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BIODIVERSITY RESEARCH

National-scale strategic approaches for managing introduced plants: insights from Australian acacias in South Africa

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ABSTRACT

Aim A range of approaches and philosophies underpin national-level strategies for managing invasive alien plants. This study presents a strategy for the management of taxa that both have value and do harm.

Location South Africa.

Methods Insights were derived from examining Australian *Acacia* species in South Africa (*c.* 70 species introduced, mostly > 150 years ago; some have commercial and other values; 14 species are invasive, causing substantial ecological and economic damage). We consider options for combining available tactics and management practices. We defined (1) categories of species based on invaded area (a surrogate for impact) and the value of benefits generated and (2) management regions based on habitat suitability and degree of invasion. For each category and region, we identified strategic goals and proposed the combinations of management practices to move the system in the desired direction.

Results We identified six strategic goals that in combination would apply to eight species categories. We further identified 14 management practices that could be strategically combined to achieve these goals for each category in five discrete regions. When used in appropriate combinations, the prospect of achieving the strategic goal will be maximized. As the outcomes of management cannot be accurately predicted, management must be adaptive, requiring continuous monitoring and assessment, and realignment of goals if necessary.

Main conclusions Invasive Australian *Acacia* species in South Africa continue to spread and cause undesirable impacts, despite a considerable investment into management. This is because the various practices have historically been uncoordinated in what can be best described as a strategy of hope. Our proposed strategy offers the best possible chance of achieving goals, and it is the first to address invasive alien species that have both positive value and negative impacts.

Keywords

Adaptive management, biological control, biological invasions, ecosystem services, invasive alien species, resource economics.

INTRODUCTION

Problems associated with biological invasions have increased rapidly world-wide in recent decades. National-level strategies are in place, or under development, in many parts of the world, underpinned by different approaches or philosophies. For example, in Australia, key interventions for plant invasions are focussed on a set of 'weeds of national significance' (http://www.weeds.org.au/natsig.htm; e.g. Spies & March, 2004; van Oosterhout, 2004; Brougham *et al.*, 2006). Strategies are also structured around functional groups that potentially require similar management responses or that have similar impacts (e.g. Paynter *et al.*, 2003; Gosper & Vivian-Smith, 2009). Other approaches seek to define management options and then select

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targets (e.g. prioritizing species for eradication, Skurka-Darin *et al.*, 2011). Area-specific or pathway-specific measures may also be used to reduce current levels of invasions and restrict future invasions (Lee & Chown, 2009). These approaches all have particular merits, but we know of no cases where they are explicitly integrated. Moreover, species-specific management strategies for invasive alien plants have tended to focus on those species for which there is general agreement regarding the need for intervention. We know of no examples of detailed national strategies for the management of groups of invasive species that cause serious problems, but that also, in some areas and contexts, provide benefits to stakeholders. Problems with conflicts of interest and the need to prioritize species for management attention are escalating as increasing numbers of cultivated species become invasive and as the needs and perceptions of stakeholders become increasingly diverse and even polarized. We believe that useful insights into this problem can be gained by exploring the situation with one of the most important genera of invasive alien plants in South Africa: Australian acacias (Richardson *et al.*, 2011).

South Africa is a good place to explore this issue because of the long history of plant introductions and the range of interventions for dealing with invasive plants that have been tried in recent decades. These interventions include several novel approaches for the management of invasive alien plant species that have both benefits and negative impacts. For example, following consultation with growers of Australian acacias, several biological control agents were introduced to reduce seed output without damaging non-reproductive parts of the target plant, with the aim of limiting spread without compromising cultivation. The country has established a national-level clearing programme that capitalizes on the opportunity to combine clearing with job creation and poverty relief (van Wilgen *et al.*, 2011). And under South African legislation, permits can be issued to allow invasive alien species to be cultivated in demarcated areas (providing steps are taken to prevent their spread), while requiring all other landowners to control the spread of the same species on their land (Richardson *et al.*, 2003; Nel *et al.*, 2004). The most recent legislation relating to invasive species also calls for a comprehensive and explicit strategy to coordinate these elements for key invasive species.

In reality, and despite the use of many and sometimes novel practices, South Africa's approach to the management of invasive alien plants to date could arguably be described as a strategy of hope. Various practices have largely been carried out in isolation and without formal protocols for adapting tactics as new information becomes available and as conditions change. In the case of acacias and some other taxa, strategies have been confounded, and in some cases derailed, by conflicts of interest that arise when species have both negative impacts and positive benefits. The development of biological control practices arose independently from historic attempts at mechanical control, and the promulgation of legislation proceeded without thorough consideration of its practical implementation or likelihood of success. Mechanical clearing programmes in the late 20th century were driven by the considerations of poverty relief and available management capacity more than by ecological considerations (van Wilgen *et al.*, 2011), and no clear targets for assessing progress have been set. While there has been some consideration of the importance of prioritization (van Wilgen *et al.*, 2007; Roura-Pascual *et al.*, 2009, 2010, 2011), these approaches have only recently begun to be incorporated into the planning that informs implementation.

In this article, we explore the potential for using 'Australian acacias' (species in *Acacia* subgenus *Phyllodineae* native to Australia; Miller *et al.*, 2011; Richardson *et al.*, 2011) to develop a framework for the national management of the group as a whole. We identify different categories of acacias based on their relative invasion risk and economic value, as well as the management goals relevant to each category. We then use this framework to allocate the combinations of management practices to each category, so as to maximize the potential for achieving the goals. We also discuss the challenges associated with the implementation of the strategy.

INTRODUCED ACACIAS IN SOUTH AFRICA

Australian acacias have been introduced and widely propagated for various reasons in South Africa for almost 150 years (Poynton, 2009). They underpin a small but important plantation forestry industry (Sherry, 1971; Dunlop & MacLennan, 2002), but some species (including all those grown commercially) are aggressively invasive (Henderson, 2001; Nel *et al.*, 2004) and have significant negative impacts on natural ecosystems and ecosystem services (De Wit *et al.*, 2001; Richardson & van Wilgen, 2004; Gaertner *et al.*, 2009). The management of this taxon (more than other groups of invasive plants in the country, with the possible exception of *Pinus* species) is complicated by conflicts of interest that arise from the combinations of positive benefits and negative impacts.

