ARTICLE IN PRESS

Ecosystem Services xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ecosystem Services

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

Towards a national strategy to optimise the management of a widespread invasive tree (*Prosopis* species; mesquite) in South Africa

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A R T I C L E I N F O

Keywords:
Alien tree
Biological invasions
Ecosystem services
Multi-criteria decision making
Natural resource management
Strategic planning and management
Tree invasions

A B S T R A C T

Invasive stands of *Prosopis* (mesquite) cover over 6 million ha of South Africa and could invade over 56 million ha. These invasive stands have major impacts on biodiversity, local livelihoods and ecosystem services. We applied several methods to develop an objective basis for a national strategy to prioritise and guide the management of *Prosopis*. Decision trees were used for assigning different control objectives (prevention of spread to unoccupied areas, local eradication, containment and asset protection) to each of the 234 local municipalities in the country. Priority assets that require protection in densely invaded areas were identified, ranked and mapped (in order of importance: water source areas, biodiversity hotspots, and areas with high agricultural and rangeland potential). Available control methods were compared in terms of costs, effectiveness, and potential to create employment. Biological control and more mechanised approaches were identified as important and the role of control-through-utilisation requires urgent research. Scenario development suggests that integrated control would be most effective. Strategic guidelines for improving the management of *Prosopis* were produced. These guidelines discuss key needs and objectives for management, targets, time frames, indicators and monitoring programs, research needs and spatially prioritized management areas. Although the strategy proposed in this paper is specific to *Prosopis* in South Africa, the principles will be useful in other regions where *Prosopis* species are invasive, and more generally for other widespread invasive tree taxa.

1. Introduction

1.1. General introduction

A small proportion of species moved by humans to new regions become naturalised, and some of these become invasive - leading to negative impacts on biodiversity, ecosystem services and human well-being in many parts of the world (Pimentel, 2011; Jeschke et al., 2014). Biological invasions are an important component of human-induced global change, along with other factors such as habitat transformation and climate change (Vitousek et al., 1997). Managing invasive species is often complicated and challenging as many invaders can simultaneously provide benefits and cause negative impacts within a given area, resulting in conflicts of interest regarding their use and management (Brown and Sax, 2004; Shackleton et al., 2007; Kull et al., 2011; van Wilgen and Richardson, 2014; Woodford et al., 2016). This makes understanding the various social, ecological, ecosystem related and economic aspects of invasions, and the implications of these invasions for different stakeholders, important for guiding best-management practices. Such a holistic and integrated understanding requires a transdisciplinary approach that transcends knowledge systems and incorporates different actors to develop plans and solutions acceptable to a diversity of key stakeholders (Max–Neef, 2005; Kueffer, 2010; Angelstam et al., 2013).

The negative impacts of many invasive species have led to the initiation of control programs across the world sometimes referred to as investing in ecological infrastructure or natural resource managment. Some notable initiatives include the Weeds of National Significance (WONS) program in Australia (Thorp and Lynch, 2000; Australian Weeds Committee, 2012.), the Working for Water (WfW) program in South Africa (van Wilgen and Wannenburgh, 2016), and the U.S. Department of Agriculture's invasive-species clearing program in the USA (USDA, 2010). Article 8 (h) of the Convention on Biodiversity also requires signatory countries to take steps to manage invasive alien species. Furthermore, the EU Regulations 1143/2014, brought into effect in January 2015, seek to comprehensively manage invasive species to reduce their impacts on biodiversity, ecosystem services and human well-being in Europe (details in Brundu and

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http://dx.doi.org/10.1016/j.ecoser.2016.11.022
Received 21 April 2016; Received in revised form 29 August 2016; Accepted 26 November 2016
2212-0416/

Please cite this article as: Shackleton, R.T., Ecosystem Services (2017), http://dx.doi.org/10.1016/j.ecoser.2016.11.022

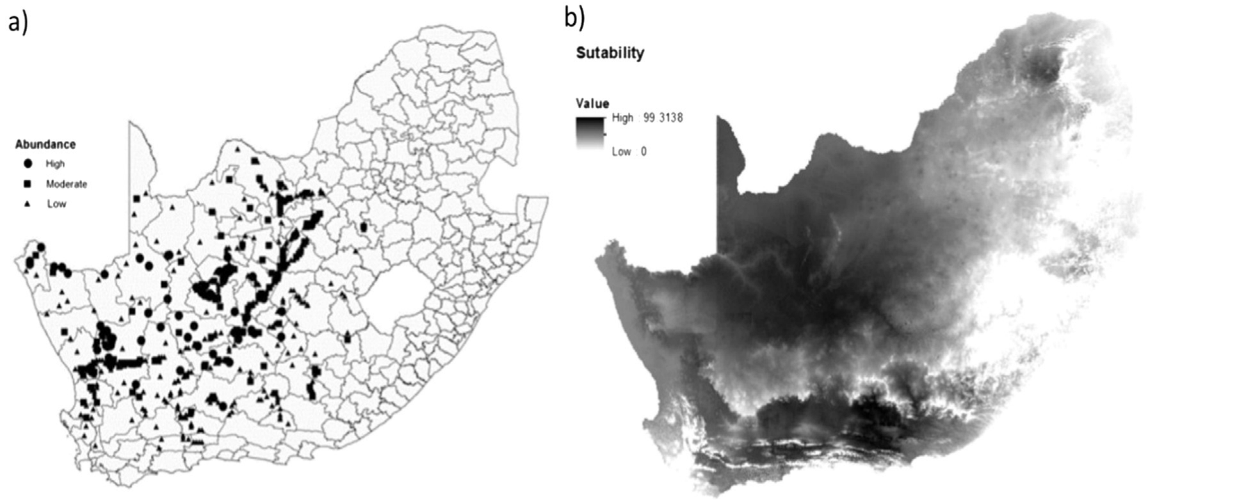

Fig. 1. (a) Distribution of *Prosopis* spp. in South Africa (Sources: SAPIA database – L. Henderson; Van den Berg, 2010; Shackleton et al., 2015a, 2015b); (b) Climatically suitable areas for *Prosopis* spp. in South Africa based on Mgidi (2004).

Richardson (2016)). Although some countries have produced high-level management strategies for dealing with invasive species, many lack species-specific plans and strategies. These management strategies are highly important to yield successful results (Downey, 2011). Australia has plans for 20 species under their WONS program (Thorp and Lynch, 2000) program, and South Africa has case-study examples for Australian *Acacia* species and *Parthenium hysterophorus* invasions (van Wilgen et al., 2011; Terblanche et al., 2016). Other management strategies have been structured around functional groups that share similarities in terms of impacts and management responses (Paynter et al., 2003; Gosper and Vivian-Smith, 2009) and approaches that focus on particular pathways of introduction or area-specific interventions (Lee and Chown, 2009). But globally many areas and species still lack specific management plans.

