A multi-scaled, transdisciplinary study on the impacts and management of *Prosopis*, one of the world's worst woody invasive plant taxa

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Declaration

By submitting this dissertation electronically, I declare that the entirety of the work contained within is my own, original work, that I am the owner of the copyright thereof (unless to the extent explicitly otherwise stated) and that I have not previously in its entirety or in part submitted this work for obtaining any qualification.

Ross Shackleton – March 2016

Abstract

Biological invasions are a growing threat to humans and the environment globally and are a substantial problem in South Africa. The tree genus *Prosopis* is a prominent invasive in South Africa and globally. This study explores the global biogeography, costs and benefits of the genus, the conflicts of interest regarding its management and use, and the options available for management. The ecological costs of the genus, as well as social costs and benefits, are explored further using South African case studies. Perceptions of the tree and its relative use compared to native trees were also assessed across multiple stakeholder groups. This provided evidence that is needed to formulate integrated management plans. Different barriers to effective management of *Prosopis* in South Africa perceived by multiple stakeholders were assessed, and strategic and prioritisation plans were developed to guide improved management. The methods included literature reviews, vegetation surveys, questionnaires and workshops.

Various *Prosopis* taxa have been introduced into over 100 countries, and areas that are currently not invaded but which have a high risk of being invaded were identified using bioclimatic modelling. Numerous detrimental effects on biodiversity, ecosystem services, human health and livelihoods and economies were identified. Vegetation surveys showed that *Prosopis* is having a major impact on native plant biodiversity across South Africa. Increased density of *Prosopis* invasions leads to decreased native tree species richness and abundance and reduced cover of perennial shrubs and grasses. *Prosopis* is also reducing population stability through reduced recruitment and increased mortality of native trees. Reductions in the supply of water and natural grazing, roots breaking infrastructure and reductions in property value were costs identified in social surveys. *Prosopis* also provides benefits including fodder, shade and fuelwood, however, the majority of all stakeholders viewed it to have higher costs. In addition, the household use of *Prosopis* is lower than that of native trees, suggesting that native trees (which are displaced by *Prosopis*), are still more important for households.

More than 90 % of respondents would like to see a decrease in *Prosopis* population densities. However, many barriers relating to the control of *Prosopis* exist – including: lack of knowledge, lack of funding, conflicts of interest, and institutional issues such as poor communication and cooperation, mismanagement, and poor prioritisation and strategic planning. Farmers and Working for Water managers raised markedly different barriers showing differences in world views.

A management strategy for *Prosopis* was developed. It outlines different control options and details an approach for the co-ordination and monitoring of projects. It was stressed that improved biological control is needed, as is improved management on private land. The controversial "control through utilisation" approach needs further research to assess its feasibility. Management approaches (prevention, eradication, containment and asset protection) were assigned to individual municipalities go guide management. Multi-criteria decision making analysis (using Analytic Hierarchy Process) was used to identify and prioritise assets for protection at various scales. An integrated managed approach, in

particular the use of biological control along with other methods was identified as key for successful managed in the future.

Using transdisciplinary approaches, this thesis provided insights on the effects of *Prosopis* invasions in South Africa, and provided objective support for improved management. Drawing on case studies conducted in the thesis and other published material, a framework for a national strategy to guide the management of this problematic invasive tree in South Africa was produced.

Opsomming

Die teenwoordigheid van biologiese indringers is 'n groeiende bedreiging vir die mens en die omgewing wêreldwyd en is 'n beduidende probleem in Suid-Afrika. Die boom genus *Prosopis* is 'n prominente indringer in Suid-Afrika en in die wêreld. Hierdie studie ondersoek die globale biogeografie, koste en voordele van die genus, die botsende belange met betrekking tot die bestuur en gebruike, en die opsies wat beskikbaar is vir die bestuur daarvan. Die ekologiese koste van die genus, sowel as die sosiale impakte en voordele, word ondersoek met behulp van Suid-Afrikaanse gevallestudies. Persepsies van die boom en sy relatiewe gebruike, in vergelyking met inheemse bome, is deur verskeie belangegroepe geassesseer. Dit verskaf bewyse vir die formulering van geïntegreerde bestuursplanne. Verskillende hindernisse tot effektiewe bestuur van *Prosopis* is in Suid-Afrika deur verskeie belanghebbendesgeïdentifiseer en geprioritiseer. Strategiese planne vir verbeterde bestuur is ontwikkel. Die studie metodes sluit literatuurstudie, plantegroei opnames, vraelyste en werkswinkels in.

Verskeie *Prosopis* spesies is in meer as 100 lande ingevoer. Gebiede waar *Prosopis* nie tans as indringer geïdentifiseer is nie, maar waar 'n hoë risiko bestaan, is met behulp van bioklimatiese modellering geïdentifiseer. Talle nadelige impakte op biodiversiteit, ekosistemiese dienste, menslike gesondheid en voortbestaan asook ekonomieë is geïdentifiseer. Plantegroei opnames het getoon dat *Prosopis* 'n grootskaalse impak op inheemse plant biodiversiteit in Suid-Afrika het. Verhoogde digtheid van indringende *Prosopis* bome lei tot ʼn afname van inheemse boomspesies, meerjarige struike en grasse. *Prosopis* beïnvloed ook ekosisteem stabiliteit as gevolg van verhoogde mortaliteit van belangrike inheemse bome. Sosiale opnames het aangedui dat verminderde water voorsiening, afnames van natuurlike weiding, wortels wat infrastrukture beskadig en verlaging in die waarde van eiendomme teweeg gebring word. *Prosopis* bied ook voordele soos voer, skaduwee en brandhout, maar die meerderheid van belanghebbendes beskou die nadelige impakte as belangriker as die voordele. Daarbenewens is die huishoudelike gebruik van *Prosopis* minder prominent as die van inheemse bome, en is inheemse bome belangriker vir huishoudings.

Meer as 90% van die respondente wil graag 'n afname in die *Prosopis* bevolkingsdigthede sien. Daar is verskeie hindernisse vir die beheer van *Prosopis*, insluitende: 'n gebrek aan kennis, gebrekkige befondsing, ʼn konflik van belange, institusionele kwessies soos swak kommunikasie en samewerking, wanbestuur, swak prioritisering en gebrek aan strategiese beplanning. Boere en bestuurders van Werk-vir-Water, identifiseer onderskeidelik verskillende hindernisse wat dui opverskillende wêreldbeskouings.