Current distribution

Around 70 species of Australian acacias have been introduced to South Africa (Richardson *et al.*, 2011), some as early as the 1830s (Poynton, 2009). Early introductions included species for stabilizing sand dunes (*Acacia cyclops*, *A. longifolia* and *A. saligna*), but this was later expanded to species with commercial value as forestry crops. Plantations of *A. mearnsii* (and to a much smaller extent *A. decurrens*) were established for bark and wood, but there has been a decline in the planted area from 300,000 ha in the mid-1900s to 120,000 ha in 2009 (Dunlop & MacLennan, 2002; Forestry South Africa, 2009). Some of the planted area was simply abandoned, resulting in unmanaged thickets. *Acacia melanoxylon* was historically grown as a high-grade timber species in plantations (Poynton, 2009), but very few commercial plantations of this species now exist. Reports of invasions date back to the start of the 20th century, and at least fourteen Australian acacias are now known to be invasive across South Africa (Richardson *et al.*, 2011; Table 1; Fig. 1a). There are also records of naturalized populations of *A. cultriformis*, *A. fimibriata* and *A. pendula* from 1980s and 1990s, but these have not been reconfirmed recently. In addition, several species are known to be grown ornamentally or in arboreta but have not been seen to show more than very limited recruitment (e.g. *A. ulicifolia* in Tokai Arboretum, Cape Town).

In 1996, it was estimated that Australian *Acacia* invasions covered *c.* 643,000 ha of South Africa (Le Maitre *et al.*, 2000) (areas given in this paragraph are expressed as the equivalent of closed-canopy stands). Estimates from a more recent study (Kotzé *et al.*, 2010) suggest that the area invaded has decreased by about 14% to 554,000 ha. Most of the estimated decline was attributed to *A. cyclops* (which declined by an estimated 81% from 291,000 to 55,000 ha) and *A. saligna* (which declined by an estimated 49% from 103,000 to 53,000 ha). Invasive stands of *A. mearnsii*, and the closely related *A. dealbata* and *A. decurrens*, on the other hand, increased by an estimated 92% from 231,000 to 443,000 ha. Both sets of estimates are crude, and the methods used by Le Maitre *et al.* (2000) and Kotzé *et al.* (2010) differed. Between 2000 and 2010, 135,000 ha of invasive acacias were mechanically cleared by the Working for Water programme at a cost of R880 million (1 US$ = ~7 South African rands; values adjusted to 2010 rands; Working for Water, unpublished data). These figures do not include clearing between 1996 (when Working for Water began) and 1999, clearing by other agencies and firewood harvesting, so the clearing effort was definitely greater. The estimated declines in *A. cyclops* could be attributed to the combined effects of biological control and substantial harvesting of firewood from invasive populations, while the decline in *A. saligna* is more likely due to biological control alone. Indications are that most other species continued to increase in area despite substantial clearing efforts.

The abundance and density of different species appears to be largely because of differences in propagule pressure brought about by the extent and intensity of propagation (Poynton, 2009; Wilson *et al.*, 2011). Species that were widely planted in large numbers are also the most abundant (e.g. *A. cyclops* and *A. mearnsii*). Conversely, species that have been less widely or

Table 1 Salient features of the distribution of 16 Australian *Acacia* species in South Africa. Fourteen are regarded as invasive, as *A. viscidula* and *A. adunca* are currently only naturalized. Dates of introduction are from Shaughnessy (1980*), Henderson (2006†) and Poynton (2009; all other records). Distribution is described in terms of range (very widespread, widespread and very localized) and abundance (abundant, common or scarce; Nel *et al.*, 2004; Wilson *et al.*, 2011).

Acacia species	Date of introduction	Range and abundance	Major biomes invaded	Beneficial uses
A. adunca	1955	Very localized and scarce	Fynbos	None
A. baileyana	*c.* 1900	Widespread and scarce	Grassland	Ornamental
A. cyclops	1835	Widespread and abundant	Fynbos (coastal)	High-quality firewood
A. dealbata	*c.* 1850	Widespread and abundant	Grassland and savanna	Potential for woodchips and bark products
A. decurrens	1870	Widespread and common	Grassland and savanna	Potential for woodchips and bark products
A. elata	1904	Widespread and common	Fynbos	None
A. implexa	1886* (1850?†)	Localized and common	Fynbos	None
A. longifolia	1827	Widespread and common	Fynbos	None
A. mearnsii	*c.* 1850	Very widespread and abundant	Grassland, Fynbos and savanna	Woodchips and bark products; firewood
A. melanoxylon	1848	Widespread and common	Fynbos and forest	High-grade timber
A. paradoxa	*c.* 1850	Very localized and abundant	Fynbos	None
A. podalyriifolia	1894	Widespread and common	Savanna and Grassland	Ornamental
A. pycnantha	1865	Localized and abundant	Fynbos	None
A. saligna	1833	Very widespread and abundant	Fynbos	Low-quality firewood and fodder
A. stricta	?	Localized and common	Forest	None
A. viscidula	?	Very localized and scarce	Fynbos	None

