water resources are greater in the eastern and coastal parts of the region. The primary reasons for these differences are: (a) a number of major invader species with high scores had generally non-overlapping climatically suitable areas, and (b) the sparse data on per capita impacts on rangelands which resulted in many species having the same score (Figures 5.1 and 5.2) so the different distributions had little effect. For example, most of the high scoring *Acacia* species can invade the eastern parts of the region, *Arundo donax* much of the moister interior, *Prosopis* *glandulosa* the dryer parts of the central and western interior, and *Eucalyptus camaldulensis* much of the region, particularly the western and southern parts.

The major species are predicted to have particularly severe impacts on the perennial river systems, especially in the eastern part of the region, in the bushveld and escarpment areas of Limpopo Province, and along the eastern side of the side of the region between the escarpment and the coast (Figure 5.6). The high-lying mountain areas of the Drakensberg, Karoo and the Eastern and Western Cape are predicted to be the least affected. The greatest impacts in the Western Cape are predicted to be in the western and southern coastal lowlands, particularly for biodiversity and water resources. A comparison of the percentages of the region in different population impact classes (Figure 5.7), shows that more than half the region is expected to experience impacts on biodiversity and water resources of between two and four. This differs from rangelands where more than half the region may experience impacts between four and six.

The distribution of the emerging species scores for population impacts on biodiversity, water and rangelands are generally similar (Figures 5.8 and 5.9). The reason for these similarities seems to be the extensive overlaps in the predicted distributions of most of the emerging species. The overlap of twenty or more of the species' distributions accounted for 22% of the total area potentially invadable by the emerging species. The impact scores of the emerging species in the highveld area are greater than those of the major species. This may, at least in part, be caused by the fact that many of the major species in the highveld region are riparian invaders so that only the riparian zones were indicated as having high scores. This distinction was not used in mapping the emerging species. The main impacts are predicted to be on the grasslands of the highveld and the grassland and savannas of the eastern escarpment, from the Soutpansberg southwards to the Eastern Cape, where the extent of the area with the maximum impact is marginally greater for species numbers and rangelands than for water resources and biodiversity (Figure 5.10). The impacts on water and biodiversity will be greater than those on rangelands in the eastern part of the Karoo and greater for water than the others in the coastal region of the Western Cape. A narrow strip along the east coast and the highland areas of Lesotho, the Karoo, Namaqualand and the Western Cape are predicted to experience relatively low impacts. The scaled population impacts of the emerging species on rangelands are concentrated between zero and two (Figure 5.10) but the proportion of the area in each of the population impact classes for biodiversity is more even for biodiversity and water resources.

5.4 Discussion

This study provides the first estimates of the potential impacts of the different major and emerging weed species on biodiversity, water and natural rangelands for a range of species and at a regional scale. Although the results should be seen as provisional, particularly for rangeland impacts, they highlight a number of aspects that are important.

The findings of this study are subject to substantial uncertainties. The per capita impact scoring system that was developed is pragmatic but is based logical deduction rather than a rigorous analysis. Many of the scores are based on personal observation and experience (by the authors and other experts) rather than documented studies as data on these impacts, whether per capita or per population, are lacking (Nel et al. 2004; Richardson and Van Wilgen 2004). The predictions of the climatically suitable areas for the different species are also subject to substantial uncertainties (Rouget et al. 2004; Mgidi et al. in prep). The predictions for the emerging species are likely to be weaker than those for the major because there are: (a) few local records and data on invasions elsewhere were limited to a few countries and (b), often, relatively few localities and (c) assumptions about the similarities of the climates in the areas invaded and at the actual location of the invasions (Mgidi et al. in prep). In addition, there is always a substantial risk that an invasive species may turn out to have unexpected indirect or direct impacts on other species or system processes which enable it to become a major invader (Brooks et al, 2004). Nevertheless, we believe that the overall results are reasonably robust and indicate areas and species that should be given priority.

5.4.1 Population impact scores (abundance x per capita impact)

A previous analysis by Versfeld et al. (1998) at the national scale was based only on estimates of the invaded area and growth form based (per capita) impacts on surface water resources. Nel et al. (2004) prioritised species based on SAPIA records of their distribution and abundance and their traits. Rouget et al. (2004) prioritised species based on their potential to increase their ranges and areas based on the overlap of those ranges. Mgidi et al. (2004) did a similar analysis for emerging species. All these analyses seem to be in reasonable agreement with this one on which species are the most important invaders and which areas will be the most affected.