ʼn Bestuurstrategie vir *Prosopis* is ontwikkel. Die strategie stel verskillende kontrole-opsies voor en 'n benadering vir die koördinering en monitering van projekte. Dit beklemtoon dat verbeterde biologiese beheer en bestuur van private grond benodig word. Die omstrede "beheer deur gebruik" benadering moet verder nagevors word om die haalbaarheid daarvan te bepaal. Bestuursbenaderings (voorkoming, uitwissing, beheer en bate beskerming) is aan individuele munisipaliteite gegee om leiding aan bestuur te gee. Multi-kriteria besluitnemings analises (met behulp van "Analytical Hierarchy Process") is gebruik om bates te identifiseer

en te prioritiseer vir bestuur op verskillende vlakke. 'n Geïntegreerde bestuursbenadering, wat in die besonder die gebruik van biologiese beheer saam met ander metodes voorstel, is geïdentifiseer as die sleutel tot suksesvolle bestuur in die toekoms.

Hierdie tesis verskaf insigte oor die gevolge van *Prosopis* indringing in Suid-Afrika, deur middel van transdissiplinêre benaderings, en verskaf objektiewe ondersteuning van die bestuursbehoefte. Danksy gevallestudies in die proefskrif en ander gepubliseerde materiaal, is 'n raamwerk vir 'n nasionale bestuurstrategie van hierdie problematiese indringer boom in Suid-Afrika daargestel.

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General introduction

Motivation

The increasing mobility of humans over the past few centuries has facilitated the movement of species into new areas far away from their origins. This has been done purposefully for the introduction of new crops, horticultural and forestry species as well as accidentally in ballast water and attached to exported and imported materials (Mack, 2003). The movement of organisms out of their natural habitats is one of the key drivers of human-induced global change (Vitousek et al., 1997) and is causing negative impacts on the environment and livelihoods worldwide. Invasions are a major cause of extinctions (Clavero, and García-Berthou, 2005), reduce the supply of ecosystem services such as water (Le Maitre et al, 1996), and cost the global economy over US$ 1.4 trillion per annum (Pimentel et al. 2000). However, many of these species are still used commercially and/or are important for livelihood subsistence (Moran et al., 2000; Shackleton et al. 2007: Wise et al., 2012). Species that provide both benefits and costs have often led to conflicts of interest around their use and management (van Wilgen and Richardson 2014).

Due to these conflicts of interest is it very important to better understand the benefits, costs, ecology and perceptions of invasive taxa such as *Prosopis* and Australian *Acacia* species to inform best practice management strategies to ensure negative impacts are minimized and potential benefits are maximised where this is feasible. When dealing with complex issues, such as invasive species that are both useful and harmful, leading to conflicts of interest, transdisciplinarity is important (Kueffer, 2010). Transdisciplinarity approaches research in a holistic manner applying and incorporating approaches from a variety of disciplines and incorporates various levels of knowledge from different stakeholders to address common but often complex problems (Max-Neef, 2005; Angelstam et al. 2013). Research on invasive species has primarily been ecological in nature, and management decisions are based on ecological factors (García-Llorente et al. 2009). However, the impacts and management also flow into the domains of economics and society (Kull et al. 2011). To understand and manage invasive species, insights are required from various disciplines (including economics, social and ecological studies) and all stakeholders need to be involved. This is essential for gaining a holistic understanding of the problem and potential solutions (Kueffer, 2010).

With respect to South Africa, understanding the impacts and benefits of invasions is crucial to guide management as there are complex social- ecological interactions. This is because large parts of South Africa fall within some of the most biodiverse regions of the world, and much of the country is semi-arid and invasive trees have a major impact on ecosystem services in these regions, notably water supply (Dzikiti et al. 2013). Such impacts are detrimental to biodiversity and to human livelihoods. However, at the same time there many communities that are benefiting from the utilisation of invasive species (Shackleton et al. 2007; Kull et al. 2011). Communities using invasive species are often some of the most marginalised people in the country due the historic injustice of colonialism and apartheid. This makes in-depth studies involving a range of stakeholders and disciplines important to get a holistic view of the benefits vs. the costs of these invasions and how best to manage them to ensure that livelihoods are not harmed but conservation is promoted. In addition, the newly updated regulations (2014) which fall under the National Environment Management: Biodiversity Act 2004 (NEM:BA) and require the development of national strategies to guide the management of priority invasive species – those with significant negative impacts (Department of Environmental Affairs, 2014). This thesis compiles data from numerous sources and case studies to develop the strategy for managing for *Prosopis* in South Africa.

This study investigates *Prosopis*, a tree genus that is invasive at a global scale, and that causes significant negative impacts (Pasiecznik et al. 2001). *Prosopis* is the second most widespread invasive plant taxon in South Africa after Australian *Acacia* species (Henderson, 2007). It focuses on various scales and is transdisciplinary in nature as it involves the use of techniques from various disciplines and incorporates a large number of different stakeholders (Figure i). The first five chapters of the thesis provide social-ecological evidence for the need for management (Figure A1). The last two chapters aim review barriers to management and develop a framework for a strategic plan to guide and improve management of *Prosopis* in South Africa using evidence from chapters 1-6 and other sources. This included identifying barriers that hinder management and adaptive solutions and the development of strategic plans to guide *Prosopis* management in the future to reduce costs and improve benefits (Figure A1). This is done across seven chapters, each of which is presented as a stand-alone paper. (Figure i).

Aims and objectives of the study

This project had numerous aims and objectives (Figure i) with the end goal of producing a management strategy for *Prosopis*. A transdisciplinary approach was taken, utilising ecological, social and economic techniques and many stakeholders to get a holistic understanding of the issue. This was important as *Prosopis* invasions provide both costs and benefits to humans (Pasieczink et al. 2001).