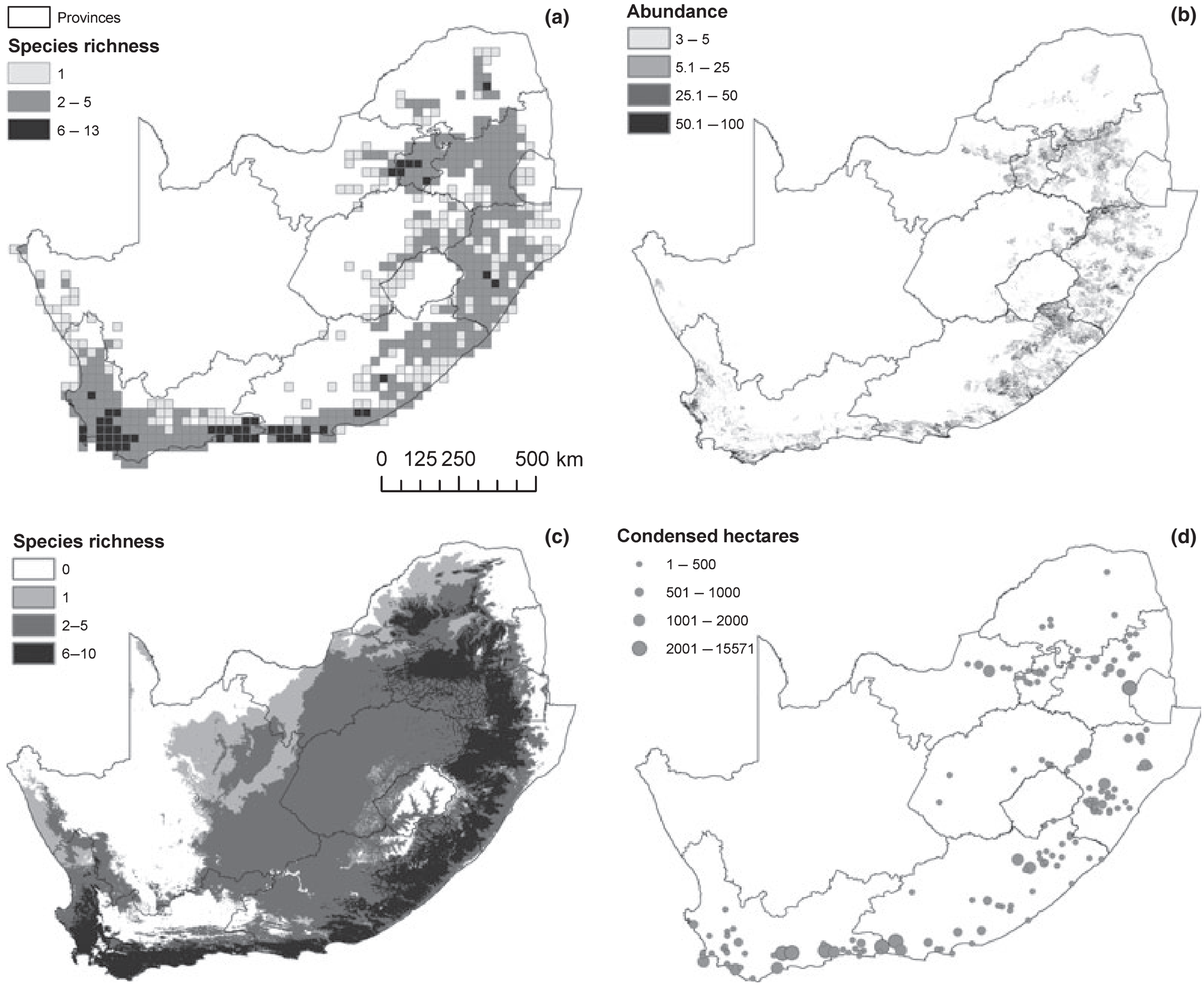

Figure 1 Current and potential distribution of invasive *Acacia* species in South Africa. (a) current species richness (based on the known occurrence of 16 *Acacia* species); (b) combined abundance of major *Acacia* invaders (*A. baileyana, A. cyclops, A. dealbata, A. mearnsii, A. melanoxylon* and *A. saligna*) (expressed in percentage ground cover); (c) potential species richness based on predicted distribution for 12 *Acacia* species (Rouget *et al*., 2004); (d) areas in South Africa where invasive Australian *Acacia* species have been cleared by the Working for Water programme between 1999 and 2009.

intensively planted are less widespread or abundant. Residence time is also an important predictor of invasive range among major invasive plants in South Africa, including Australian acacias (Wilson *et al*., 2007). There is thus considerable potential for many species to expand their range into suitable but as yet unoccupied areas (Rouget *et al*., 2004; Fig. 1c).

Impacts

Invasive Australian acacias have significant negative impacts on biodiversity (e.g. Gaertner *et al*., 2009), on ecosystem functioning (Yelenik *et al*., 2004) and on a range of ecosystem services (e.g. De Wit *et al*., 2001; Le Maitre *et al*., 2011). The impacts of these species on water resources, grazing and biodiversity have been evaluated at a national scale (van Wilgen *et al*., 2008a) and are estimated to cost more than R4 billion annually, most of which (70%) is attributed to reductions in water resources in the grassland and fynbos biomes (De Lange & van Wilgen, 2010). Additional impacts, which have not been quantified over large areas, include changes to erosion and river-bank stability, fire hazard (van Wilgen & Richardson, 1985), aesthetic and recreational aspects and increased soil nitrogen (Yelenik *et al*., 2004, 2007; Gaertner *et al*., 2011). These impacts affect many sectors of society, including the poorest of the poor (Kull *et al*., 2011).

Benefits and commercial production

Benefits are derived from both commercial activity and the harvesting of products (mainly firewood) from invasive populations. Plantations of *A. mearnsii* are owned by *c*. 2700 growers (1200 commercial farmers and 1500 small-scale growers) who collectively employ 30,000 people, mainly in the grasslands of the eastern coastal provinces and the escarpment (i.e. rural areas where there are very high levels of unemployment and poverty). In 2009, 1.2 m tonnes of timber was produced (Forestry South Africa, 2009), most of which was exported as woodchips. In addition, 180,000 tonnes of wattle bark was converted to tannin products. The value of the wattle industry, in terms of raw material produced, was R791m in 2009, 85% of which was in the pulp and paper sector.

Invasive Australian acacias are harvested by many people, who utilize the wood both for their own consumption and for sale (Kull *et al.*, 2011). The main species involved are *A. mearnsii* (throughout the eastern half of the country) and *A. cyclops* (in the south-western coastal regions). Such benefits lead to a desire in some areas to retain invasive stands or even increase them (e.g. in rural communities in the Eastern Cape; Shackleton *et al.*, 2007). No data are available on the use of *A. melanoxylon*, which has localized importance as a high-grade timber species.