The Australian *Acacia* species were consistently found to be among the species with the greatest potential impacts on water resources, mainly because they invade both riparian and dryland habitats. This analysis shows that these same *Acacia* species, and *A. elata* among the emerging species, also got high scores for their potential impacts on biodiversity because they are all transformers. The similar scores and ecological attributes of these species emphasise the importance of effective control measures, including biocontrol, to ensure that the clearing of species such as *Acacia mearnsii* does not result in it being replaced by a similar species, for example *A. dealbata*. Versfeld et al. (1998) also highlighted the importance of *Prosopis* species because of their impact on water resources. This analysis also picks out the high impact scores, and thus potential impacts, of *Prosopis* species on biodiversity and natural rangelands. The latter impact was emphasised by Harding and Bate (1991) in their assessment of the potential impacts of invasive *Prosopis* species. *Eucalyptus camaldulensis* emerges as having a potentially severe impact on water resources because it is a riparian invader, is also known to be able to use groundwater at substantial depths (Thorburn and Walker, 1994: Dawson and Ehleringer, 1991, Dye 1996; Henderson 2001) and about 65% of the region is climatically suitable for it to invade.

A new aspect that does emerge from this analysis is the significance of the potential impacts of a number of the shrub and herbaceous species such as *Chromolaena odorata*, *Mimosa pigra*, *Lythrum salicaria* and *Ulex europaeus* and the *Opuntia* species on biodiversity and rangelands. *Lythrum salicaria* is considered a major wetland invader (Lowe et al. 2001; ISSG 2004), especially in the south-eastern United States of America (USDA NRCS 2004) and received high impact scores for biodiversity and water resources. Its final scores were reduced because its climatically suitable area is confined to the coastal region and only comprises 7% of South Africa (Mgidi et al. in prep). It has only been recorded from wetlands on the Cape Flats, Cape

Town (Henderson 2001) but it has the potential to invade ecologically important wetlands throughout the coastal areas and should be considered a top priority for eradication.

5.4.2 Total impact scores (range x population impact)

The total impact scores differed substantially from the population impact scores. A number of species with large climatically suitable areas, for example *Opuntia ficus-indica* and *Arundo donax*, achieved high scores for their scaled impact on biodiversity despite low per capita impact and abundance scores. The top-rated major and emerging species included a mixture of herbaceous and shrub or tree species. The scores for the total impact on water resources also showed some shifts with *Eucalyptus camaldulensis* emerging with a score of 10 because of its high per capita impact and extensive climatically suitable area: 65% of the region. At this stage, substantial invasions by this species were found in surveys of both the Western Cape and in Mpumalanga (Forsyth et al. 2004), but it has the potential to be a successful invader in much of the region (Mgidi et al. 2004). *Arundo donax* emerges as an important but often overlooked species which could have significant impacts on water resources because of the large proportion of the river systems it could invade. This species has very high rates of photosynthesis (Rossa et al. 1998), a trait which is often associated with high water-use, but appropriate measurements of transpiration are lacking. It is likely that its transpiration rates could be as high as those of native reedbeds (*Phragmites australis*) which can reach the equivalent of 11mm per day on the Sabie River (Everson et al. 2001). *Prosopis glandulosa* also achieved a high score for impacts on water resources. Research has provided preliminary confirmation of its ability to reduce groundwater levels (Fourie et al. 2003) and thus deplete important aquifers that supply rural communities. It will be able to invade a large proportion of the arid interior (Mgidi et al. 2004) and effective control measures are needed to minimise its potential impacts. The total impacts on rangelands picked out herbaceous species with toxic effects on livestock (e.g. *Xanthium strumarium, Nicotiana glauca* and *Lantana camara*) and the *Opuntia* species, notably *O. ficus-indica* and *Opuntia stricta*. *Lantana camara* was among the top 10 despite having only 15% of the region climatically suitable for invasion. As noted earlier, the lack of data strongly influenced the estimated impacts on rangelands, and the scores should be treated as provisional until a more thorough assessment of this aspect becomes available.

5.4.3 Geographic distribution of impacts

A visual comparison of the regional distribution of the population impacts on biodiversity and water for the major invaders found that they differed substantially from those based on species numbers (Figures 5.5 and 5.6; Rouget et al. 2004). This was not so for the population impacts of the major species on rangelands or for the population impacts scores of the emerging species which were similar to the species scores (Figures 5.8 and 5.9; Mgidi et al. in prep.). This has important implications as it means that the spatial distribution of the numbers of species may not be a good predictor of the potential impacts. Likewise, the relationship between the numbers of naturalised species and pest species found by Rejmánek and Randall (2004) may not be a good indicator of the potential impacts.

The predicted distributions for both major and emerging species highlight the risk they pose for to the eastern part of the country, especially the grassland biome and an extensive but narrow belt in the eastern lowveld and coastal hinterland. These areas are potentially vulnerable to both an increase in the area invaded by most of the major species and to invasions by the emerging species. The high potential impact scores for the eastern regions of the country are a source of concern. These areas are among the most productive for domestic livestock and game farming (Tainton 1999). The grasslands that form the dominant vegetation of the highveld and of the eastern escarpment include catchment areas with relatively high-yields which contribute a disproportionately high fraction of the total surface runoff (Midgley et al. 1994). These grasslands appear to have been relatively resistant to invasion, particularly by alien grass species, but this situation may be changing (Richardson et al. 2000; Milton 2004). These catchments are critical sources of water for the major urban, agricultural and industrial developments in Gauteng and in the Durban-Pietermaritzburg and Richards Bay regions of KwaZulu-Natal. The water resources of many of these catchments are already over-utilised and have insufficient water to meet both the socio-economic demands and the requirements of the ecological reserve (DWAF 2004). Additional invasions or invasions by new species could have significant impacts on these catchments and control operations in these areas should be given priority. Many of the major and emerging species can invade riparian habitats and this would increase their impact on water resources. For example, research in North America indicates that *Tamarix ramosissima* - currently found in parts of the Karoo and the dryer parts of the grassland biome (Henderson 2001) - is able to outcompete the native *Prosopis* for groundwater (Cleverly et al. 1997). These findings suggest that invading *Tamarix* could have a greater impact on water resources per unit area than *Prosopis*. Clearing or other control measures for *T. ramosissima* should be given a high priority to prevent it becoming a widespread problem.