These included conducting a global review on the biogeography, invasions process, costs, benefits and management of *Prosopis* to provide a global perspective on the genus which could be used to compare and inform local management practices in South Africa (Chapter 1). As *Prosopis* is so widespread it was used as a model to understand what drives management practices on a global scale, which is useful to inform policy and management formulation. The thesis then uses South Africa as a case study to better understand the environmental and social impacts, benefits and perceptions of *Prosopis*. In this study techniques for assessing plant population stability in rare and threatened species (Quotients and Permutation Indices), were applied to aid our understanding of how *Prosopis* invasions impact the population stability of native trees. In addition numerous techniques from the social domain were applied to understand the role of *Prosopis* for different stakeholders in South Africa. Understanding the social aspects of biological invasions is still lacking considerably (García-Llorente et al. 2008), however, the recognition of its importance is growing. We investigate people's perceptions regarding *Prosopis* to guide management strategies to suit their needs. In addition, a new approach for assessing the benefits of invasive species was applied; this involved a comparative study which allowed for the calculation of the relative value of *Prosopis* compared to substitutes (native tree species).

The aims and objectives of the above studies were to provide evidence to guide management of *Prosopis* in South Africa along with other published studies. In the last two chapters the focus is on improving control of *Prosopis* through understanding barriers to management and developing a national strategy. Systematic identification and understanding of barriers hindering effective management and potential adaption and strategic responses is common in other fields such as climate change and medicine (Spires et al. 2014), but lacking in the domain of natural resource management and conservation. We therefore adopted techniques used in climate change and applied to aid understanding barriers to management for *Prosopis*. The last goal of the thesis was to produce a national strategy to improve the management of *Prosopis* in South Africa incorporating case studies from the PhD and many other sources and planning techniques. This project collated insights from multiple stakeholders to give a better and holistic understanding of *Prosopis* invasions, thereby seeking to minimize conflicts of interest which is discussed further in an additional article published in *Quest* (Figure A1). Further details are presented in the chapter synopses below.

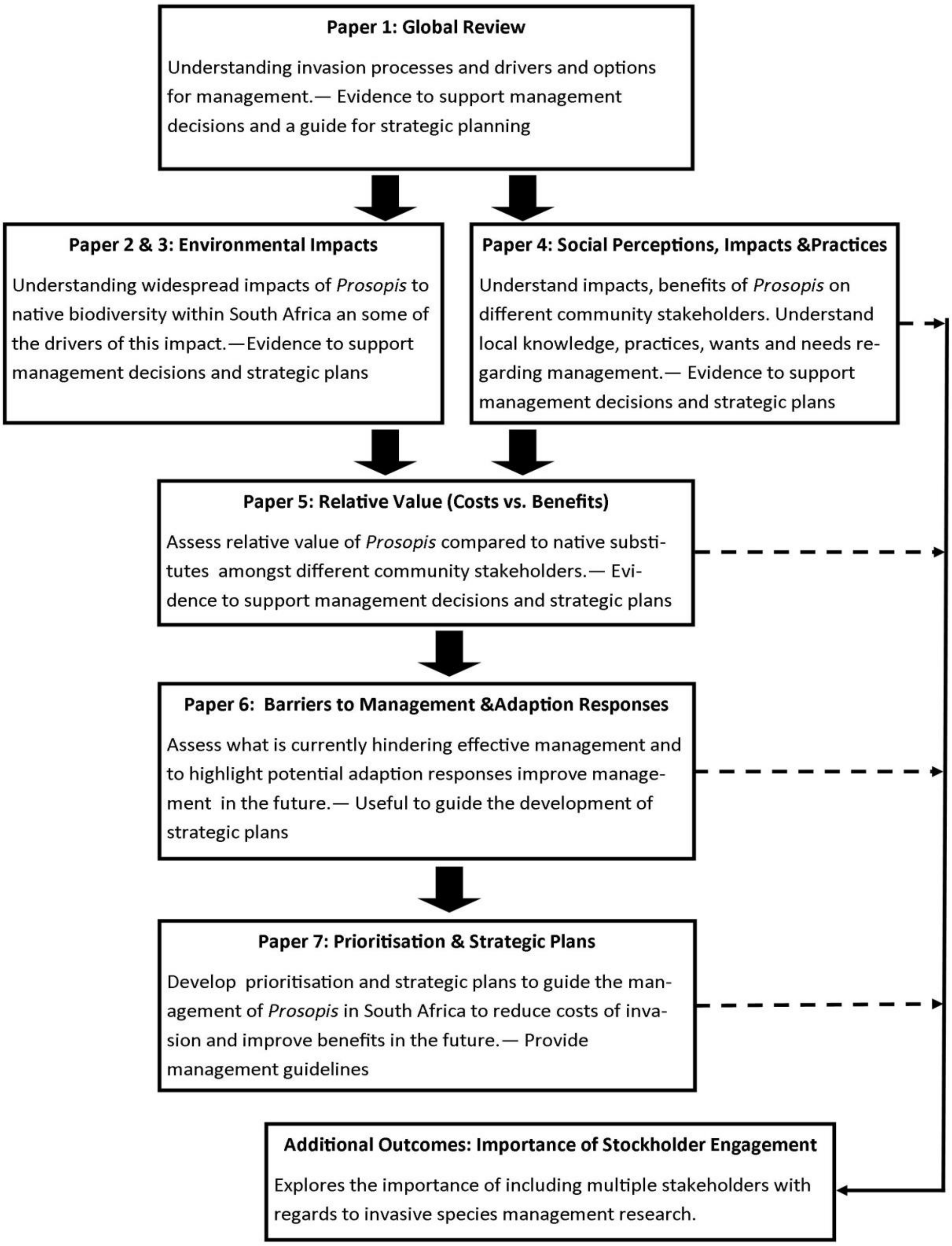

Figure i: The broad aims of each chapter and how they link together within the thesis.

Chapter synopses

The following section provides a short synopsis on the focus of each chapter and where it was published or submitted.

Chapter 1: *Prosopis*: A global assessment of the biogeography, benefits, impacts and management of one of the world's worst woody invasive plant taxa

Reference: Shackleton R.T., Le Maitre, D.C., Pasiecznik. N.M. and Richardson, D.M. 2014. *Prosopis*: A global assessment of the biogeography, benefits, impacts and management of one of the world's worst woody invasive plant taxa. *AoB Plants* 6:plu027 doi: 10.1093/aobpla/plu027.

Chapter 1 presents a global review of the genus *Prosopis*. It looks at its biogeography, introduction history, wide-scale benefits and costs, drivers of management in different countries and possible management options. It then highlights what is still needed to improve knowledge and management of this genus worldwide. This chapter provides an overview of the broad-scale trends of *Prosopis* invasions, and provides evidence for the need to manage *Prosopis* using numerous case studies from around the globe and discusses possible management options.