The lack of strategic planning and objective prioritisation for specific species and land areas has reduced the effectiveness of large-scale invasive species management programs such as WfW (van Wilgen et al., 2012a; van Wilgen and Wannenburgh, 2015; Shackleton et al., 2016). The requirements for managing invasive species in South Africa are set out in general terms in the National Environmental Management: Biodiversity Act (NEM: BA, 2004) and are given effect in the regulations on invasive species in terms of this act (DEA, 2014). For example, the Act stipulates that all organs of the state must prepare plans for eradication, control and monitoring of listed invasive species, and that strategies must be produced for dealing with invasive species that have significant negative impacts (DEA, 2014). However, different species or groups of species require different types of information and different management approaches to be effective.

Numerous approaches have been used for developing strategies to guide the management of invasive species, including area- and pathway-based approaches, risk assessments, impact assessments and spatial planning and prioritisation (Downey et al., 2010; van Wilgen et al., 2011). Prioritisation of invasive species based on the associated risks and impacts is widely recognized as being crucial for effective large-scale planning of interventions (Pheloung et al., 1999; Robertson et al., 2003; Downey, 2010; Downey et al., 2010). Despite such recognition, these approaches have rarely been applied (Roura-Pascual et al., 2009, 2010; Grice et al., 2011; Forsyth et al., 2012; Le Maitre et al., 2015). Objective spatial prioritisation (ranking of land areas by importance) must be done to guide management and to optimise the allocation of limited funds (van Wilgen et al., 2012a). Various methods have been used for spatial planning; these include decision trees and multi-criteria decision-making analysis (MCDA) methods such as Analytic Hierarchy Process (AHP) (Grice et al., 2011; Forsyth et al., 2012; Le Maitre et al., 2015). Decision trees have been used to assign management approaches to different areas, for example for prevention of spread to unoccupied areas, local eradication, containment, and asset protection (Grice et al., 2011; Le Maitre et al., 2015). There is a range of options for containment and asset protection, including different combinations of mechanical and chemical control, control through utilisation, biological control and cultural control. Each option has its advantages and disadvantages, making stakeholder involvement in assessing wants and needs essential (van Wilgen et al., 2011; Shackleton et al., 2014). Multi-criteria decision analysis (MCDA) provides a tool for prioritising areas for control when there are multiple objectives and divergence and contestation in stakeholder agendas relating to management (Saaty, 1990; Forsyth et al., 2012). AHP is useful for reaching consensus regarding management options among different stakeholders. It also facilitates transdisciplinary engagement (Angelstam et al., 2013), which is crucial in cases where invasive species generate conflicts of interest (Saaty, 1990; Forsyth et al., 2012). This paper therefore aims to use various approaches to develop strategic guidelines to better manage widespread *Prosopis* invasions in South Africa.

1.2. *Prosopis in South Africa*

1.2.1. *History, distribution and impacts*

Prosopis species were introduced to many parts of the world over the past two centuries and are now naturalised or invasive in over 100 countries and islands (Shackleton et al., 2014). Numerous *Prosopis* species were introduced into South Africa from the Americas in the late 1800s and were widely distributed to farms in the arid interior of the country in the mid-1900s to provide fodder, fuelwood and shade (Poynton, 2009). *Prosopis* became naturalised and later invasive, and now a hybrid swarm involving numerous species (Mazibuko, 2012) is the second most widespread invasive plant genus in South Africa after *Acacia* (Henderson, 2007). Invasive stands occur throughout the arid and semi-arid interior of South Africa at varying levels of abundance (Fig. 1a). *Prosopis* occurs within the boundaries of 61 of the 234 municipalities in the country, across almost half the country (Fig. 1a). Past surveys estimated that *Prosopis* covers 1.8 million ha of South Africa (83% in the Northern Cape) (Versfeld et al., 1998; Van den Berg, 2010). Using compounded annual spread rates of 8% pa (Van den Berg, 2010) and the latest distribution records, we estimate that invasions currently cover over 6 million ha in South Africa (43% of which is in the Northern Cape). *Prosopis* could potentially invade up to 56 million ha (63% of which would be in the Northern Cape) in the future based on climatic suitability models (Mgidi, 2004) (Fig. 1b).

There is growing evidence of negative impacts due to *Prosopis* invasions in the country. These include negative impacts on ecosystem services, notably groundwater and grazing (Ndhlovu et al., 2011; Dzikiti et al., 2013), biodiversity (Shackleton et al., 2015a, 2015b and references therein) and local livelihoods and economies (Wise et al., 2012; Shackleton et al., 2015c). These negative impacts are expected to increase, and the benefits from *Prosopis* to decrease, as invasive stands become more widespread and increase in density, and as the reliance on natural products from *Prosopis* simultaneously declines (Wise et al., 2012; Shackleton et al., 2015d). However, *Prosopis* is still used for fodder, fuelwood, shade, medicine and as an ornamental plant in South Africa and other regions (Wise et al., 2012; Shackleton et al., 2014). The key challenge for managing *Prosopis* is therefore to reduce the negative impacts on biodiversity, ecosystem services and human well-being, while maintaining certain benefits (provisioning services) where needed and feasible.

1.2.2. Legislation and management

South African legislation classifies invasive species into three categories based on their use and impact (DEA, 2014) – similar to categories used in Australia (Australian Weeds Committee, 2012). In the Northern Cape province, *Prosopis* is listed as a Category-3 invasive taxon, which means that existing plants may be retained, while propagation, use or trade is prohibited. This is due to the fact that it has both benefits and costs for ecosystem services and human well-being. Furthermore, the utilisation of *Prosopis* pods on private land for fodder is specifically exempted from the prohibitions, allowing farmers to use this resource, despite the fact that this clearly promotes spread and associated negative impacts. In other South African provinces mesquite is a Category-1 invader which means that invasive populations must be controlled wherever they occur. The legislation stipulates that the Department of Environmental Affairs must coordinate and produce strategies to prevent new introductions, and control or eradicate current invasive species. Organs of state (national and provincial departments and municipalities) need to produce area-based management plans for those invasive species listed in the regulations. In addition, species with significant impacts require national-scale management strategies and programs. The current NEM: BA provisions and the regulations are ambitious and are widely considered to be unrealistic for many taxa (including *Prosopis*) that are extremely widespread, especially where the success of management hinges on effective cooperation between multiple stakeholders. The regulations provide direction and a level of institutional support for certain activities, but will be reviewed, updated and improved in the future. The consideration of requirements for the effective management of *Prosopis* discussed here accommodates key aspects of the existing legislation, and provide additional considerations that will hopefully guide the revision of the legislation in the future.