A number of the regional centres of endemism for plant species fall within the regions which are potentially vulnerable to invasion, including and Barberton, Wolkberg, Sekukhuneland and Soutpansberg centres and parts of the Drakensberg Alpine Centre as mapped by Van Wyk and Smith (2001). Most of the Maputaland Pondoland floristic region falls within the areas with high scores for biodiversity impact. The same areas have been highlighted as priorities for conservation of species, habitats and process by an analysis done for the National Biodiversity Strategy and Action Plan (Rouget et al. in prep). This part of the region includes grasslands, and grass understoreys in savanna and woodland vegetation, which may become more prone to invasion as climatic conditions change (Richardson et al. 2000; Milton 2004). Theoretical studies have suggested that species-rich vegetation types should be relatively resistant to invasion but analyses of the vulnerability of different vegetation types at small scales found that they are, in fact, more vulnerable (Stohlgren et al. 2002). Diverse riparian communities appear to be inherently vulnerable to invasion (Planty-Tabacchi 1997; Stohlgren et al. 2002) which raises important concerns about both the impacts on river ecosystem biodiversity and water resources.

It is important not to put undue emphasis on the magnitude of the values and the high values in the eastern region. Although the impact scores for much of the semi-arid and arid interior are relatively low, these areas are vulnerable to species with high per capita impacts on biodiversity, water and rangeland resources such as *Prosopis* and *Opuntia* species, *Eucalyptus camaldulensis* and *Arundo donax*. These dry environments are inherently fragile and slow to recover from degradation by invaders or overuse (Dean and Milton 1999). Invasions by even a limited number of invaders could have significant impacts on both the ecosystems and the human society which depends on the sustained yields of goods and services (Harding and Bate 1991). This is especially true of the riparian zones of the ephemeral rivers which support unique communities of plants and animals (Milton 1999; Dean et al. 1999, 2002). Similar considerations apply to the Western Cape lowlands where the remaining fragments of natural vegetation have a very high conservation priority (Cowling et al. 2003). The mediterranean climate suits relatively few of the major and emerging weeds but many of these species (e.g. *Eucalyptus camaldulensis, Lythrum salicaria, Acacia paradoxa*) have high impact scores and are well known invaders.

The process of developing priorities for invasive plant species control is not a simple one. For example, there are often conflicts of interest where a group or sector benefits from products yielded by a species while others experience the impacts with little benefit (Van Wilgen et al. 2001; De Wit et al. 2002; Rouget et al. 2002). One instance of this is that reductions in river flows due to invasions in headwater catchments affect the availability of water to all the users, and to ecosystems and the services that people receive from them, downstream as far as the coast (Turpie 2004). The first attempt to set clear national priorities for the Working for Water Programme to ensure that funding was appropriately targeted was made by Versfeld et al. (1998). Their analysis was based only on species impacts on water resources and the catchments that were the most affected. The information presented in this paper provides a more comprehensive assessment for use as the scientific input into the decision making process, but the final process has to take into account the views of a range of stakeholders with differing points of view and value systems (Maguire 2004). This information needs to be combined with analyses of the socio-economic of impacts (costs and benefits) to ensure that decisions are based on the complete picture (Maguire 2004; Turpie 2004).

The study presented in this paper has examined the potential spread of a sub-set of both the currently important species and the species that are emerging as important invaders. Impacts were scored using a rating system for abundance and per capita impact and the extent of climatically suitable range for the species. At the species level, it is important not to overlook species with a high per capita or population impact, especially where they are among the few species whose climatic requirements permit them to invade particular environments. The semi-arid and arid areas of the interior and Western Cape lowlands are two areas where this caution applies. The analysis of the spatial distribution of the impacts emphasises that the eastern regions of the country are an important priority for investment aimed at reducing the potential impacts of both the major and emerging species. This is particularly important for protecting water resources, ensuring that important centres of species endemism and richness are conserved, and that the productivity of key natural rangelands for the livestock and game farming industries are maintained.

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Tables

Table 5.1: A summary of the growth form distributions of the 71 major and 28 emerging plant invaders assessed in this study. Data from Henderson (2001) and data sets compiled by Nel et al. (2004).