Chapter 2: The impact of invasive alien *Prosopis* species (mesquite) on native plants in different environments in South Africa

Reference: Shackleton, R.T., Le Maitre, D.C., van Wilgen, B.W. and Richardson, D.M. 2015. The impact of invasive alien *Prosopis* species (mesquite) on native plants in different environments in South Africa. *South African Journal of Botany* 97: 25-31.

Chapter 2 provides evidence of the negative impacts of *Prosopis* invasions on native plant species over large parts of South Africa. The results show that as *Prosopis* density increases, the cover, density and species richness of native trees, shrubs and grasses decreases. It also describes the ecology of *Prosopis* in areas with different levels of water availability. This chapter provides evidence for the need to manage *Prosopis* to reduce impacts on biodiversity and ecosystem services related to plants.

Chapter 3: *Prosopis* invasions in South Africa: Population structures and impacts on native tree population stability

Reference: Shackleton, R.T., Le Maitre, D.C. and Richardson, D.M. 2015. *Prosopis* invasions in South Africa: Populations structures and impacts on native tree population stability. *Journal of Arid Environments* 144: 70-78.

Chapter 3 provides further information on the ecology of *Prosopis* and its impacts on the population structure and stability of native tree species. It highlights how, by causing decreased recruitment and increased mortality, *Prosopis* is having a negative effect on various native tree populations where they coexist. It gives further support for the need to manage *Prosopis* to protect native biodiversity and the services that natural ecosystems provide.

Chapter 4: Stakeholder perceptions and practices regarding *Prosopis* (mesquite) invasions and management in South Africa

Reference: Shackleton, R.T., Le Maitre, D.C. and Richardson, D.M. 2015. Stakeholder perceptions and practices regarding *Prosopis* (mesquite) invasions and management in South Africa. *Ambio* 44: 529-536.

Chapter 4 looks at local knowledge, perceptions and practices regarding *Prosopis* across multiple stakeholder groups. It identifies the benefits and costs of *Prosopis*, and assesses the knowledge and willingness of people to manage the species. It also delves into the level of understanding of current management practices and the factors that shape the knowledge, perceptions and actions of different stakeholders. Results from this chapter highlight that there is currently wide-scale private management of *Prosopis*, however, further management is needed based on large social and economic costs arising from these invasions.

Chapter 5: Use of non-timber forest products from invasive alien *Prosopis* species (mesquite) and native trees in South Africa: Implications for management

Reference: Shackleton, R.T., Le Maitre, D.C., van Wilgen, B.W. and Richardson, D.M. 2015. Use of non-timber forest products from invasive alien *Prosopis* species (mesquite) and native trees in South Africa: Implications for management. *Forest Ecosystems* 2:16 DOI 10.1186/s40663-015-0040-9.

This chapter examines the relative use, at a household level, of raw materials from *Prosopis* compared to those provided by co-occurring native tree species. It highlights that the relative importance of *Prosopis* is low and that use is declining, suggesting that control measures to reduce the extent of *Prosopis* would be acceptable.

Chapter 6: Identifying barriers to effective management of widespread invasive alien trees: *Prosopis* species (mesquite) in South Africa as a case study

This chapter was submitted to *Global Environmental Change* on 7 September 2015

Chapter 6 explores the barriers that affect the management of *Prosopis* in South Africa, and the responses that could be used to improve management. Over 100 barriers were identified, including social, ecological and economic factors. It also contrasts the differences between barriers identified by different stakeholders, highlighting the fact that different stakeholders have very different views on the goals of management. These barriers were used to guide the development of the national strategy and prioritisation plans that are described in Chapter 7.

Chapter 7: Strategic planning and prioritisation for the management of a widespread invasive tree (*Prosopis:* mesquite) in South Africa

This chapter is intended for submission to *Ecosystem Services*

Chapter 7 produces strategic management and prioritisation plans for *Prosopis* in South Africa. It combines information and insights from the preceding chapters and draws additional insights from workshops and questionnaires. Decision trees were used to spatially assign management approaches (prevention, eradication, containment and asset protection) to particular areas, and multi-criteria decision making analysis was used to prioritise assets that need to be protected. These assets were, in order of importance, water, and biodiversity and to maintain agricultural and rangeland potential. The chapter presents a strategy to guide the management of *Prosopis* in South Africa and highlights needs and outcomes for management.

Additional outcomes: Stakeholder involvement: making strategies workable: future-science and society

An article in the popular science magazine *Quest* also emerged from the research conducted for this thesis. This popular article, co-authored with Dr Ana Novoa, looked at the importance of involving stakeholders in invasive species research and management using studies on *Prosopis* and cacti as case studies. This article is included as an appendix to the thesis.

Novoa, A. and Shackleton, R.T. 2015. Stakeholder involvement: making strategies workable: future-science and society. *Quest* 11: 54-56.

Chapter 1: *Prosopis*: A global assessment of the biogeography, benefits, impacts and management of one of the world's worst woody invasive plant taxa

This chapter was published in *AoB Plants*

Reference: Shackleton R.T., Le Maitre, D.C., Pasiecznik. N.M. and Richardson, D.M. 2014. *Prosopis*: A global assessment of the biogeography, benefits, impacts and management of one of the world's worst woody invasive plant taxa. *AoB Plants* 6:plu027 doi: 10.1093/aobpla/plu027.

(Please use the following link http://aobpla.oxfordjournals.org/content/6/plu027.full to access appendices)

Abstract

Invasive species cause ecological, economic and social impacts and are key driver of global change. This is the case for the genus *Prosopis* (mesquite; Fabaceae) where several taxa are among the world's most damaging invasive species. Many contentious issues ("conflicts of interest") surround these taxa, and management interventions have not yet sustainably reduced the negative impacts. There is an urgent need to better understand the factors that drive invasions and shape management actions, and to compare the effectiveness of different management approaches. This paper presents a global review of *Prosopis*, focussing on its distribution, impacts, benefits and approaches to management. *Prosopis* has been introduced to 129 countries globally and many more countries are climatically suitable. All areas with naturalised or invasive *Prosopis* species at present are potentially suitable for more taxa and many Asian and Mediterranean countries with no records of *Prosopis* are bioclimatically suitable. Several *Prosopis* species have substantial impacts on biodiversity, ecosystem services, and on local and regional economies in their native and even more so in their invasive ranges; others provide multiple benefits to local communities. Management efforts are underway in only a small part of the invaded range. Countries where more research has been done are more likely to implement formal management than those where little published research is available. Management strategies differ among countries; developed nations use mainly mechanical and chemical control whereas developing nations tend to apply control through utilisation approaches. A range of countries are also using biological control. Key gaps in knowledge and promising options for management are highlighted.