Working for Water is a government-funded public-works program which has dual goals. It aims to: (1) provide employment to and develop skills of disadvantaged communities; and (2) manage invasive species to reduce their negative impacts on the environment and restore the delivery of ecosystem services (van Wilgen et al., 2012a; van Wilgen and Wannenburgh, 2016) to improve human well-being. Providing employment and developing skills is an overriding political imperative in South Africa, where the past apartheid policies have left many people marginalised and poorly educated and skilled. Projects under WfW control are managed on behalf of the Department of Environmental Affairs by implementing agents (including government departments, municipalities, national and provincial conservation authorities, and forestry, agricultural and water management organizations). The projects are contracted out to local service providers, most of them from previously disadvantaged backgrounds, and are supervised by regional managers employed by the implementing agents (van Wilgen and Wannenburgh, 2016). Contracts are typically planned to provide employment for periods of 2–3 months. Field teams include a contractor with teams, usually comprising about 10 semi-skilled workers, who are paid to clear demarcated areas (van Wilgen and Wannenburgh, 2016). WfW receives an annual budget of about R 1.1 billion to manage invasions nationally, and is extremely well funded compared to other natural resource management and ecosystem restoration projects in South Africa (van Wilgen et al., 2012b).

The management of *Prosopis* invasions in South Africa has been primarily funded and co-ordinated by the WfW program over the past two decades, although many private landowners have also managed invasions on their land at their own expense (Shackleton et al., 2015c). Working for Water spent approximately R 1 billion (US $ 74 million) [estimated from data in van Wilgen et al. (2012b) and van Wilgen and Wannenburgh, (2015)] between 1996 and 2015 on attempts to control *Prosopis* populations. Despite this substantial investment, the prevailing strategy has failed to prevent the rapid and accelerating spread and densification of *Prosopis* in the country, and invasive stands continue to spread rapidly (8% per annum; Van den Berg, 2010; van Wilgen et al., 2012a,b). This has lead to substantial impacts on ecosystem services and human well-being, which continues to rise with increasing invasion. The ineffectiveness of control efforts to date has been attributed to, among other things, the lack of effective prioritisation and strategic planning, the primary focus on job creation rather than on ecological outcomes, and poor on-the-ground management practices (Forsyth et al., 2012; van Wilgen et al., 2012a; Shackleton et al., 2014; van Wilgen and Wannenburgh, 2016; Shackleton et al., 2016). Although biological control was initiated in the late 1980s, the insect agents have shown a limited ability to reduce rates of spread (Zachariades et al., 2011). Further research to find more effective biological control agents has been delayed because of perceived conflicts of interest about the relative benefits of the tree, although now improved biocontrol is widely considered an essential component of improved management of *Prosopis* in South Africa (Zachariades et al., 2011; Wise et al., 2012; Shackleton et al., 2015c).

The extent of *Prosopis* invasions, their rapid spread and major negative impacts on human livelihoods and the environment makes it important to manage them effectively to reduce costs and improve benefits. This paper describes the development of a national strategy to prioritise and manage invasive *Prosopis* in South Africa, where emphasis has been placed on a developing a holistic and more nuanced understanding of the status quo and future management options drawing on the literature and views of multiple stakeholders.

2. Developing the strategy

Insights from several approaches and sources were synthesised to develop the foundation for a strategy to guide the management of invasive *Prosopis* in South Africa using the scheme shown in Fig. 2. This involved five main steps. The first two steps involved collating background information on the positive and negative impacts, distribution and ecology of *Prosopis* using the literature which included specific case studies that often involved different stakeholders. This was used as justification for the need to control *Prosopis* and to guide the development of the strategy for *Prosopis* management in South Africa (Fig. 2). Step three reviewed current and past management of *Prosopis* (Fig. 2). This included a literature review, workshops and surveys to identify key barriers that impede effective management and the identification of strategic and adaptive approaches that need to be applied to improve control of *Prosopis* (Shackleton et al., 2016). Step four used various approaches to define components of a national strategy for *Prosopis* (Fig. 2). This included drawing on published literature, in particular insights from the Australian WONS program and strategies developed for two other invasive plant taxa in South Africa (van Wilgen et al., 2011; Australian Weeds Committee, 2012; Terblanche et al., 2016) to assess different control options and identify needs for developing strategies and associated implementation plans.