Growth Form	Major	Emerging
	Percentage of Total	
Climber	8.45	7.14
Grass or reed	1.41	10.71
Herb	8.45	14.29
Tree and shrub	59.15	64.29
Tall tree	22.54	3.57
	Number of species	
All growth forms	71	28

Table 5.2: The distribution of the percentages of the region predicted to be climatically suitable for the 71 major and 28 emerging plant species. Data for the major species from Rouget et al. (2004) and for emerging species from Mgidi et al. (in prep).

Climatically suitable area (% of the region)	Major (%)	Emerging (%)
<5%	9.86	7.14
5-25	43.66	39.29
25-50	28.17	28.57
>50	18.31	25.00

Legends for Figures

Figure 5.1: Distribution of the population impact scores (abundance x per capita impact) for the 71 major invading plant species' impacts on biodiversity, water resources and rangeland productivity.

Figure 5.2: Distribution of the population impact scores (abundance x per capita impact) for the 28 emerging invader plant species' impacts on biodiversity, water resources and rangeland productivity.

Figure 5.3: Distribution of the total impact scores (population impact x potential range) for the 71 major invader plant species' impacts on biodiversity, water resources and rangeland productivity. The total impact score for each species was then rescaled to the range 0 to 10. Data for the potential range as a percentage of the region from Rouget et al. (2004)

Figure 5.4: Distribution of the total impact scores (population impact x potential range) for the 28 emerging invader plant species' impacts on biodiversity, water resources and rangeland productivity. The total impact score for each species was then rescaled to the range 0 to 10. Data for the potential range as a percentage of the region from Mgidi et al. (in prep.)

Figure 5.5: Geographic distribution of the number of major invader plant species using the same number of classes as the impacts on water resources (Figure 5.6) to facilitate comparisons.

Figure 5.6: Geographic distribution of the relative impacts on water resources of the major invader plant species. The cumulative total impact scores were rescaled to the range 0-10 to simplify interpretation.

Figure 5.7: Summary of the percentage of the region with different cumulative impact scores for the major invading plant species. The total impact scores for each species at each grids point was summed to get the cumulative impact which was then rescaled to the range 1-10 (for more information see methods). The value in the zero class is the proportion of the country that is not climatically suitable for any of the major species.

Figure 5.8: Geographic distribution of the number of emerging invader plant species using the same number of classes as the impacts on water resources (Figure 5.9) to facilitate comparisons.

Figure 5.9: Geographic distribution of the relative impacts on water resources of the major invader plant species. The cumulative total impact scores were rescaled to the range 0-10 to simplify interpretation.

Figure 5.10: Summary of the percentage of the region with different cumulative impact scores for the emerging invading plant species. The total impact scores for each species in each area at each grid point was summed to get the cumulative impact which was then rescaled to the range 1-10 (for more information see methods). The value in the zero class is the proportion of the country that is not climatically suitable for any of the emerging species.

CHAPTER 6: CONCLUSIONS

This project highlighted the advantage of using both quantitative data and expert opinion to prioritise invasive alien plant species and identify areas most vulnerable invasions. We believe the combination of data and expert opinion has significantly increased our level of confidence in the results and enabled us to produce a more rigorous, scientifically defendable and thorough analysis. The use of either the datasets or expert opinion on their own would not have been as effective and is not recommended. We believe that the results can be by used by management to devise appropriate action plans.

6.1 Species

- Lists of both major and emerging invaders in the form of clusters were derived (see Appendices 2.1 and 2.2 in Chapter 2), and these can be used by managers to develop strategies and plans to effectively control invasive alien plant species. The study of the major species (Chapter 3) and the impacts (Chapter 5) can be used with the information the species' clusters to prioritise species based on the following information: species posing the highest threat to a particular habitat (e.g. riparian, localised and abundant clusters); species posing a threat to most parts of the country (e.g. widespread and abundant cluster). Emerging invaders that are believed to have a large propagule pool size and large potential invisible habitat should be given attention but, as a group, the invasion potential of the emerging species proved to be more difficult to assess. The 28 emerging species assessed in Chapters 4 and 5 can be assed in terms of their potential to expand their range and their potential impacts. The other emerging species have not been investigated in detail and, given the poor correlation of invasion potential with the expert ranking (Chapter 4), the classification of these species should be treated with caution.

- Among the major invaders, many of the most important species have been identified by previous studies, for example the Acacia and Prosopis species but a number of other species also achieved high scores (Chapter 5). These include Lantana, Eucalyptus camaldulensis, Mimosa pigra, Populus and Opuntia species. The importance of dealing promptly with emerging invaders is highlighted by the extensive areas of the country that could be invaded by species which have been recorded at only one or two localities. These include Cestrum parqui, Celtis sinensis, Lythrum salicaria and Mimosa pigra.

- Actual : potential distribution ratios for major invaders can be calculated from the obtained results and these will give indications of the time these major invaders have to reach full invasive potential. This information, along with the expert estimates of time taken to reach full potential (Table 6.1), will be useful to managers as they plan on which species' control efforts to invest in. For example, major invaders that have either reached or almost reached their full invasion potential are less of a threat than those that still have large potential areas to invade or are in the exponential phase of their expansion (Hobbs and Humphries 1995).