1.1 Introduction

The increased movement of humans around the world has facilitated transportation of many species to environments far from their native ranges. This has been done purposefully – to introduce new crops, horticultural and forestry species – and accidentally, for example as weed seed in grain shipments (Mack, 2003). These introductions have led to the rise of biological invasions which cause substantial ecological, social and economic impacts, and are one of the key drivers of global change (Vitousek et al. 1997; Pimentel et al. 2000). However, many alien species have been embraced by humans and are crucial for local livelihoods and national economies through the goods and services they provide (Shackleton et al. 2007; Kull et al. 2011; van Wilgen et al. 2011).

It is important to understand the dynamics of invasive species to reduce their negative impacts and maximize their benefits, but frameworks linking theory and management for biological invasions are lacking (Hulme, 2003; Wilson et al. 2014). Management is inefficient in many areas due to lack of knowledge on key aspects of the invasive species. It is crucial to understand the reasons for introductions, uses (benefits), costs, ecology and scales of invasions and to elucidate perceptions and potential contentious issues when creating sustainable management plans (Kull et al. 2011; van Wilgen and Richardson, 2014; Wilson et al. 2014). This is true for invasive species in the genus *Prosopis*.

Taxa of *Prosopis* (mesquite; Fabaceae) occur in most of the world's hot arid and semi-arid as native or introduced species (Pasiecznik et al. 2001). The genus *Prosopis* as described by Burkart (1976) consists of 44 species. They have been introduced globally and have become naturalised or invasive in many places (Rejmánek and Richardson, 2013). Several *Prosopis* species are also 'weedy' in parts their native ranges (Pasiecznik et al. 2001). In this paper we define native species as those whose presence in an area is not attributable to introduction by humans (this includes species that have spread into areas without assistance from humans by overcoming biogeographic barriers). Alien taxa are those whose presence in an area is attributable to introduction by humans. Naturalised taxa are alien taxa that are self-sustaining. Invasive taxa are naturalized taxa that have spread substantially from introduction sites (further details in Pyšek et al. 2004). We define 'weedy' taxa as native taxa that have increased in abundance and/or geographic range in their native ranges.

Numerous *Prosopis* taxa are recognised as major invaders across large parts of the world (Pasiecznik et. 2001; Brown et al. 2004). "*Prosopis*" is listed as one the 20 weeds of national significance in Australia and taxa in the genus are declared as major invasive species in Ethiopia, India, Kenya and South Africa, and Sudan is advocating for its eradication (Australian Weeds Committee, 2012; FAO, 2006; Low, 2012; van Wilgen et al. 2012). Factors that make many *Prosopis* species successful invaders include the production of large numbers of seeds that remain viable for decades; rapid growth rates; an ability to coppice after damage (Felker, 1979; Shiferaw et al. 2004); root systems which allow them to efficiently utilise both surface and ground water (to depths of more than 50m) (Nilsen et al. 1983; Dzikiti et al. 2013); and allelopathic and allelochemical effects on other plant species (Elfadl and Lukkanen, 2006). Many *Prosopis* species can also withstand climatic extremes such as very high temperatures and low rainfall, and they are not limited by alkaline, saline or unfertile soils (Pasiecznik et al. 2001; Shiferaw et al. 2004). Interspecific hybridization also enhances invasiveness in many introduced regions (Zimmermann, 1991).

Prosopis invasions generate environmental, social and economic benefits and as well as harm (Chikuni et al. 2004; Geesing et al. 2004; Wise et al. 2012). This has led to contentious issues surrounding the genus (Richardson, 1998b; van Wilgen and Richardson, 2014). Some advocates promote it as a 'wonder plant' while others call for its eradication, or contrast its positive and negative aspects, e.g. 'Boon or bane' (Tiwari, 1999), 'Pest or providence, weed or wonder tree?' (Pasiecznik, 1999), 'Invasive weed or valuable forest resource?' (Pasiecznik, 2002). Contrasting views, contradictory perceptions and unclear policies are limiting options for constructive dialogue between different parties. This is exacerbated by problems in identifying and differentiating morphologically similar species, and by a general lack of knowledge on the distribution, scale of invasion, benefits, impacts and effective management approaches. Furthermore, many different approaches for managing *Prosopis* have been tried in different situations, without a thorough evaluation of the relative effectiveness of the methods. The Food and Agricultural Organization has called for a sound, unbiased global overview of *Prosopis* to act as a prerequisite for the holistic management of the genus (FAO, 2006). Such reviews have been useful for guiding and prioritising management and improving knowledge in other groups of woody invasive plants (Richardson and Rejmánek, 2004; Griffin et al. 2011; Kull et al. 2011; Richardson and Rejmánek, 2011; Wilson et al. 2011).

The aims of this paper are thus to: (a) contrast benefits and costs of invasive *Prosopis*; (b) update knowledge on *Prosopis* occurrence and introductions globally and highlight the potential range expansion of *Prosopis*; (c) elucidate ecological, economic and social factors that shape attempts at managing *Prosopis*; (d) compare and contrast the effectiveness of different management approaches in different regions; and (e) identify priorities for research and policy development. We review the literature and collate data from many sources. Details on the approach for the literature review, approaches used for statistical analyses and climate matching are provided in ([SUPPORTING INFORMATION - File 1]).

1.2 Benefits and costs

1.2.1 Benefits, costs and invasiveness of different species

Prosopis provides benefits and generates costs which have led to contentious issues surrounding the genus (Figure 1.1). The 'usefulness' of *Prosopis* has led to the large-scale introduction of five species in particular (*P. chilensis, P. glandulosa, P. juliflora, P. pallida* and *P. velutina*) and the subsequent naturalisation and invasion of these taxa and their hybrids leading to the provision of benefits and costs in their new ranges [SUPPORTING INFORMATION, File 2]. Although *P. pallida* is invasive in many areas (Rejmánek and Richardson, 2013) it appears to be less aggressive than some other species (Pasiecznik et al. 2006).