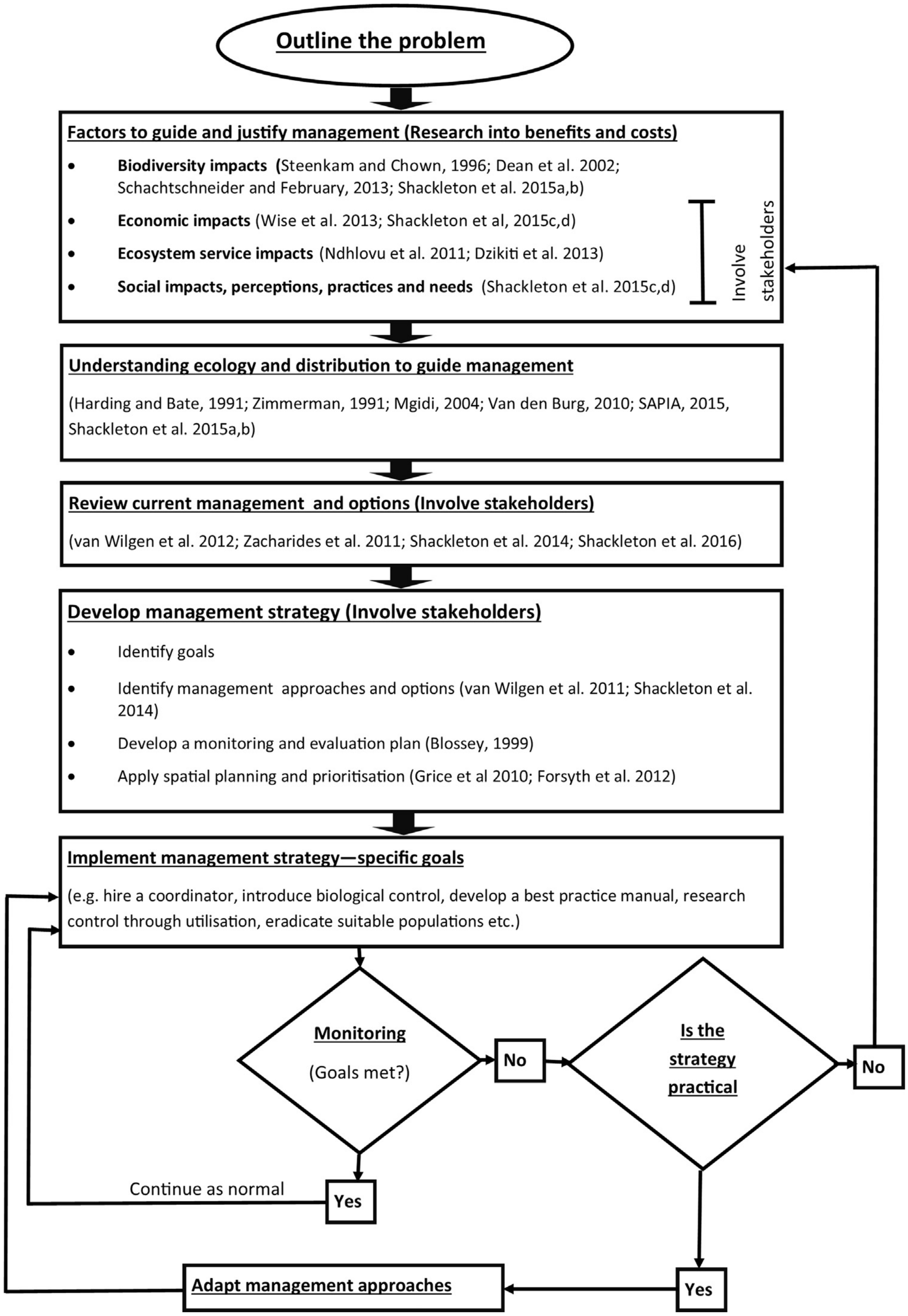

Fig. 2. Framework and sources used to develop a national strategy for *Prosopis* in South Africa.

Multi-stakeholder workshops involving farmers, academics and private and public managers were convened to develop and debate an overarching goal for the strategy. These workshops were also used to identify crucial needs and outcomes for the strategy and for scenario planning (Table 1; Fig. 3). The effectiveness and role of different control options and approaches were discussed in these workshops and through interviews with key informants (Table 2). Decision-tree models (Grice et al., 2011) were used to assign appropriate control objectives to different parts of South Africa (Fig. 4). Using the current and potential distribution (Fig. 1), the Grice et al. (2011) decision-tree framework was used to allocate management priorities to each of the 234 municipalities in South Africa (Fig. 4). The decision tree allocated each municipality to one of five management areas: Prevention which included: (1) passive surveillance for areas currently with no *Prosopis* records and that are not climatically suitable; (2) active surveillance for areas with no records of *Prosopis* which are climatically suitable for its growth; (3) local eradication where *Prosopis* is localised at low densities and where eradication is potentially feasible; (4) containment for populations that cannot be eradicated and that fall near the border between invaded and uninvaded areas; and (5) asset protection for areas with widespread dense invasions, where containment is not feasible. Questionnaires were sent to farmers and managers to collect information on perceptions of these different control objectives. Multi-criteria decision making analysis (using AHP, Saaty, 1990) was used to achieve an objective, spatially-explicit, prioritisation of assets for protection in areas with widespread *Prosopis* invasions (Forsyth

Table 1
A list of strategic planning needs, management process options and actions and timeframes, indicators and outcomes to achieve the goal of improving the effectiveness *Prosopis* management in South Africa.

Strategic goals and needs	Management process, actions and options	Time frames, indicators and outcomes
Co-ordination and stakeholders involved		
Develop a national *Prosopis* committee and control program and a multiple stakeholder working group	• Develop a program with a coordinator • Identify sources of funding and develop a budget for the next five years • Set up a multi-stakeholder *Prosopis* working group (max. 15 people) to review progress, informing their sectors, and guide research and management implementation [include: , WfW staff, representatives from other government departments (e.g. Agriculture, Forestry and Fisheries, Economic Development, Energy, Public works, Rural Development and Land Reform, Water affairs,) other research agencies (CSIR, ARC), farmers and private invasive species management and use contractors and businesses] • Engage with neighbouring states that also have *Prosopis* and develop cross border approaches and plans	• Appoint coordinator in the next 6 months • Develop detailed five year program and budget in the next year • Review and adapt the plan every 5 years • Set up working group in the next year that meets biannually • Set up a meeting with neighbouring states to discuss coordinated management in the next year • Develop a set of indicators to monitor invasion and management success • Report back to stakeholders at least once annually (e.g. farmers union meetings) and promote awareness and build cohesion
Appoint a provincial and district coordinator within WfW	• Identify and appoint a coordinator for each province and district that has *Prosopis* • Produce a document outlining the roles and responsibilities of the coordinator	• Appoint coordinator in the next 6 months • Produce a document of roles and responsibilities in the next year – review every 5 years
Legislation and governance		
Review, revise and implement/ enforce legislation	• Use working group and coordinator to review and, if needed, revise legislation on *Prosopis* • Enforce legislation – specially WfW contracts with farmers • Establish incentives for compliance and disincentive schemes for noncompliance	• Review legislation over the next 5 years • Improve compliance with legislation and in particular contracts • Alternatively develop an incentive scheme for compliant farmers in the next year e.g. herbicide subsidies • Indicator – number of landowners provided or provides incentive subsidies
Develop a research agenda	• Identify priority research areas to be addressed, these include particularly (1) biological control, (2) control through utilisation, and (3) monitoring especially of social, ecological and economic outcomes	• Produce a 5-year research plan (driven by working group and coordinators) in the next 2 years • Produce critical research of further biological control and potential utilisation in the next 3 years
Develop a best practice manual for private landowners	• Producer a booklet and/or online document to distribute to farmers with the aim to build awareness, improve monitoring and guide management of *Prosopis* on private land	• Produce manual in the next year – update every 5 years as new research becomes available
Develop a standardised monitoring plan	• Produce a report identifying key indicators of management success and invasion spread and standardise monitoring across different organs of state • Produce annual monitoring reports	• Develop a set of monitoring guidelines in the next year (with a detailed set of standardised indicators) • Produce annual reports • Revise after guidelines after 5 years
Strategic objectives based on spatial differentiation planning		
Strategic objective 1a) Prevention (passive surveillance)	• Passive surveillance	• Annual occurrence maps and reports – eradicate any new populations • Set up citizen spotter network for *Prosopis* in the next year it could be linked into an accessible reporting platform based on SAPIA and or iSpotIndicator – number of new populations identified
Strategic objective 1b) Prevention (active surveillance)	• Active surveillance (partially along pathways of spread – riparian areas and livestock transport routes) • Targeted awareness and education programs amongst the public	• Annual occurrence maps and reports – eradicate any new populations • Incorporate engaging with farmers unions at their quarterly meetings into the mandate of area managers/coordinators to provide and get feedback, get reports of new occurrence as well as raise awareness • Set up citizen spotter network for *Prosopis* in the next year (see above) • Indicator – number of new populations identified and management costs
Strategic objective 2) Local eradication	• Identify populations for eradication • Provide specialised funding for populations targeted of local eradication • Employ a national eradication coordinator for *Prosopis* if not then for all plant species • Monitor and control populations earmarked for eradication every year months for at least 5 years	• In the next year produce a report with a budget earmarking populations for eradication • Reports every 6 months on progress of all populations targeted for eradication • Enforce legislation and contract compliance in these areas • Incentivise farmers to prevent further invasion • Build awareness in areas targeted for eradication • Report back to stakeholders at least annually (e.g. at farmers union meetings) and promote awareness and build cohesion • Indicator - number of populations eradicated and management costs
Strategic objective 3) Containment	• Use multiple control approaches to maximise control	• Enforce legislation • Report back annually • Incentives control through subsidies