6.2 Using estimated rates of spread to prioritize species

One approach to prioritising different species is to combine information on the potential to invade, expressed as the ratio of actual to potentially invadable area and estimates of the potential spread rate. We will focus on the major species. The ratio of actual : potential area was taken from Appendix 3.1 (Chapter 3), and Lesley Henderson and Stefan Neser provided a first, expert assessment of the potential rate of spread of the major invader species on the categories: slow, medium, medium/fast and fast (Appendix 6.1) which were converted to numerical scale from 1-3 (Figure 6.1).

The rationale is that species with a high actual : potential ratio approaching (i.e. close to 1), have almost reached their full potential. The time it will require to reach full invasion potential is likely to be less than for invaders whose actual : potential ratio is moderate to low. Species with low ratios have a large expansion potential. The next criterion is how long they are likely to take to reach that potential. This is indicated by their potential rate of spread because a species with a low spread rate will take longer to invade a given area than a species with a high spread rate. In Figure #.1, both the actual : potential area and range of rates of spread have been divided into quadrants to provide a conceptual management framework for control operations. Invaders falling within different quadrants would require different management priorities and strategies. For example:

- Invaders in quadrant 1 would require very active monitoring, and would serve as priority candidates for investigation as species for future biocontrol research to reduce their ability to form dense stands.
- Invaders of quadrant 3 should be monitored and if showing signs of spread, should be cleared immediately. These invaders should also be considered for future biocontrol research, but to a lesser extent than those in quadrant 1.
- Strategic targeting of areas for control operations should focus on invaders within quadrants 2 and 4, outside the shaded areas. Areas should be prioritised based on ecological, hydrological, socio-economic and land use criteria.

Examples of species in quadrant 1 are: *Chromolaena odorata, Acacia saligna, Paraserianthes lophantha*; quadrant 2: *Macfadenya unguis-cati, Achyranthes aspera, Pinus halepensis* and *P. elliottii.* Species in quadrant 3 include: *Agave americana*, *Populus* species and in quadrant 4 (on the line): *Opuntia aurantiaca* and *Solanum sisymbrifolium.* Using biocontrol as an example, the species from a given quadrant could then be prioritised in terms of the potential for biocontrol: Is there an agent available locally? Is one available elsewhere? Other criteria could also be used such as the potential impact on water, biodiversity or rangelands and whether or not is predicted climatically suitable area and current distribution overlap with areas which are particularly vulnerable to any, or all, of these impacts

6.3 Areas

- The results show that most of the major and emerging invaders are confined to an area between the coast and the coastal mountains or escarpment from the Western Cape to the Southern cape, towards the Eastern Cape and KwaZulu-Natal, along the Drakensberg, and the highveld. These are all areas of high human population and where much of the natural vegetation has been transformed. Management should therefore, focus on these areas and/or catchments around these areas when they develop their management plans around invasion control.

- The priority areas for emerging species differed from those of the major species (Chapter 5). Most of the emerging species have the potential to invade the grassland biome, particularly the highveld, and the adjacent areas of the savannah biome. Relatively few appear to have the potential to invade the arid interior or the sub-tropical coastal regions and lowveld. The vulnerability of the grassland biome to invasions is a concern because the grasslands have emerged as conservation priority in the National Biodiversity Assessment (pert of the NBSAP) and are include key headwater catchment areas for most of the major rivers of the northern regions of South Africa.

- The analysis of the impacts on biodiversity, rangelands and water (Chapter 5) highlighted the importance of assessing the potential impacts and not just the species numbers in an area. For the major species, the distribution of the impacts on rangelands was very similar to the distribution of the number of species. The distribution of the impacts on biodiversity and water were similar to each other but differed from those on rangelands. The main reason for this seems to be the low degree of overlap in the distributions of a number of high scoring species. This conclusion is supported by the similar distributions for the impacts of emerging species on biodiversity, rangelands and water. In this case overlaps in the distribution of more than 20 species accounted for more that 20% of the total area invadable by all species.

- The climate matching technique used to estimate the potential distribution of emerging invaders (Chapter 4) has showed great potential for use as a screening tool for potentially problem species not yet in the country. At the same time, climatic matching analysis for the emerging species clearly showed that there is no substitute for local records, emphasising the importance of supporting early warning systems.

6.4 Reference

Hobbs, R. J. and S. E. Humphries. 1995. An integrated approach to the ecology and management of plant invasions. Conservation Biology. 9:761-770.

Legend for Figure

Figure 6.1: Conceptual management framework for focussing control operations of major invaders, based on actual: potential distribution ratio, and rate of spread estimates. For more information see the text

Appendix 6.1: Expert estimates of rate of spread of major invaders (prepared by Lesley Henderson and Stefan Neser in 2003).