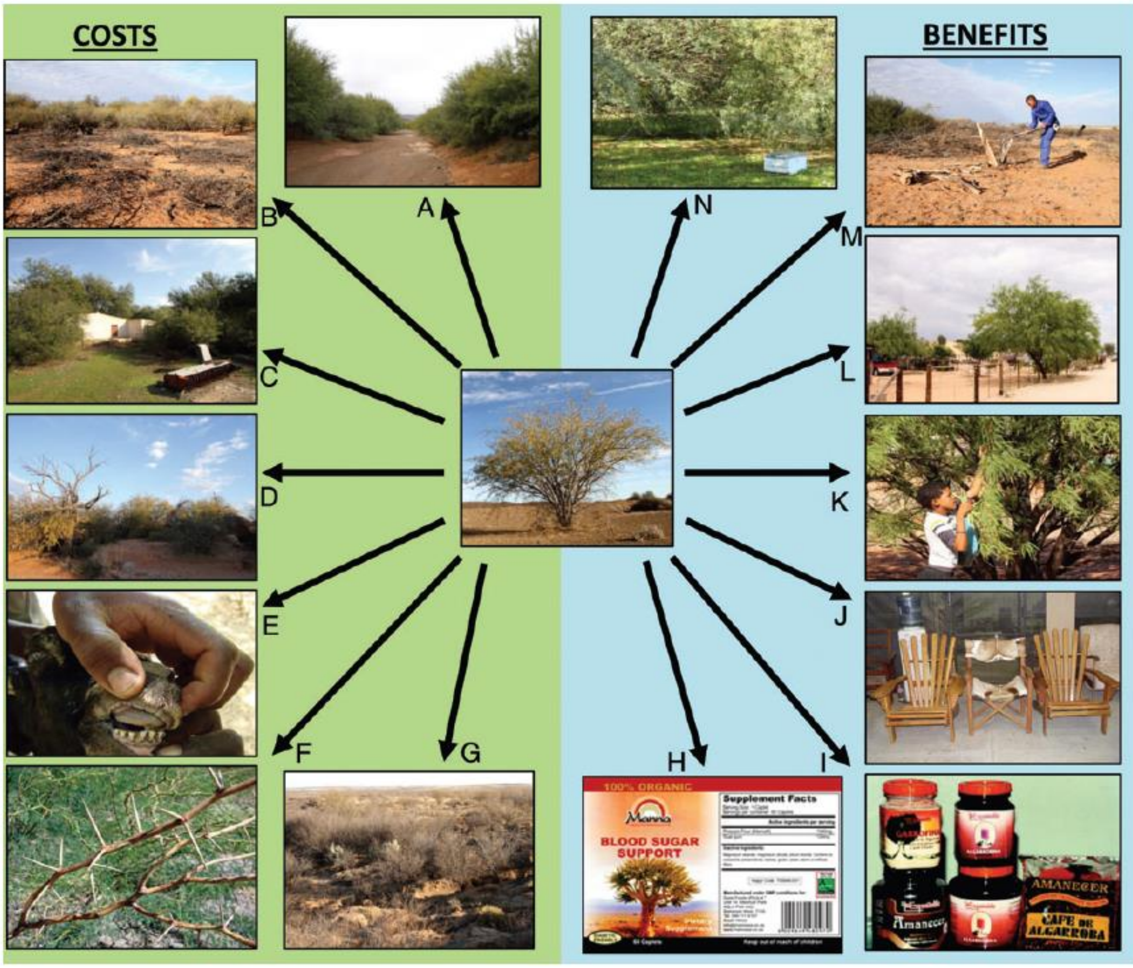

Figure 1.1: Costs and benefits of introduced *Prosopis* species: (a) Invasive *Prosopis* stand altering hydrology in Loeriesfontein, South Africa; (b) Cleared *Prosopis* in the foreground and uncleared in the background illustrating impenetrable thickets, loss of land, loss of grazing potential and the effort needed for its control in Kenhardt, South Africa; (c) Loss of access to a barn and encroachment of fields in Calvinia, South Africa; (d) The death of a native tree (*Searsia lancea*) due to competition from *Prosopis* in Kenhardt, South Africa; (e) The effects of *Prosopis* pods on a goat's teeth in Kenya; (f) *Prosopis* thorns that cause tyre damage and injure humans and livestock; (g) *Prosopis* causing loss of topsoil and erosion in Prieska, South Africa; (h) 'Manna' – a blood sugar medicine made from *Prosopis* in South Africa (www.mannaplus.co.za); (i) Food products made from *Prosopis* in Peru; (j) Timber from *Prosopis* used to make furniture in Kenya; (k) Young boy collecting *Prosopis* pods to feed livestock in Askham, South Africa; (l) *Prosopis* used for shade and ornamentation in Askham, South Africa; (m) *Prosopis* used fuel in Kenhardt, South Africa; (n) A bee hive placed in an invasive *Prosopis* stand Calvinia, South Africa. Photos: S. Choge (j); G. Cruz (i); P. Manudu (e, f); R. Shackleton (a, b,c, d, g, k, l, m, n).

Several species are also weedy and thus provide both benefits and costs in their native ranges (*P. affinis, P. caldenia, P. campestris, P. chilensis, P. cineraria, P. farcta, P. glandulosa P. hassleri, P. humilis, P. juliflora P. kuntzei, P. nigra, P. pubescens, P. ruscifolia, P.*

strombulifera P. tamarugo, P. velutina) [SUPPORTING INFORMATION, File 2]. At least 19 (invasive and weedy) of the 44 species in the genus are known to generate benefits and costs with the rest being only beneficial. The invasiveness and potential negative impacts of many *Prosopis* species is still unknown, as only a handful have been introduced.