MANAGEMENT TACTICS AND PRACTICES

A range of tactics and associated practices are used in the management of Australian acacias in South Africa (see Wilson *et al.*, 2011 for a general review of control methods). In this section, we provide a brief description of broad management tactics and specific practices that will form the essential building blocks of a management strategy.

Tactics and their desired outcomes

Prevention

Preventing the introduction of new and potentially invasive taxa is an important component of any strategy to deal with invasive alien species. An understanding of the diversity and patterns of transport will be needed to effectively prevent the accidental introduction of new species, while intentional introductions should be preceded by adequate risk analysis. Overall, the desired outcome would be to prevent any new potentially invasive species from being introduced.

Eradication

Populations of acacias that are sufficiently small and localized should be targeted for eradication. Eradication efforts are currently underway on *A. paradoxa* (Zenni *et al.*, 2009), while ongoing work is identifying small populations that have been neglected and assessing to see whether the invasive populations are still of a size where eradication is feasible and cost-effective (Moore *et al.*, 2011; Wilson *et al.*, 2011). The desired outcome is the total removal of all seeds and adults of potentially invasive species at a bioregional scale. Eradication is most effective when combined with prevention to ensure that reintroduction does not readily occur.

Containment

Containment is an appropriate tactic for species where eradication is not feasible, but where there is still considerable scope for expansion to presently unoccupied areas. The focus of management should be on preventing spread to new areas. The desired outcome of this tactic would be to prevent the further expansion of populations with restricted distributions.

Impact reduction

Impact reduction is the only feasible tactic for widespread invasive species. In the case of acacias, the focus is on a combination of mechanical, chemical and biological control in priority areas. Prioritization is done of the basis of agreed criteria. In this case, the desired outcome would be a reduction in distribution and density.

Value addition

For many introduced acacias, value can be added by utilizing the products that they offer (Table 1). This can occur both through the establishment, tending and harvesting of plantations and through harvesting products from invasive populations. The desired outcome is to maximize benefits without compromising any attempts to reduce negative impacts.

Available management practices

There are a range of practices that can be used to achieve the outcomes highlighted above. Some methods are applicable to a single tactic, while others might contribute to a range of tactics which in turn might be combined to achieve a particular goal (Table 2).

Risk assessment

Although species imported into South Africa have not been assessed to date in terms of their invasive potential, new legislation will soon require this for any species that is not yet in the country. There is a therefore a need to develop effective protocols for risk assessments.

Early detection and rapid response

The feasibility of eradication is investigated for new invasive species, and control is coordinated across all sites where the species is found. Where eradication is deemed unfeasible, management authorities are alerted to the presence of the new threat.

Mechanical and chemical control

Areas invaded by Australian acacias are cleared using a combination of felling and herbicidal treatment of stumps to prevent resprouting. Cleared areas can then be burnt both to

Table 2 Strategic goals and appropriate tactics and management practices associated with eight categories of invasive alien plants. Categories are as in Fig. 3. The management practices of education and awareness and prioritization apply to all categories and are not explicitly included here.

			Management practices				
Category	Strategic goals	Management tactics	Risk reduction and rapid response	Mechanical and chemical control	Biological control or manipulation	Spatial prioritization	Social interventions
Widespread invaders with significant benefits	Measurable reduction of impacts to a sustainable and tolerable level Retention of benefits where possible	Containment and impact reduction Value addition	Not applicable	Containment and reduction in density	Biological control restricted to seed attackers, but other forms should be considered where the value of impacts exceeds that of benefits Development and use of sterile cultivars compulsory for commercial growers	Focus on eradication in sparsely populated areas with suitable habitat Prioritize control efforts in areas of high impact	Streamflow reduction levies where applicable Payment for ecosystem services through municipal tariffs Encourage harvesting from wild populations Place and enforce strict legal obligations on growers to control spread Legal obligations for control on landowners Education and awareness raising Commercial production
Widespread invaders with few benefits	Measurable reduction of impacts to a sustainable and tolerable level	Containment and impact reduction	Not applicable	Reduction in density	Biological control unrestricted	Focus on eradication in sparsely populated areas with suitable habitat Prioritize control efforts in areas of high impact	Payment for ecosystem services through municipal tariffs Encourage harvesting from wild populations Legal obligations for control on landowners Education and awareness raising
Emerging invaders with few benefits	Measurable reduction of impacts to a sustainable and tolerable level within invaded areas Prevention of spread to unoccupied areas	Containment and impact reduction	Early detection and rapid response required for areas not yet invaded	Containment and reduction in density	Biological control unrestricted	Focus on eradication in sparsely populated areas with suitable habitat Prioritize control efforts in areas of high impact	Payment for ecosystem services through municipal tariffs Allow harvesting from wild populations, but do not encourage (need to avoid dependency) Legal obligations for control on landowners

Table 2 (Continued).

Category	Strategic goals	Management tactics	Management practices: Risk reduction and rapid response	Mechanical and chemical control	Biological control or manipulation	Spatial prioritization	Social interventions
Emerging invaders with significant benefits	Prevention of spread to unoccupied areas Retention of benefits where possible	Containment and impact reduction Value addition	Early detection and rapid response required for areas not yet invaded	Containment and reduction in density	Biological control restricted to seed attackers Use of sterile cultivars should be encouraged	Focus on eradication in sparsely populated areas with suitable habitat Prioritize control efforts in areas of high impact	Streamflow reduction levies where applicable Payment for ecosystem services through municipal tariffs Allow harvesting from wild populations, but do not encourage (need to avoid dependency) Place and enforce strict legal obligations on growers to control spread Legal obligations for control on landowners Education and awareness raising Small-scale commercial production
Eradication candidates	Eradication of invasive species that have limited distribution	Eradication	Early detection and commitment to rapid and sustained response	This would form the major practice in support of eradication	Biological control not needed unless eradication fails	None needed	Payment for ecosystem services through municipal tariffs Close collaboration with landowners to ensure eradication
Curiosity plants and non-invasive crops	None	Monitoring	Monitor for signs of invasion, and reclassify species if appropriate	Not needed	None	None needed	Exempt from restrictions
New imports	Significant reduction in risk of introductions of potentially invasive species	Risk assessment to ensure that only non-invasive species imported Prevention of illegal or accidental introductions at source	Risk assessments compulsory for all new proposed imports Early detection and rapid response required for accidental introductions	Not applicable	None	None needed	None needed

destroy seeds and to stimulate germination, thereby depleting soil-stored seed (Pieterse & Cairns, 1986, 1988). One or more follow-up clearings are required to remove seedlings, either manually or by means of herbicidal sprays (van Wilgen *et al.*, 1994).