(continued on next page)

Table 1 (*continued*)

Strategic goals and needs	Management process, actions and options	Time frames, indicators and outcomes
		● Map changes in containment zones annually ● Report back to stakeholders at least once annually (e.g. farmers union meetings) and promote awareness and build cohesion ● Indicator - the reductions of outward spreading invasions and management costs
Strategic objective 4) Asset protection	● Each district municipality must produce a spatial prioritisation plan using the criteria in this paper or similar ones (Table 1) ● Use multiple control approaches to maximise control and be adaptable ● Engage with stakeholders (farmers union meetings other departments)	● Report back annually ● Map changes in asset protection zones annually ● Report back to stakeholders at least once annually (e.g. farmers union meetings) and promote awareness and build cohesion ● Research and release an effective biological control agent in the next 5 years. ● Produce a report on feasibility of the control through utilisation option in the next 3 years. ● Enforce legislation ● Indicator - number of ha cleared and the improvements in supply or health/quality of assets earmarked to be protected including both benefits to ecosystems and human-wellbeing and management costs

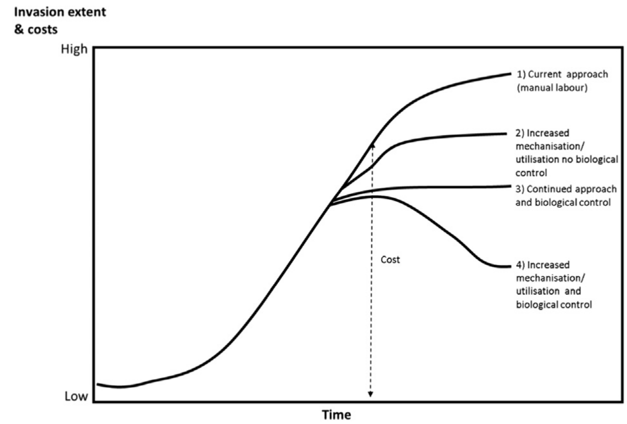

Fig. 3. Scenarios of the potential extent of *Prosopis* invasion and associated costs over time based on different control options, combinations of options, and their potential effects on invasion extent.

et al., 2012) (Fig. 5; Table 3). It involved multi-stakeholder workshops and the use of questionnaires. Step five focused on the monitoring and evaluation as part of the strategy, and options to follow based on the outcomes of monitoring. This was developed using the literature and from information gathered at multi-stakeholder workshops and interviews with key informants. See Appendix 1 for a more in-depth description of the approaches used in the development of the strategy for *Prosopis*.

3. Elements of the strategy

The strategy outlines important factors needed to guide the management of *Prosopis* in South Africa. This includes an overarching goal for the management of *Prosopis*. It also outlines how the management of *Prosopis* needs to be coordinated, which stakeholders need to be involved, mandates and legislation requirements, the assessment of different control options, the role and importance of spatial planning to guide management as well as monitoring and evaluation needs. The implementation of the recommendations provided in this strategy should greatly improve the effectiveness of control of *Prosopis* in South Africa.

3.1. Goal

The goal that was agreed on by multiple stakeholders to guide the management of *Prosopis* in South Africa was: “To effectively control, contain, and monitor *Prosopis* invasions to reduce their costs to humans and the environment in South Africa over the next 20 years.” This goal may need to be reviewed as part of adaptive-management strategy - based on updated knowledge and experience and on management performance highlighted by the indicators identified below (Table 1).

3.2. Co-ordination of programs and stakeholders involved

The need for coordination, as identified in the workshops, was seen as important for the strategy (Shackleton et al., 2016). Participants also highlighted that coordination and cooperation at different levels (international to local) is crucial for alignment with South African legislation and to ensure the overall success of management initiatives (Table 1). It was also identified that cross-border coordination and cooperation is needed to ensure successful management (Table 1), since widespread invasions of *Prosopis* occur in Botswana and Namibia. This would be particularly important with regards to the implementation of further biological control.

We therefore propose that national and regional coordinators and a

Table 2
A comparison of control options in terms of their benefits and costs, mean operation costs, time frames and employment opportunities.

Control approach	Options for different approaches	[a] Cost to clear/contain dense invasion [b] Time to clear a ha; [c] Number of people employed/ha	Considerations
Biological control	Seed feeding beetles *Algarobius prosopis, A. bottimeri and Neltumius. arizonensis* – to reduce rates of spread	[a] Marginal (a few R million for research thereafter minor funding for monitoring) [b] Only reduces rates of spread and decreases densities due to lower recruitment [c] Moderate – researchers and lab assistants rearing and distributing facilities	Has not worked very well as colder winters in South Africa cause population crashes. Was initially used as benefits were higher in the past and the aim was to reduce rates or spread and not mortality to allow for continued use.
	Lethal control: *Evippe* spp. released in Australia (further potential agents exist for increasing tree mortality or to contain rates of spread)	[a] See above [b] Unknown – Evidence in Australia suggests that biological control has made vast impacts on containing and reducing rates of spread but not leading to mass mortality yet (Decreased canopy cover by two thirds in some areas) [c] Moderate – researchers and lab assistants rearing and distributing facilities	Will be the most cost-effective method if correct agent is discovered. There is increasing support for the positive role of biological control in Australia (van Klinken and Pichancourt, 2015; van Klinken, 2012) and further agents that will cause mortality need to be released into South Africa. Would need to collaborate with neighbouring states (SADC) for agreement to release agents
Mechanical & chemical control	Cut stump (standard WfW approach)	[a] ± R 5000–7000 for (wages and herbicide) [b] ± 3 days/ha [c] High −11 people	It is the slowest *Prosopis* clearing method, but it best meets the dual goal of high employment and invasive species clearing under WfW's mandate. This approach is appropriate for eradication programs, however, for widespread populations it needs to be applied in combination with more mechanised approaches.
	Mechanised approach – heavy machinery (back-actors & bulldozers)	[a] ± R 6000–8000 (wages and machinery running costs) [b] ± 1–2 ha/day [c] Low ± 1–2 people	This approach is destructive to the environment – but very effective for clearing areas that will be used for agriculture as stumps are removed. If agriculture is to be sustained, no follow up is required which makes it more cost effective. The use of this approach needs to be prioritised in areas with high agricultural potential using the approach highlighted in Table 3 and Fig. 4. In rangelands, forestry harvesting machinery can be used to mitigate soil damage
	Mechanised approach – herbicide spraying with aircraft	[a] ± R 1000 [b] < 1000 ha/day [c] Low ± 1–2 people	Will control populations fastest – and ground teams will be needed for follow-up control – will therefore not impact employment significantly. The potential impact of herbicides on the environment and restoration needs to be investigated further.
Control through utilisation	Example used is for making pellets for bio-energy to be exported to Europe * (production of 20 000 t per annum). There are numbers other utilisation possibilities.	[a]*Labour intensive methods (R9000/ha) -Machinery intensive (R10000/ha) [b] Labour intensive ± 3 days/ha – Machinery intensive ± 1–3 ha/day [c] High ± 20 people for both methods	This is still a controversial approach and needs further research. Programs need to be fairly large scale to have an impact on invasions (e.g. making flour and medicine touted as a utilisation success will not be adequate). Net profit margin is estimated at 10% per of capital and operational costs which is ± R 3 million/annum and could be reinvested into control. Privatisation of control could be implemented with this approach taking pressure off the state. Investigation into the feasibility of approach is required urgently. Other utilisation possibilities include charcoal, paper and mulching. Localised enterprises should be set up to reduce transport costs.
Other approaches	Livestock management	[a] No clearing – this management approach prevents spread (dispersal) *Fencing could be expensive if needed [c] Low	This approach can provide additional employment opposites. Has other rangeland benefits as well. If fencing is needed costs will rise, but will also aid employment
	Transport managed	[a] No Clearing, simply prevention of spread (dispersal) by holding livestock before transport [c] Low	Not clearing per se, but essential for managing a pathway of spread
	Fire	[a,b,c] Low	Largely unfeasible in the arid conditions where most invasive stands occur and for fire-resistant hybrids. As invasions move into the high rainfall grassland areas of South Africa this approach may become increasingly attractive. Small concentrated fires at the base of large trees have been used effectively for killing single isolated trees.