Scientific name	Common name	Rate of spread
Riparian spp.		
Acacia dealbata	Silver wattle	medium/fast
Ageratum conyzoides	Invading ageratum	fast
Ageratum con/houstonianum	Mexican ageratum	
Arundo donax	Giant/Spanish reed	medium
Bidens formosa	Cosmos, Mexican aster	medium
Cardiospermum grandiflorum	Balloon vine	medium/fast
Eucalyptus camaldulensis	Red river gum	medium/fast
Morus alba	White/Common mulberry	medium
Populus alba/canescens	White poplar/ Grey poplar	
Populus canescens	Grey poplar	slow
Sesbania punicea	Rattlebox, purple sesbane	medium/fast
Populus nigra var. italica	Lombardy poplar	slow
Ricinus communis	Castorbean, Castor-oil Plant	medium/fast
Salix babylonica	Weeping willow	medium
Salix fragilis	Crack/Brittle willow	medium
Verbena bonariensis	Verbena	medium
Landscape/ riparian spp.		
Acacia baileyana	Bailey's wattle	medium
Araujia sericifera	Moth catcher	medium/fast
Acacia decurrens	Green wattle	medium/fast
Acacia saligna	Port Jackson willow	medium/fast
Acacia Cyclops	Red eye, Rooikrans	medium/fast
Paraserianthes lophantha	Brush wattle	medium/fast
Rubus fruticosus	Bramble, Wild Blackberry	medium
Caesalpinia decapetala	Mauritius thorn	medium/fast
Casuarina equisetifolia	Horsetail tree	medium
Cestrum laevigatum	Inkberry	medium
Chromolaena odorata	Chromolaena	fast
Pinus patula	Patula pine	medium/fast
Rubus cuneifolius	American bramble	medium
Senna occidentalis	Coffee senna, coffeeweed	medium/fast
Schinus terebinthifolius	Brazilian pepper-tree	medium
Senna didymobotrya	Candle bush, Popcorn cassia	medium
Solanum seaforthianum	Potato creeper	medium
Psidium guajava	Guava	medium
Macfadyena unguis-cati	Cat's claw creeper	medium/fast
Jacaranda mimosifolia	Jacaranda	medium/fast
Acacia longifolia	Long-leaved wattle	medium/fast
Acacia melanoxylon	Australian blackwood	medium/fast
Ipomoea indica/purpurea	Morning glory	medium
Opuntia monacantha	Cochineal/Drooping prickly pear	medium
Lantana camara	Lantana	medium

Acacia mearnsii	Black wattle	medium/fast
Solanum mauritianum	Bugweed	medium
Melia azedarach	Syringa	medium/fast
Nicotiana glauca	Wild tobacco	medium/fast
Schinus molle	Pepper Tree	medium
Achyranthes aspera	Prickly chaff flower , Apamarga	fast
Cuscuta campestris	Common dodder	medium
Atriplex nummularia	Old-man Saltbush	medium
Prosopis glandulosa var torreyana/velutina	Honey mesquite	medium
Pyracantha angustifolia	Yellow fire-thorn	medium
Robinia pseudoacacia	Black locust	medium/fast
Solanum sisymbriifolium	Wild tomato, dense-thorned bitter apple	medium
Xanthium strumarium	Large cocklebur	fast
Landscape spp.		
Acacia pycnantha	Golden wattle	medium
Eucalyptus lehmannii	Spider gum	medium
Hakea drupacea	Sweet hakea	medium
Hakea sericea	Silky hakea	medium
Leptospermum laevigatum	Australian myrtle	medium
Pinus pinaster	Cluster pine	medium/fast
Pinus radiata	Radiata pine, Monterey pine	medium/fast
Pinus halepensis	Aleppo pine	medium/fast
Agave americana	Agave	slow
Opuntia ficus-indica	Sweet prickly pear	medium
Opuntia robusta	Silver dollar cactus	medium
Cereus jamacaru	Queen of the night	medium
Pinus elliottii	Slash pine	medium/fast
Opuntia aurantiaca	Jointed cactus	medium
Opuntia imbricata	Imbricate prickly pear	medium
Opuntia stricta	Pest pear of Australia	medium
Echinopsis spachiana	Torch cactus	medium
Atriplex lindleyi	Sponge-fruit saltbush	medium

CHAPTER 7: RECOMMENDATIONS

The results of this project can be used to focus strategic, national scale planning of invasive alien plant control operations, serving as a means of prioritising both species and areas. Below, we briefly summarise the results in terms of recommendations relevant to alien plant managers, and describe some of the future research areas that this project has identified as important.

7.1 Recommendations for management

7.1.1 Use list "clusters" to prioritise species for control

Appropriate management activities can now be assigned to different "clusters" of major and expert ratings of emerging invaders that were identified as part of Task 1 (Chapter 2). For example, eradication could be explored as a feasible option for species that are confined to small areas or just beginning to become invasive. For the most widespread species, efforts should focus on identifying priority areas to focus management actions.