Biological control

Nine insect species and a fungus have been introduced as biological control agents into ten *Acacia* species in South Africa (Impson *et al.*, 2009). These can be considered as two general types based on the action – reproductive feeders and unrestricted feeders. In the case of *Acacia* species with economic benefits, only biological control agents that do not damage vegetative plant parts have been considered (Dennill & Donnelly, 1991). Five species of seed weevils in the genus *Melanterius* (which feed on ripening seed pods) and two species of cecidomyiid flies that form flower-galls have been released. While the large seed production and large existing seed banks mean that extremely high and consistent damage rates over many seasons are required before the densities of these species will be affected in the absence of other control measures, reductions in seed production can reduce spread rates (e.g. see Higgins *et al.*, 2001 and Rouget & Richardson, 2003 for *A. cyclops*) and also the costs of follow-up control. For Australian acacias with no commercial value, more damaging biological control agents have been considered, provided that the agents are highly host specific. To date, two species of pteromalid wasps and a rust fungus, all of which are gall forming, have been released (Impson *et al.*, 2009).

Payment for ecosystem services

Because clearing projects can deliver hydrological benefits, some water utilities and municipalities raise funds through water tariffs and use these to contract workers to control invasive alien plants in their water catchments. This approach provides access to funding for clearing programmes that would be difficult to justify for other, less easily quantifiable, benefits, such as biodiversity protection (Turpie *et al.*, 2008).

Harvesting from invasive populations

The harvesting of products, notably firewood, from the populations of invasive acacias provides an important source of fuel for rural communities, as well as a source of income to many through the sale of firewood (Kull *et al.*, 2011). These practices are encouraged as they can, theoretically, assist in control. However, they can also forge dependencies that introduce an additional conflict of interest.

Development of sterile cultivars

The invasive potential of commercially farmed *Acacia* species could be substantially reduced by inducing sterility through gamma radiation of seed or the production of triploids through chromosome doubling techniques. Flowering in plants grown from irradiated seed can be significantly reduced (Beck *et al.*, 2006; Beck & Fossey, 2007), and tetraploid *A. mearnsii* plants have been developed (Beck *et al.*, 2003a,b,c, 2005; Mathura *et al.*, 2006; Fossey *et al.*, 2009). Controlled crosses between tetraploids and diploids are being made and their progeny tested. Should this approach prove successful, sterile plants can be produced through vegetative means for commercial deployment (Beck-Pay, 2008).

Although genetic modification shows promise for the development of sterility (Strauss *et al.*, 1995; Strauss & Brunner, 2001; Lennetyinen *et al.*, 2004) and has been discussed in South Africa for many years (De Zwaan, 1980), this practice has not been actively pursued in South Africa. A large proportion of the South African Forest Industry subscribes to the Forestry Stewardship Council's (FSC) criteria for forest and forest product certification, and Principle 6.8 of the FSC prohibits the use of genetically modified organisms. However, should the technology prove to be reliable, it should be considered regardless of the consequences for FSC certification, which is clearly well intentioned but counterproductive in this case.

Spatial prioritization

Prioritization of control operations at a range of spatial scales should focus resources for control on areas where they will achieve the greatest benefit. At a national level, we propose the recognition of five distinct zones that will differ with regard to the broad approach of management (Fig. 2). Within the zones where impact is currently highest (Fig. 2), further prioritization at finer spatial scales will be necessary to focus control efforts where they can achieve the best impact.

Control operations in South Africa were largely initiated at provincial or finer scales without explicit reference to a logical framework or systematic plan. Efforts have recently been made to address this shortcoming through the development of formal prioritization approaches, using multicriteria decision techniques (van Wilgen *et al.*, 2008b; Roura-Pascual *et al.*, 2009, 2010). Criteria used included the importance of areas for water production, grazing potential and areas identified as priorities for the conservation of biodiversity. Prioritization studies are now focusing resources on areas where the available funds will deliver greater returns on investment. In particular, unnecessary effort should not be expended on dealing with introduced Australian acacias found in areas where the climate or habitat is not conducive to spread and where impacts are not severe.

Commercial production

Commercial production in South Africa is focused almost exclusively on *A. mearnsii*. Normal silvicultural practices such as planting, fertilization and other tending, and harvesting are important (Sherry, 1971; Dunlop & MacLennan, 2002), and steps are also taken to protect plantations from fire and insect