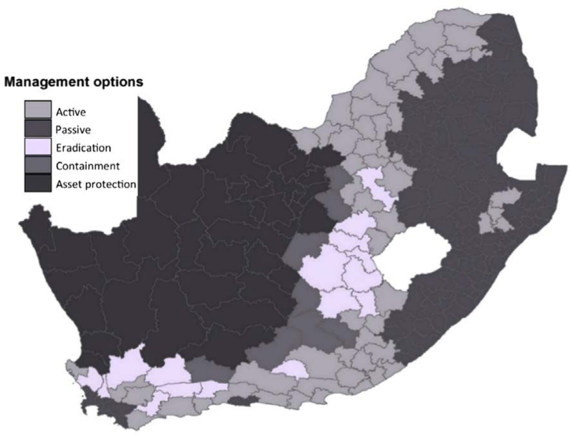

Fig. 4. Spatial differentiation of approaches for managing invasive *Prosopis* species in South Africa to be applied to each municipality in the country using the decision-tree framework of Grice et al. (2011).

multiple-stakeholder working group consisting of WfW managers, representatives from different government departments and research institutions was well as private stakeholders (farmers, private utilisation and control companies) need to be appointed in the next year to guide management (Table 1). The coordinators and working group should direct *Prosopis* management implementation and other matters, such as the formulation of a research agenda and best-practice manual for private landowners. They should also oversee stakeholder engagement, monitoring and performance evaluations and manage bureaucracy between stakeholders and in the WfW program (Table 1).

Report-backs should be conducted at least annually and plans should to be reviewed and updated at least every 5 years - a process which should be driven by the coordinators. Feedback should be given annually to interested and affected stakeholders, primarily via farmers unions (Table 1), to build cohesion, cooperation, awareness and accountability. The state is unable to manage *Prosopis* alone, and productive engagement with private landowners is a crucial part of the strategy. Citizen spotter networks need to set up and supported, and regional managers need to engage with, and report to, farmers at union meetings (Table 1). A best-practice manual that can be widely distributed to promote awareness among private landowners and management by non-governmental stakeholders would facilitate action.

3.3. Mandates of programs and legislation

Mandates for the strategic program must be adopted by WfW operations and must be implemented in line with the latest legislation on invasive alien species (Table 1). Compliance with contracts between WFW and farmers as well as legislation is currently low; this is a major barrier hindering effective management of *Prosopis* (Shackleton et al., 2016). Therefore, efforts need to be made to raise awareness of the legislation and the benefits of management among stakeholders. Getting substantial buy-in and cooperation of private landowners is crucial if control is to be successful. However, the WfW needs to improve its accountability and success rates as well to facilitate confidence among other stakeholders (Shackleton et al., 2016). Additionally, compliance with legislation needs to be encouraged as non-compliance leads to wastage of limited funds (Table 1). Incentive and disincentive schemes could help improve compliance (Shackleton et al., 2016) and need to be initiated as soon as possible. It is also suggested that the regulations need to be reviewed soon and possibly amended to include measures aimed at improving the likelihood of compliance in the long run (Table 1). We also suggest that a case be made to move *Prosopis* from a category 3 species in the Northern Cape to a category one species which would ensure improved management and compliance. This is based on the growing body of evidence that under current and future invasion rates the costs are higher than the benefits (Wise et al., 2012; Shackleton et al., 2015a, b, c).

Table 3
Criteria and sub-criteria and their relative weightings used in prioritisation of assets to be protected in areas with dense *Prosopis* invasions.

Primary criteria and sub-criteria	Relative weight (%)	
	Primary criteria	Sub-criteria
Maintain and improve water assets	**68.2**	
Reduce vulnerability to water loss		56.7
Ensure water supply through clearing catchments from the top down		35.7
Protect areas of good water quality		7.6
Maintain and protect areas of important biodiversity	**17.0**	
Critical biodiversity areas (CBAs)		65.3
National freshwater ecosystem priority areas (NFEPA)		21.7
Maintain gains (already protected areas)		13.0
Maintain and improve agricultural potential (cropping, vineyard, orchards)	**9.4**	
Maintain and improve rangeland potential (grazing)	**5.4**	