If actual : potential distribution ratios for major invaders are low, they have a large potential to expand as they have already demonstrated their ability to have a large impact on natural ecosystems in South Africa; these should receive more greater attention than those major invaders that have reached, or have nearly reached their full invasion potential (i.e., their actual: potential distribution ratios are close to 1). The actual : potential distribution ratios are presented in Appendix 3.1 of Rouget et al. (2004). Species with a high ratio include many of the *Opuntia species, Eucalyptus camaldulensis, Araujia sericifera, Achyranthes aspera, Pinus elliottii, P. halepensis and Solanum sisymbriifolium*. For these species the focus should be on measures that can reduce the rate of spread. Species with little potential include *Acacia saligna, A. cyclops, A. mearnsii, Lantana camara and Psidium guajava*. For these species the emphasis needs to be on preventing them from forming dense stands.

The list, arranged according to expert ranking on potential habitat invadable and propagule pool size, of emerging invaders (see Appendix 2.2 of Nel et. al., 2004) can be used as a means of focusing biocontrol research so that early, more effective action can be taken. This list needs to be combined with the priorities identified in the analyses of a subset of the emerging species (Chapter 4) and the assessment of the impacts (Chapter 5).

7.1.2 Use current and potential distribution maps to prioritise areas for control

The distribution of the major invaders which are 'widespread-abundant' (Fig. 2.3a of Chapter 2) follows a similar pattern to the distribution of areas where high numbers of major invaders are recorded (Fig. 2.2a of Chapter 2). This suggests that these areas are at the most risk of being severely affected by invasive alien plants because not only do they contain high numbers of invasive alien species, but the invasive alien species that do establish also have the ability to become abundant within these areas. This is in sharp contrast to the northern interior and north-western coast of the country, where both the number of major invaders and their associated abundance levels tend to be low. On the other hand, the impact scores of a number of these invaders are high (e.g. Prosopis species) and this must not be overlooked. Emerging invaders do not appear to be establishing in areas which were previously not invaded and exhibit similar distribution patterns to the major invaders. This may not be the case for all the emerging invaders identified by Nel et al. (2004, Chapter 2) and further investigations are needed to refine the priorities for different areas.

Prioritizing catchments for alien-plant management can be approached in various ways, with different approaches being more suitable for certain parts of the country than others. Three main approaches that could be combined in a national-scale prioritization are:

(i) Water resources: Areas such as the highveld and escarpment grasslands are important areas for woody water-using invaders because they form the headwaters of key river systems. One way to prioritise here would be to combine catchments most at risk with data from the Internal Strategic Perspectives on catchment water stress. Data for low flows also exists, and can be used to assess where to concentrate control efforts of the invasions.

(ii) Productive land: The eastern seaboard and lowveld is most important especially given the impacts of HIV/AIDS on rural communities, which will reduce current ability to clear and levels of harvesting for wood. Likewise, the highveld and interior grasslands are important areas for commercial livestock production and are vulnerable to invasions by many of the emerging invaders. The map of pasture productiviety being produced by the ARC would be a good baseline data set.

(iii) Biodiversity and water. The Cape Mountains and Agulhas Plains to Still Bay (not much runoff) are very vulnerable to invasion by woody plant species. Much of the grassland biome and adjacent savannah biome and many areas along the escarpment have been identified as conservation priorities by the National Biodiversity Strategy and Action Plan and include centres of plant species richness and endemism. Priority should be given to control operations in these areas.

7.2 Recommendations for future research

These recommendations incorporate two of the three expressions of interest which were submitted to Working for Water Programme by the CSIR in May 2004. The three expressions of interest were:

Development of a consensus list of invasive alien plant species for CARA and the National Biodiversity Bill. This is being dealt with in a separate process but the outputs of Chapters 2-5 should be taken into account in compiling those lists.

Invasion Risk Assessment which is dealt with in two recommendations 7.2.3 on screening and 7.2.4 on early warning systems. The findings of the climate matching studies in Chapters 3 and 4 will be an important input to research in this area of interest.

Assessment of National Spatial Priorities for the Working for Water Programme: Catchment Prioritization. This is dealt with under recommendations 7.2.5 on further research on the emerging species and 7.2.6 on refining the national scale priorities presented in Chapter 5.

7.2.1 Update and maintain the Southern African Plant Invaders Atlas (SAPIA) database

We have found several areas for improvements which will make the SAPIA database more user-friendly. For example, 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. How best to deal with species and species groups should be spelt out to users in detailed metadata.

This project involved the expert review of overall distribution and abundance of all species recorded in SAPIA. Where we felt that the distribution or abundance reflected by SAPIA was not adequate (e.g. where there may have been a collection bias) this was corrected. It may be helpful to document where these inconsistencies with expert opinion occurred as a means of understanding the limitations of the data within SAPIA, and trying to improve it in future collections.

Locations for all future atlassing collections should be given in latitude and longitude readings from a GPS (i.e. point localities) and NOT quarter degree squares. This circumvents the problems of scale discussed in Section 5.1.3 and 5.2.5, and the data become more useful for local-scale modelling.