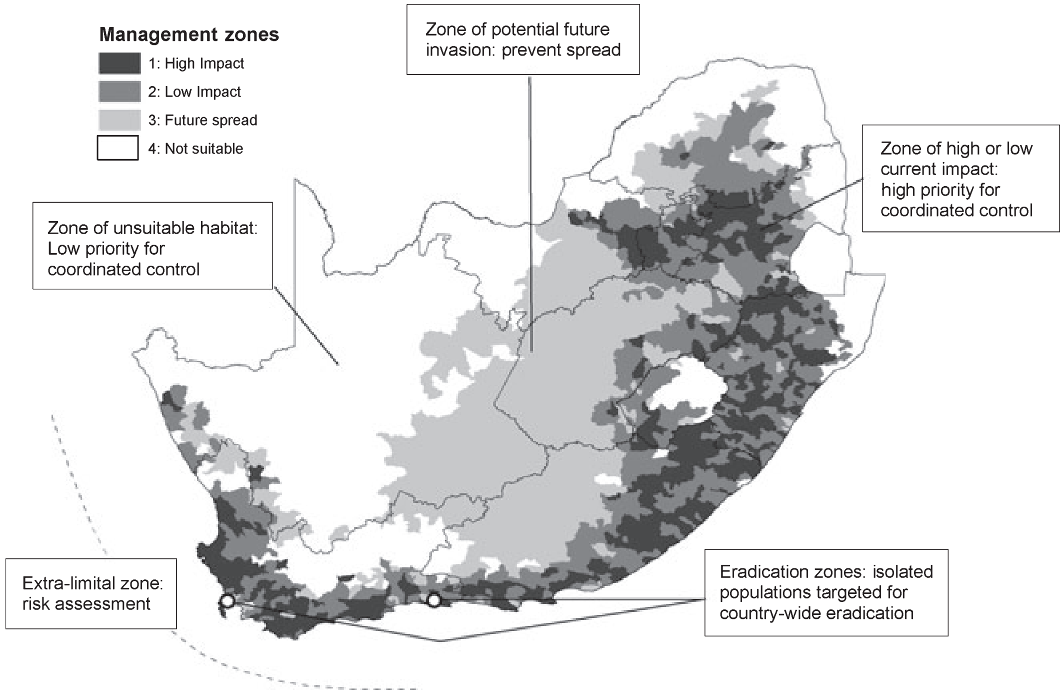

Figure 2 Management zones based on the estimates of the distribution on invasive Australian *Acacia* species in South Africa (Kotzé *et al.*, 2010) and of habitat currently uninvaded but suitable for invasion (Rouget *et al.*, 2004). The location of current candidates earmarked for eradication (*Acacia paradoxa* and *A. stricta*) is shown.

pests. To date, it has not been necessary to protect plantations from biological control agents, but this would become necessary if plant-damaging agents were released. Currently, commercial producers do not take any effective steps to prevent the spread of invasive plants from production areas, although they have agreed to the release of biological control agents that limit seed production (Carruthers *et al.*, 2011).

Education and awareness

Many invasive alien plant problems are exacerbated by a lack of awareness. This can be overcome to some degree by targeted awareness programmes. For example, Australian acacias were until recently sold by nurseries, but a concerted effort on the part of authorities to raise awareness of the problem has eliminated these species from nursery stock across the country.

Legislation

South Africa has a powerful legislative framework to address biological invasions. The Conservation of Agricultural Resources Act (CARA) defines three categories of invasive alien plants. Category 1 weeds are invasive species that must be controlled or eradicated where possible; category 2 invaders have commercial importance and will be allowed by permit to grow in demarcated areas, and whose products can be traded, provided that steps are taken to prevent spread; and category 3 invaders have ornamental value, and are allowed by permit to remain in demarcated areas, but further trade and plantings are prohibited, and steps must be taken to prevent spread. Several Australian acacias have been placed into various categories in terms of this Act. The more recent National Environment Management: Biodiversity Act has yet to finalize its regulations but will introduce similar categories that will compliment those provided for by CARA. The major difference is that invasive alien plants in category 1 will be split into subcategories that recognize that some species with a very high invasive potential will need to be placed under a government-sponsored management programme, in which landowners will be assisted with their legal obligations to control the spread of particularly aggressive invasive species. South African water legislation also requires that landowners who practice commercial forestry to pay for reductions in water run-off that arise from planted areas (Richardson *et al.*, 2003). Finally, South African law allows for the prohibition of planting of alien species into areas where they are not present or widespread. Such steps should be taken in areas where suitable habitat occurs, to ensure that areas currently free of impacts remain so.

DEVELOPING A STRATEGIC APPROACH TO MANAGEMENT

Defining categories of management

We propose that species be grouped into categories for the purposes of defining specific management goals (Fig. 3). The proposed scheme is based on a comparison of the value of

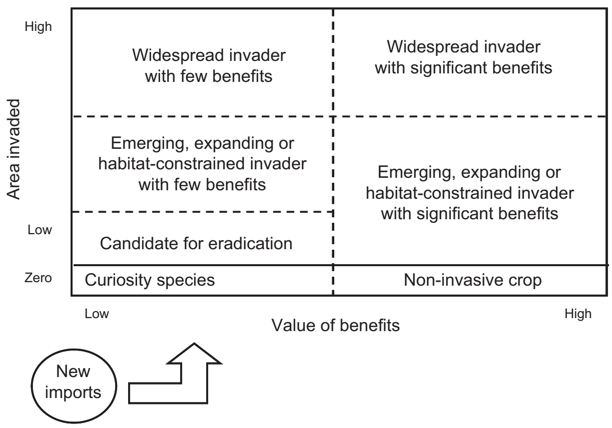

Figure 3 Proposed categorization of introduced Australian *Acacia* species based on area invaded and the value of benefits delivered.

benefits with the value of impacts generated by a species. Both axes of this comparison should ideally be expressed as monetary values. However, although a component of the benefits (i.e. commercial production) can be readily expressed as a monetary value, assigning such values to impacts is problematic. We therefore use invaded area as a quantifiable surrogate metric for the value of impact, and we use the value of commercial acacia operations as our measure of benefit. This conceptual scheme yields eight management categories: two categories of widespread and two of emerging invaders (with either few or significant benefits); eradication candidates (species that meet the criteria for eradication, Simberloff, 2009); 'curiosity plants' (species that occur in small numbers, often as horticultural specimens, and do not display invasive tendencies); non-invasive crop species (species with significant beneficial value that display no invasive tendencies); and potential new imports (species that have not yet been introduced to the country).

Setting goals and combining management practices

Management encompasses the setting of goals and the implementation of practices that will facilitate their achievement. Allocation of species to categories allows us to identify strategic goals that are tailored to the specific circumstances relevant to each of the eight categories (Table 2). By combining and coordinating the management of invasive *Acacia* species in each particular zone (Fig. 2), more progress towards goals can be achieved than has been the case in the past. We therefore propose that the available management activities and practices be appropriately combined for each management category and strategically implemented collaboratively by affected parties at appropriate scales (Table 2). This would certainly be preferable to the strategy of hope that has dominated up to now, with improvements including (1) identifying and agreeing on priority areas for control; (2) articulating and agreeing on goals for ecosystem restoration with affected stakeholders; (3) using all, and not just some, of the available and appropriate control practices; (4) ensuring that appropriate proportions of funding are allocated to each practice (for example, biological control is grossly underfunded in relation to the returns on investment that it delivers, van Wilgen & De Lange, 2011); (5) ensuring ongoing engagement with stakeholders to resolve any issues; (6) incorporating and utilizing all available legal instruments to provide incentives for landowners to get actively involved and to ensure compliance where necessary; and (7) agreeing on and assigning responsibilities for implementation, monitoring and assessment. Species in the categories 'widespread invaders with high benefits' and 'emerging invaders with high benefits' provide the most significant challenges. Reaching agreement on the management goals will require structured negotiation among stakeholders.