3.4. Control options and approaches

Various control options exist for *Prosopis,* each with their own

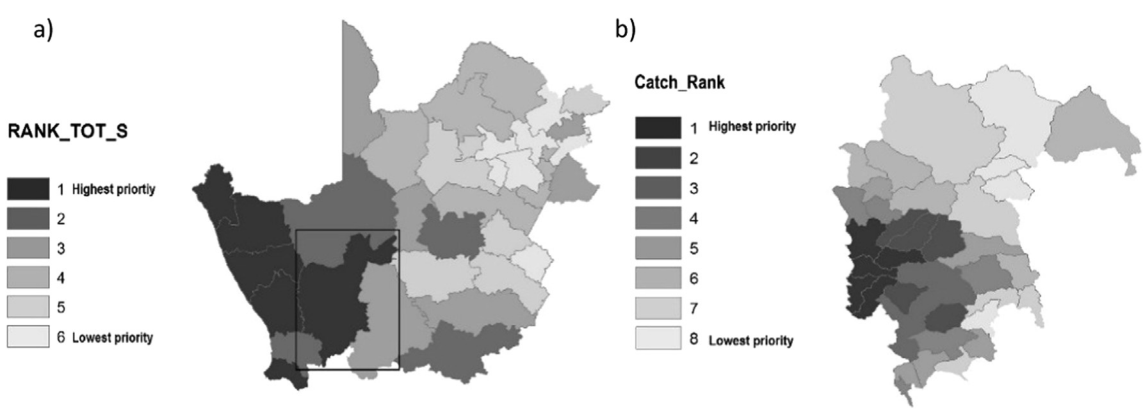

Fig. 5. Spatial prioritisation of management for invasive *Prosopis* species in South Africa using criteria identified and ranked by means of Analytic Hierarchy Process (AHP) illustrated in Table 3 (a) shows spatial prioritisation of municipalities within the asset protection category in South Africa highlighted in Fig. 3: (b) gives an example of fine-scale prioritisation of quaternary catchments in the Hantam municipality (the rectangle in (a); this municipality was ranked as highest priority in a).

benefits and costs, as identified in the literature and through stakeholder workshops and interviews (Shackleton et al., 2014; Table 2). The current labour intensive cut-stump method applied by WfW, is ineffective and *Prosopis* is spreading fast enough to annul the attempts of management to reduce extent and density (van Wilgen et al., 2012a). Furthermore, the current "shot-gun" approach (involving the random implementation of control measures, without spatial prioritisation or evaluation of control effectiveness) has led to small gains in isolated areas, but has not resulted in a reduction in the overall extent of the problem and holistically restores landscapes and the associated ecosystem services (van Wilgen and Wannenburgh, 2016; Shackleton et al., 2016). This is largely because WfW focuses primarily on labour intensive methods and gives less attention to optimizing combinations of clearing methods to reduce the extent of invasions (van Wilgen and Wannenburgh, 2016; Shackleton et al., 2014).

This strategy outlines that an integrated management approach needs to be applied if *Prosopis* is to be controlled effectively (Fig. 3). Integrated management includes the combination of two or more different control approaches (Fig. 3; Table 2) (van Wilgen et al., 2000). We suggest that in particular three important control options need to be considered: (1) The release of more lethal biological control agents as the most important factor (Fig. 3; Table 2). If effective agents can be found, the biological control will be the most cost-effective approach to controlling invasions (Appendix 2). Lethal forms of biological control for *Prosopis* are showing success in Australia and it is very likely the same agent (a leaf-tying moth) will be suitable for South Africa (van Klinken and Pichancourt, 2015). Well researched and tested biological control for plants is considered a safe and highly cost effective method (Sheppard et al., 2005; Page and Lacey, 2006; van Wilgen et al., 2012a). (2) Less labour-intensive methods such as aerial spraying and the use of heavy machinery, which can clear areas at greater rates, are also needed if *Prosopis* is to be managed effectively in areas where important assets needs to be protected (Table 2). Safe herbicides for aerial spraying are useful and have been successfully used to manage some species, but research is needed to develop application methods that do not contaminate ground water and have non-target effects (Matarczyk et al., 2002; Paynter and Flanagan, 2004; Toth and Winkler, 2008). The cut-stump method can be used for eradication and containment programs and to maintain high employment in the WfW program (Fig. 4). (3) The potential role of large-scale control through utilisation needs further research (Fig. 3; Tables 1 and 2), but it is important to note that there is disagreement regarding the usefulness of this approach. On the one hand, it could speed up control and provide opportunities for rural development, but in the long run could create a dependency on a species whose distribution others want to reduce (Table 2). Promoting utilisation could also create a perverse incentive that would actually increase rates of spread in cases where people establish new plantations to reap the perceived benefits of utilisation. One senior WfW manager said at one of the workshops "There is more than enough *Prosopis* for everybody (different control techniques) and still more to go around." Production of a best-practice manual containing information on impacts of *Prosopis* and management options would be useful for improving awareness and for achieving large-scale buy in among landowners and for improving the effectiveness of control (Table 1). The use of spatial planning and prioritisation (Figs. 4 and 5) to direct and prioritise control approaches is needed to improve control effectiveness in the long run especially in of light limited funding and capacity (see Fig. 4; Fig. 5; Table 3) (Shackleton et al., 2016). See Appendix 2 for more details on the different control options highlighted above and in Table 2.

3.5. Spatial planning of management areas

Spatial planning is useful as it breaks down large areas into smaller, more manageable units and identifies control actions needed for each and helps to guide funding allocation for each municipality (Grice et al., 2011). Numerous stakeholders considered this as important for improving management success of *Prosopis* (Shackleton et al., 2016). Using current and potential distribution (Fig. 1), municipalities were divided into five management categories (prevention: (passive and active surveillance); eradication, containment and asset protection) (See appendix 1 for further details on the methods used). Fifty-seven municipalities fell into the active prevention (surveillance) category and half (116) fell into the passive prevention (surveillance) category (where climatic suitability was poor) (Fig. 3). Active surveillance should focus on the main pathways and vectors of spread, including riparian areas and major livestock-transport routes. Awareness and reporting programs need to be established to allow citizens (particularly farmers) to submit new reports of invasion, making surveillance easier and more cost effective; these need to be facilitated by the local coordinators (Table 1). Monitoring of these land units for new invasions will be the least costly management approach, but good coordination and planning will improve success considerably (Table 1). Of the municipalities requiring active control, 16 fell within the eradication category, and 8 within the containment category. A large number of municipalities (37) fell within the asset-protection category, including all of the 15 largest municipal districts in South Africa. Their large size means that further fine-scale prioritisation is needed to focus on the assets that need to be protected, such as areas of high biodiversity, economically valuable land and landscapes supplying crucial ecosystem services. To this end, we applied AHP to identify and spatially prioritise land areas (see Section 3.5 below) with important assets requiring protection. Farmers and managers consider local eradication and containment of further spread to be the most cost effective and most important management approach for reducing the overall impacts of *Prosopis* on humans and the environment across South Africa (Appendix 3). Prevention (active and passive surveillance) was ranked as the lowest priority as it was seen as the least costly operation and easiest if well-coordinated by farmers with *Prosopis* invasion on their land. However, we believe this to be very important and if we had consulted farmers with no invasions in climatically suitable areas they most likely would have ranked it as the highest priority (Appendix 3). The labour-intensive cut-stump approach (used by WfW) will work best for eradication zones and provides the much needed employment. However, a combination of approaches will be needed if containment and asset protection management is to work (Fig. 3). We recommended that progress with management in each municipality should be reviewed every year. These reviews should be based on the indicators mentioned in the second half of Table 1 (such as changes in population density and cost as well as factors such as changes in human well-being and the supply of ecosystem services). Additionally, each province or municipality should spatially differentiate management zones at finer scales using individual farms or catchments to facilitate effective management and to provide the means for more effective funding allocation (Table 1).