Maintenance of SAPIA is of crucial importance. This database could play a central role in strategic planning for the Working for Water Programme, as well as for future research, monitoring and auditing. It should thus be afforded a far more strategic status in the Working for Water Programme.

We suggest that the biodiversity information system created by the Western Cape Nature Conservation Board (WCNCB), and adopted by at least 3 other provinces in SA (KZN, Gauteng, Northern Cape), be considered as a basis for disseminating information in SAPIA. The biodiversity information system is a tried and tested South African database, and interfacing with this database will greatly facilitate exchange between biodiversity and conservation management in all provinces.

7.2.2 Use invasion potential areas to assess ecological benefits in strategic planning

Strategic planning at both national and local levels should be used to guide operations in the Working for Water Programme. Such planning has the advantage of focussing resources in areas where they will yield the greatest impact, and coordinating management activities across the Programme. This in turn leads to more efficient use of limited resources (both people and funding).

The results of this project could feed into a national strategic planning exercise for the Working for Water Programme, which should aim to prioritise management activities based on the ecological, hydrological, socio-economic and agricultural benefits they yield. Invasion potential of areas would be one of the criteria used to assess the ecological benefits of control operations in each area or catchment.

During this project, it also became evident that this national scale project was being used to try to facilitate local decisions. Whilst the results presented here are helpful to planning at a broad national scale, they are frequently misleading at a local scale, and we have therefore identified the need for urgently developing a local scale decision-support tool, which would enable regional managers of the Working for Water Programme to prioritise species and areas at a more local level. At this scale, ecological criteria such as position in the landscape, topography, density of infestation, prevailing wind direction, surrounding vegetation become more relevant. The socio-economic and management criteria will also be more detailed at the level of local decision-making.

7.2.3 Explore and implement screening/ invasive alien plant risk assessment techniques

Greater global travel and the lifting of trade restrictions have resulted in increased rates of exotic species introductions to many countries. Recent developments to free world trade are likely to increase the numbers of exotic species imported into and kept in South Africa, hence increasing the risk of their establishing naturalised exotic populations in this country. Preventing invasions of exotic species is far less costly than post-establishment control. Policy makers are therefore trying to restrict traffic in undesirable exotic species, but are hampered by inadequate knowledge about which species pose a risk.

Preventing the import of all exotic species is neither feasible nor desirable; not all exotic species pose the same level of threat for becoming invasive. Studies internationally, particularly in Australia and the USA, have focused on trying to distinguish between species that pose a high risk and those that pose a lower risk. In South Africa, there are several options to screening that have already begun to be explored through the invasive alien species lists provided by the Conservation of Agricultural Resources Act (CARA) and the National Biodiversity Act, soon to be enacted. These should be explored in relation to their pros and cons, their implementation through the relevant authorities and stakeholders and prevailing world scientific practice at present as a first step in deciding how to approach this pro-active form of management.

7.2.4 Early warning systems

There does not seem to be any formal procedure for ensuring that observations of invasions by new or emerging species can be reported, properly evaluated and given an appropriate level of priority for action. Examples of the need for this are some of the species which have been identified as emerging invaders and are known to be significant invaders elsewhere such as *Lythrum salicaria, Acacia paradoxa, Arundo donax, Cestrum parqui* and *Cortaderia* species. Research is needed to assess the effectiveness of early warning systems in other countries, design procedures that will ensure that there is a response and the identify criteria and procedures for determining the actions that need to taken. The SAPIA database would be a key element in this system by providing a mechanism for recording observations of potentially emerging invaders to be objectively documented.

7.2.5 Assessment of emerging invaders

The study presented in Chapter 4 only assessed 28 of the 84 emerging invaders identified by Nel et al. (2004, Chapter 2). The analysis of their potential to invade highlighted the poor relationship between expert ratings and invasion potential of these 28 species. Priority should be given to assessing at least a further subset of the remaining species, perhaps those that were rated as least likely to become a problem, to test the expert ratings and determine whether other characteristics of those species may provide a more reliable method of predicting the invasion potential.

7.2.6 More detailed assessment of priorities based on impacts on water, biodiversity and rangelands

Chapter 5 provides a broad brush assessment of the relative impacts that both the major and emerging invaders could have on water, biodiversity and rangelands. This gives the broad picture needed for prioritisation at a national and provincial scale but is not suitable for setting priorities at, for example, a Water Management or secondary, or finer, catchment scale. Datasets which can be used to refine these priorities for water resources will soon be available as the Internal Strategic Perspectives studies are completed for each of the Water Management Areas. Likewise the reports on the national priorities for terrestrial and river ecosystems compiled for the National Biodiversity Strategy and Action Plan are also being finalised. The Agricultural Research Council are also preparing detailed assessment of the productivity of natural pastures in South Africa. These datasets will all become available as GIS data layers which will allow for a more rigorous analysis of priorities at finer catchment scales based on the maps of climatically suitable areas prepared for the major (Chapter 3) and emerging (Chapter 4) invader species.