1.2.2 Uses/benefits

Prosopis species have been used for a variety of products for more than 5000 years in their native ranges (Pasiecznik et al. 2001). The numerous goods and services provided by *Prosopis* have led to global introductions and have made some species important for local communities. *Prosopis* is commonly used for fuel, fodder, windbreaks, shade, construction materials and soil stabilisation through its invasive ranges in Africa and Asia (Pasiecznik et al. 2001; Wise et al. 2011). In some areas the benefits from *Prosopis* are, or were, regarded as a key income source for many households. In one village in Malawi, 44% of people relied on *Prosopis* products as a primary or supplementary source of income (Chikuni et al. 2004). Communities in Kenya have benefited greatly from the sale charcoal and *Prosopis* pods for fodder, boosting the local economy in some areas by US$ 1.5 million per year (Choge et al. 2012). In India, *Prosopis* provides up to 70% of fuelwood needs for local households in some dry region villages (Pasiecznik et al. 2001).

Although utilisation is most common in rural settings to sustain local livelihoods, *Prosopis* products are also exploited on a large scale by private companies. In South Africa, pods are collected to produce organic medicines (“manna”) which are said to have properties that stabilise blood sugar levels in humans. This company is making profits of US$100,000 per annum and potential increase profits ten-fold if the product is marketed internationally (Wise et al. 2012). A company in Brazil, Riocon, has an annual turnover of US$6 million a year from the sale of *Prosopis* pod flour for animal feeds (A. Davi, Ricocon, pers. comm.).

1.2.3 Negative impacts/costs

Prosopis invasions also have a variety of negative social, ecological and economic impacts (Figure 1.1 and 1.2). They alter ecosystem services such as water supply, hydrological functioning, grazing potential and soil quality (DeLoach, 1984; Bedunah and Sosebee, 1986; Archer, 1989; Le Maitre et al. 2000; van Klinken et al. 2006; Ndhlovu et al. 2011; Nie et al. 2012; Dzikiti et al. 2013;). Native biodiversity in many parts of the world has also been negatively impacted by invasive *Prosopis* species (Steenkamp and Chown, 1996; Dean et al. 2002; El-Keblawy and Al-Rawi, 2007; Belton, 2008; Kaur et al. 2012).

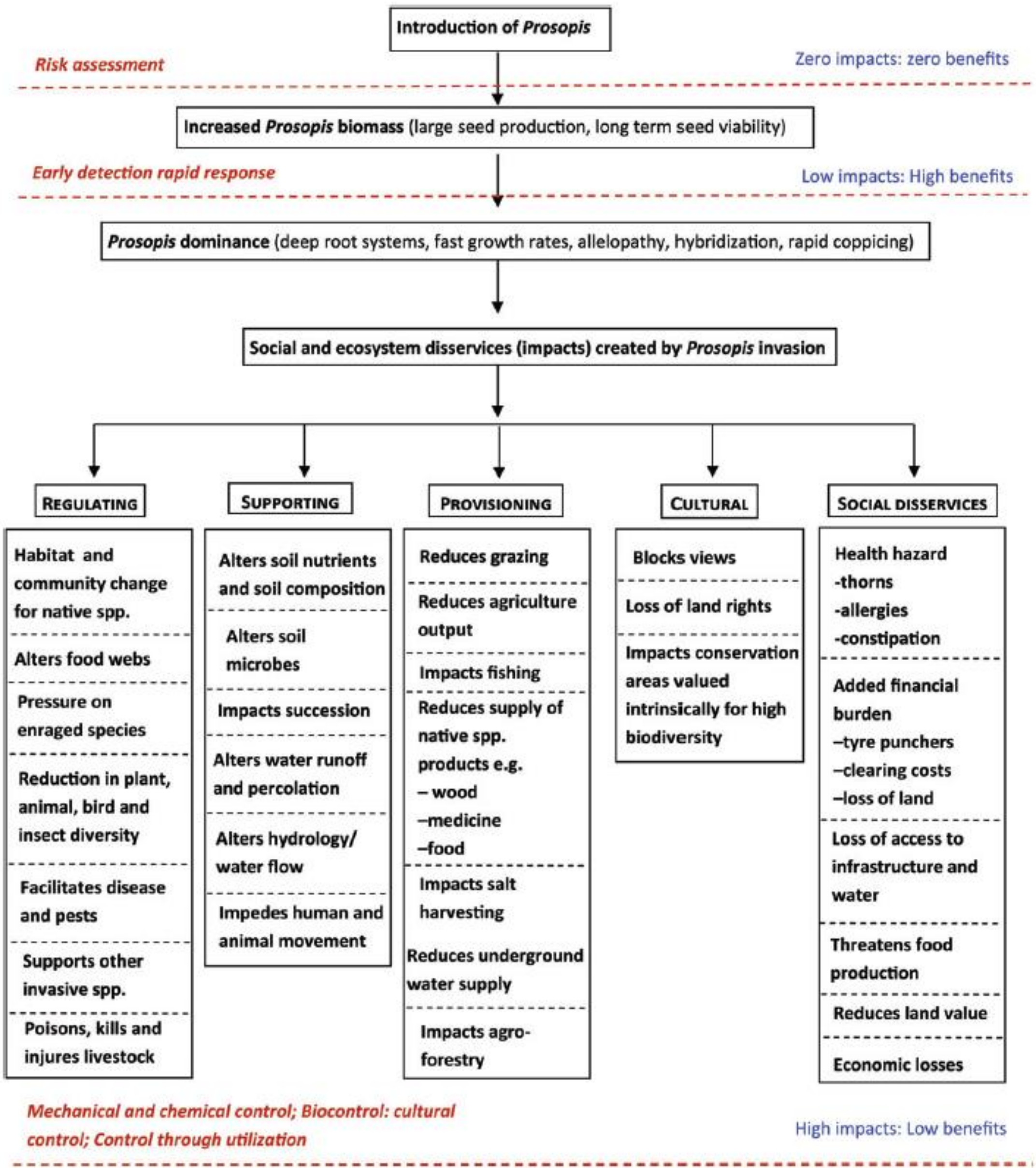

Figure 1.2: Cause-and-effect network diagram showing the negative effects of *Prosopis* invasions and management options that can be used to target each stage of invasion.

Local communities in Kenya, Sudan, Eritrea, Malawi and Pakistan noted a range of negative consequences arising from invasive *Prosopis* (Choge et al. 2002; Chikuni et al. 2004; Mwangi and Swallow, 2005; Laxén, 2007; Bokrezion, 2008; Kazmi et al. 2009). These included, effects on livestock health, *Prosopis* thorns causing tyre punctures and flesh wounds, dense thickets reducing access to water points, roads, infrastructure and agricultural and range lands, drying up of water sources, reducing natural forest cover and the services from these forests, as well as providing refuge for thieves.