3.6. Prioritisation of assets to protect in areas of widespread invasion

Six primary criteria and six sub-criteria were identified and ranked in a multi-stakeholder workshop using AHP for use in spatially prioritising assets within the "asset protection" management zone (Figs. 4 and 5; Table 3). This linked to protecting biodiversity, ensuring the production of key ecosystem services (such as grazing potential and water supply) and maintaining food production and economic output. The primary criteria included: maintaining and improving water assets (68.2% importance), maintaining and protecting areas of important biodiversity (17.0%), maintaining and improving agricultural potential (9.4%), and maintaining and improving rangeland potential (5.4%) (Table 3). This corresponded closely to the assets that farmers and WfW managers highlighted as being important and that require protection in individual questionnaires (Appendix 4).

Both the questionnaires and the workshop highlighted the importance of initiating effective management of invasions at the top of catchments to prevent re-invasion after flooding of rivers, which is linked to the management of pathways (Lee and Chown, 2009; Wilson et al., 2009). However, many municipalities fall into lower catchments, which is why broad-scale prioritisation of municipalities is needed to ensure effective management and to facilitate practical funding allocations (Fig. 4a). Most of the high-priority municipalities within the asset protection zone (Fig. 4) were in the western part of South Africa (Fig. 5a). The western part of South Africa contains important watersheds in the form of three major mountain ranges (Cederberg, Roggeveld and Nuweveld), and are relatively wet in comparison to other areas *Prosopis* invaded, which gives them a greater rangeland and cropping potential. This area is also located in a global biodiversity hotspot, the Succulent Karoo) (Cowling et al., 1998). These criteria also need to be applied to produce spatial prioritisation maps at finer scales (provincial and municipal level) to better guide management implementation and budget planning at local levels (Table 1). Farm or catchment boundaries should be used to spatially prioritise areas requiring protection at finer scales based on the criteria in Table 3. An example of this is provided for the Hantam municipality (Fig. 5b) which was ranked as a "highest priority" municipality within the asset protection zone of South Africa (Figs. 4, 5a). Similar to the example for the whole of South Africa (Fig. 5a), the highest priority catchments lie to the west (Fig. 5b) for the reasons identified above. This is linked to preserving areas providing the most valuable ecosystem services. Using this prioritisation approach will ensure that limited funding is spent on most important areas, to improve the supply of ecosystem services, biodiversity conservation and improve the economic potential of the land.

3.7. Monitoring, evaluation and indicators

Monitoring and evaluation are crucial in any environmental management program or strategy (Fig. 2). They are needed to assess whether plans are being implemented correctly and are working, and to identify successes and failures and to facilitate adaptive management options (Stem et al., 2005). This has not been done in the past and is considered a major barrier hindering effective management of *Prosopis* (Shackleton et al., 2016). WfW has focused on monitoring outputs (Hectares cleared and Jobs created per project) which is short term and one dimensional. We still have no understanding on the changes in ecosystem services and livelihoods pre and post clearing.

Basic factors like *Prosopis* population size (mapping) and costs of management still need to be monitored rigorously – but there is also need for more in-depth monitoring of factors like changes in the supply of ecosystem services, livelihood vunerability and economic production, compliance with legislation, the effectiveness of different control techniques, and successes and failures of different management interventions (Table 1). Levels of awareness before and after interventions should also be assessed. Monitoring needs to be standardised at various levels and in different areas to allow for cross comparisons through the use of common indicators (Table 1). These could include the number of populations eradicated in the "eradication zone" and metrics relating to the cost and land area treated (Table 1). The level of employment is an important indicator for the WfW program, as are quantitative measures of the effectiveness of management. However, less emphasis should be placed on the former if real progress is to be made in reducing the extent and density of invasive populations. Adaptive management approaches are important, and progress in management needs to be evaluated regularly (annually) and plans updated as required (at least every 5 years) to optimise control over time (Table 1). Feedback must also be given to interested and affected stakeholders at least annually (Table 1) to promote mass buy-in and involvement.

4. Conclusions

This study has explored and provided support for the aspects that need to be considered in producing strategic and prioritisation plans for a widespread invasive tree genus in South Africa for which control to date has been largely ineffective (van Wilgen et al., 2012a, b; Shackleton et al., 2016). The strategy for *Prosopis* produced here should help to improve management success; and it is hoped that the approach followed in this paper will be useful to guide the production of similar plans for other invasive species, as required in the recent introduced NEM:BA regulations (DEA, 2014). It could also help to inform management options and approaches for *Prosopis* and other invasive trees elsewhere in the world. These strategies to manage invasive trees should help prevent the loss of ecosystem services and biodiversity in areas that are currently not invaded and help to better restore the provision of ecosystem services and improve human well-being in areas where invasions are managed.

Current approaches are not effectively controlling populations and are expensive (van Wilgen et al., 2012b; Shackleton et al., 2016). We therefore suggest key elements to improve the management of *Prosopis* in South Africa outlined in the strategy. This includes the more effective use of an integrated managed approach to reduce the spread and impacts of *Prosopis* invasions (Table 1; Fig. 2). Key elements of such an approach include the implementation of more damaging biological control (Zachariades et al., 2011; van Klinken, 2012) as well as research on the feasibility of mass-scale utilisation as a control approach. Spatial differentiation (Grice et al., 2011), involving dividing the country into smaller management units, is crucial for planning and implementing management. Important assets that need to be prioritised for control were identified, ranked and spatially prioritised, to further aid budget allocations and focus control operations in key areas to maximise the benefits of control. This also needs to be applied at finer scales as part of the strategy. Improving compliance and participation of private landowners is vital for effective management. Employing coordinators and setting up a research and monitoring program are also crucial to improve, review and adapt the management of *Prosopis* and provide evidence of the benefits of that management Implementation of this strategic plan should greatly improve the control success of this problematic invasive tree within South Africa in the future, and reduce negative effects and raise benefits.

Acknowledgements

We thank all the participants that were involved in the study for their time and insights. Funding was provided by the DST-NRF Centre of Excellence for Invasion Biology and the Working for Water Programme through their collaborative research project on "Integrated Management of invasive alien species in South Africa" and the National Research Foundation (grant 85417 to DMR; grant 87550 to BWvW).

Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoser.2016.11.022.

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