Studies have indicated that formally combining management practices has the potential to deliver enhanced benefits if implemented effectively. For example, De Wit *et al.* (2001) considered the economic viability of a range of management scenarios for *A. mearnsii* that included doing nothing or combining between one and four management practices (mechanical control, biological control, harvesting from invasive populations and improved control of spread by growers). They concluded that a 'do nothing' scenario (no attempts made to control the spread of the species) was not sustainable and that the most attractive scenario, in economic terms, would be to combine physical clearing and plant-attacking biological control with the continuation of the commercial growing activities. While the benefits of such approaches have been demonstrated in theory, they have not been implemented in a sustained, coordinated and inclusive manner in practice.

IMPLEMENTING THE STRATEGY

Dealing with change and uncertainty

Australian *Acacia* species were introduced to South Africa in response to the needs of the mid-1800s. These included attempts to deal with the problems of mobile sand dunes and to provide a source of timber and tanning products for which alternatives were not available. Initially, these benefits were realized but were subsequently eroded when acacias began to invade (Fig. 4). Growing global concerns about the erosion of biodiversity, and the role that invasive alien species played in driving this phenomenon, led to the adoption in the late 20th century by many countries of the Convention on Biodiversity, which included a commitment to combat the negative effects of invasive species. Attitudes regarding the value of acacias shifted significantly over time against this background. In the one example for which estimates of relative value (the sum of the value of all benefits minus the value of all negative impacts) are available (*A. mearnsii*, De Wit *et al.*, 2001), relative values were initially high as the wattle industry grew, but as invasions started to manifest themselves, these values were first matched and then exceeded by impacts (Fig. 4). As a result, control measures were introduced, but the degree to which they have halted or reversed the trend is poorly understood. The dates at

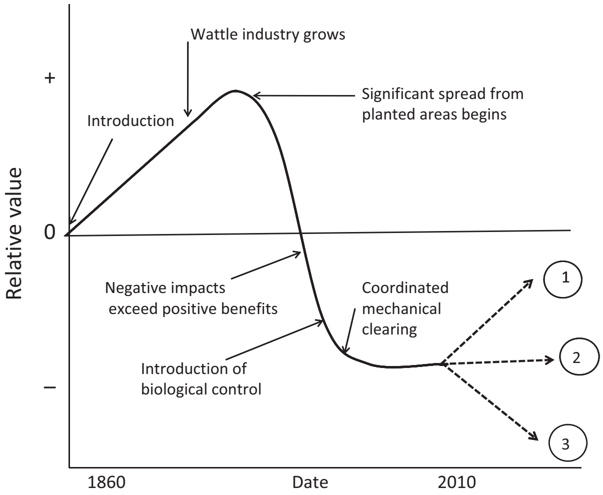

Figure 4 Conceptual illustration showing changing values associated with *Acacia mearnsii* in South Africa. The hypothetical historic trajectory of relative value (sum of benefits minus sum of impacts) is shown over time. Possible future scenarios are indicated by dashed lines.

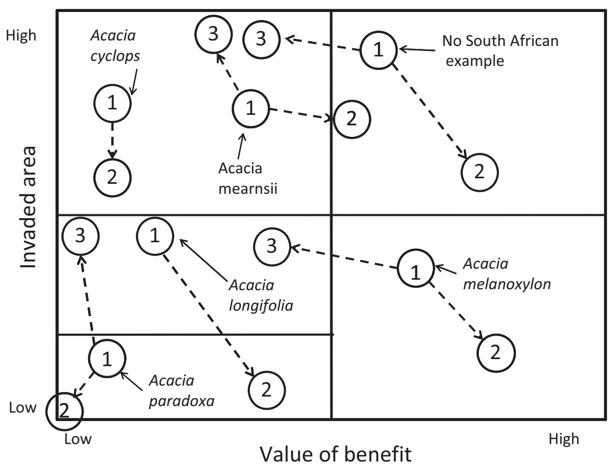

Figure 5 Conceptual diagram indicating the possible trajectories in the classification of Australian *Acacia* species under different management scenarios. 1 = maintenance of status quo, where the implementation of management practices is incomplete, not fully coordinated and sustained, or partially ineffective; 2 = preferred scenario, where the optimum combination of management practices is fully implemented, and practices are effective; 3 = worst-case scenario, where key management practices are not implemented, or fail. Species lacking a worst-case scenario are currently under effective biological control.

which critical points on the hypothetical trajectory in Fig. 4 were reached is not known, and to quantify the true trajectory, commensurable estimates of costs and benefits over time would have to be made.

Currently, the attempts to maintain a flow of benefits from acacias while simultaneously reducing the impacts of invasion vary in their effectiveness, and much uncertainty exists the actual or potential effectiveness of various management practices (Table 3). A number of future trajectories are possible (Figs 4 & 5), and these will play out against a background in which values and attitudes will continue to change as new knowledge and understanding are generated. The problem is therefore multifaceted, requiring the consideration of ecological, social and economic aspects. Such social/ecological systems are complex – that is they are characterized by nonlinear relationships and unpredictable outcomes (see Snowden & Stanbridge, 2004; Snowden & Boon, 2007 for overviews of these concepts). All of these factors point to the need for a new approach to the problem that is flexible enough to allow objectives to be revisited as social needs and values change and that is able to adapt as knowledge increases (Roux *et al.*, 2006). We therefore recommend that the implementation of a strategy to deal with acacias should take place within a framework of adaptive management. Adaptive management is an approach where goals are set, and the outcomes of management practices are monitored and assessed in terms of achieving these goals. Importantly, adaptive management includes an explicit plan for learning that can trigger changes to management or the revision of goals as uncertainty is resolved. The use of adaptive approaches for managing complex systems is gaining growing acceptance among ecosystem managers (Stankey *et al.*, 2005; Moore & Conroy, 2006; Duncan & Wintle, 2008; Armitage *et al.*, 2009) and would provide a useful basis of a strategic framework for dealing with Australian acacias in South Africa.

Lines of responsibility

Our proposed strategy will fail unless clear lines of responsibility are defined and accepted by the various roleplayers. While we do not provide details in this study, it is clear to us that all involved would need to commit to the strategy and to collaborate across spatial scales and domains of responsibility along the lines suggested for water resource management (Rogers *et al.*, 2000). For example, in South Africa, coordinated agreement on goals and approaches would need to be endorsed at a national level within the departments responsible for the environment, water, agriculture, forestry and conservation. These endorsements would need to be cascaded down to finer levels of responsibility within provinces and municipalities. Involvement of the private sector, especially growers and rural landowners, would be essential. Coordinated and prioritized plans at each level would need to provide details regarding responsibilities for implementation, monitoring and assessment.

Fulfilling policy intent

South Africa has adopted a progressive constitution, in which all citizens have the right to a clean and safe environment and in which there is a commitment to sustainable development. These constitutional imperatives are given effect through progressive environmental legislation, which requires citizens,

Table 3 Goals, effectiveness and key uncertainties associated with different practices to manage Australian acacias in South Africa.

Management practice	Goal of practice	Effectiveness in achieving goals	Key uncertainties
Risk assessment	Reducing the risk of introducing potentially invasive species	Not yet effective because of a lack of protocols	Ability of models to assess invasive potential Does not cater for accidental and/or illegal introductions
Eradication	Elimination of potentially invasive species with limited distributions	Can be effective given that necessary conditions exist: early detection, sufficient resources, authority to act, known natural history and leadership (Simberloff, 2009)	Whether all necessary conditions will be met and sustained
Containment using mechanical and chemical control	Reducing invasions and their impacts	Varies with species and level of coordinated effort. Can be effective when combined with biological control	Whether long-term follow-up to deal with seed banks will be sustained, and whether it will be effective
Biological control to reduce seed output	Reductions in the rates of spread	Effectiveness varies from substantial to complete (Zimmermann *et al.*, 2004)	Whether biological control agents will establish and become effective Long-term effectiveness of seed reduction in containing spread
Biological control to damage or kill plants	Reductions in vigour and population size	Effectiveness varies from substantial to complete (Zimmermann *et al.*, 2004)	Whether biological control agents will establish and become effective Ability of commercial growers to protect crops
Payment for ecosystem services	Sustained funding for mechanical and chemical control	Not known	Capacity to implement effectively at local government level is weak
Harvesting from invasive populations	Increased benefit from (and simultaneous reductions in) invasive populations	Ineffective by itself, but makes a contribution by reducing the cost of initial clearing	Lack of commitment to follow-up Degree to which a dependency on the resource will be created
Development of sterile cultivars	Elimination of invasive potential of commercially farmed species	Ineffective by itself, but would make a contribution to reducing propagule pressure from commercially farmed areas	Feasibility of developing sterile cultivars Market resistance to the use of genetically modified organisms
Spatial prioritization	Maximizing efficiency by focussing work on areas with greatest impacts and chance of control success and avoiding effort in non-priority areas	Will increase the chances of achieving objectives in priority areas	Organizational commitment to refocus work and abandon existing projects
Education and awareness	Increasing broad support for control and reducing the risk of unintentional practices promoting spread	Not known	Conflicting value systems
Legislation – compulsory control	Ensuring that control efforts are ubiquitous	Ineffective to date	Sufficiency of resources in the case of most landowners Commitment to prosecute offenders
Legislation – assigning responsibility for seed spread to growers	Ensuring that the 'polluter pays'	Ineffective to date	Sufficiency of resources in the case of most growers Disagreement regarding the source of invasive populations Commitment to prosecute offenders
Legislation – prohibition of cultivation, production and trade	Reducing the risk of unintended spread	Ineffective by itself, but would make a contribution to reducing propagule pressure	Capacity to enforce compliance

among other things, to deal with invasive alien species and to protect the integrity of ecosystem services. The country's actions, embodied in the current government's Accelerated and Shared Growth Initiative for South Africa (ASGISA) policy, however, emphasize growth and consumerism over conservation and sustainable development. This reflects the widespread perception that environmental conservation can only be afforded once the more important needs relating to social welfare have been addressed. This perception fails to make the link between environmental protection and the well-being of poor people, who rely more heavily on ecosystem services and who often bear the brunt of the impacts brought about by invasive alien species.

In the case of acacias, our review and experience suggest that a clear commitment to action will be required on the part of government if the strategic intent of minimizing negative consequences is to be realized. This will mean that the issue of addressing the negative impacts of invasive species will have to take priority over the protection of industries based on such species, in cases where the negative impacts exceed benefits. In reality, activities such as plantation forestry should be allowed to continue but should be required to comply with prescribed conditions, for example the use of sterile cultivars to prevent further invasion from plantation areas. In addition, if measures that may negatively affect production are required to reduce invasions, then the interests of those who suffer greater losses through environmental damage should take precedence over those of the industry, if the magnitude of these losses is demonstrably larger than the benefits derived. For example, plant-damaging biological control agents could be introduced, and the onus to protect crops from such agents would lie with the growers. Formulating and implementing such policy intent will require political courage and sustained commitment but will be needed if impacts are to be reduced.

The conflicts that arise when commercially important or otherwise useful species become invasive are not confined to acacias or to South Africa. For example, the recent and widespread expansion of forestry plantations based on alien conifers in South America (Simberloff *et al.*, 2010) and of pastures based on alien grasses in Australia (Rossiter *et al.*, 2003) both threaten to transform landscapes and the services they currently deliver. Our proposed approach could be adopted to address these issues as well.

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BIOSKETCH

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