In many parts of Africa *Prosopis* invasions are a leading cause of detrimental impacts on local community structure and functioning, leading to an increase in their vulnerability. This includes the potential loss of land rights for local livestock herders in Mali and violent conflict over limited natural resources between neighbouring communities in Ethiopia and Kenya (Centre for Sustainable Development Initiatives, 2009; Djoudi et al. 2011; Stark et al. 2011). One Kenyan community has even taken the FAO and the Kenyan government to court over the harm created by the introduction of *Prosopis* (Pasiecznik et al. 2006a). Native weedy *Prosopis* taxa are also estimated to cause a loss of US$ 200-500 million per annum to the livestock industry in the USA (DeLoach, 1984). In South Africa costs of managing *Prosopis* invasions are substantial averaging $ 35.5 million per annum (van Wilgen et al. 2012).

1.2.4 Benefits vs. costs and the dimensions of contentious issues

Perceptions and benefits and costs of invasive alien species are strongly influenced by invasion abundance (Binggeli, 2001; Shackleton et al. 2007). As abundance increase associated costs rise and benefits fall due to issues such as resource accessibility (Wise et al. 2012). In India, *Prosopis* was initially seen as beneficial, but over time the negative consequences became more apparent, leading to increasingly negative perceptions of the plant from some quarters (Pasiecznik et al. 2001). A similar situation arose in Kenya where, as *Prosopis* became invasive, it was described as a 'bad omen' by some local people (Choge and Chikamai, 2004) and more than 65 % of people in three villages mentioned that their lives would have been better off if *Prosopis* was never introduced (Maundu et al. 2009). In Sudan, over 90 % of livestock farmers viewed *Prosopis* as a problem as it became more widespread (Elsidig et al. 1998).

In many areas, invasive *Prosopis* trees do not sustain their full use potential due to intraspecific competition in dense stands which, generally, form over time. In such cases relatively few pods are produced for fodder and human consumption and dense invasive stands become impenetrable for humans and livestock making utilisation of resources difficult (Chikuni et al. 2004; Mwangi and Swallow, 2005). Wise et al. (2012) show that net economic benefits decrease as invasion densities increase in South Africa. They predict that the net cost of having *Prosopis* in the country will become negative in 4-20 years depending on future rates of spread. A framework by Shackleton et al. (2007) also shows that useful invasive aliens initially have high benefits, but as invasion densities increase, costs rise which lead to an increase in human vulnerability. This raises questions about the introduction of 'miracle' species in the past such as *Acacia*, *Leucaena* and *Prosopis* because the adverse impacts tend to exceed the benefits as the invasions progress, if left unmanaged (Pasiecznik, 2004, de Wit et al. 2001; Wise et al. 2011; Low, 2012). As well as and the continued promotion of invasive alien species like *Prosopis* for biofuels today (Witt, 2010; Naseeruddin et al. 2013).

The fact that the detrimental effects emerge only after invasions have reached unmanageable levels exacerbates contentious issues surrounding invasive species and may delay management decisions, in many cases restricting the implementation of effective management. There have also been conflicts of interest regarding which form of management to implement – how best to preserve, exploit and even enhance benefits while reducing negative impacts of *Prosopis* invasions (Zimmermann 1991).

1.3 Introductions, current and potential distributions of *Prosopis*

1.3.1 Introductions

Dates and sources of introduction: Intercontinental introductions of *Prosopis* species have occurred over several centuries (Figure 1.3). The first reports were of the introduction of *Prosopis* species from the Americas to Senegal in 1822, and to Australia, Hawaii, India, Philippines, South Africa, Sri Lanka and Sudan in the late 1800s and early 1900s (Pasiecznik et al. 2001). However, most of the widespread introductions were made into Africa and Asia between the 1970s and 1990s (Figure 1.3) as part of reforestation programmes after major droughts in Sahel. Many areas, notably India, South Africa and Sudan, have had multiple introductions over many decades. There is no evidence of new introductions post 1990 with the last recorded introductions being in Malawi and Burkina Faso in 1986 (Ræbild et al. 2003; Chikuni et al., 2004). There have, however, been recent calls for the introduction of known invasive *Prosopis* species to new locations. Hasan and Alam (2006) recommend that the planting of *Prosopis* would be beneficial to combat degradation in Bangladesh. Pravesh (2011) proposed using *Prosopis* to stabilise dunes to protect important biologically diverse wetlands and mangrove forests in Iran. The promotion of biofuels could also lead to the spread of invasive woody species such as *Prosopis* (Witt, 2010). There has also been extensive natural spread (commonly by means of flood water) and human assisted spread (livestock trade) into new areas within countries where it is already naturalised and invasive (Van den Berg, 2010).

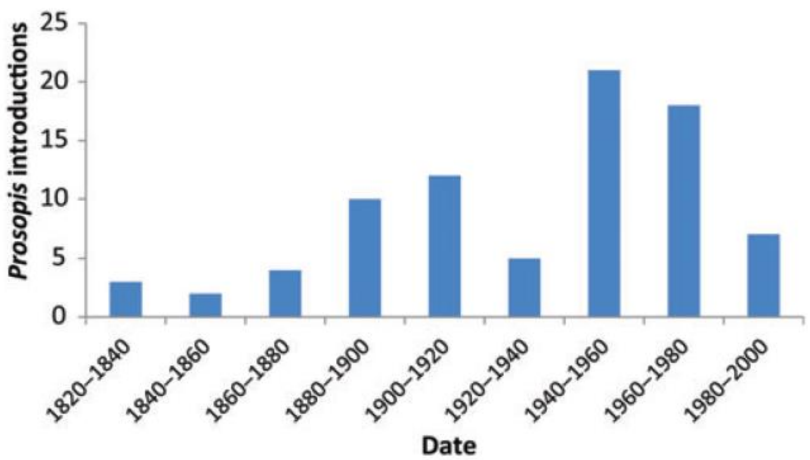

Figure 1.3: Time scale of all *Prosopis* introductions globally (n = 82 known species-country introduction dates)

Seed introductions have come from both native populations and from naturalised and invasive populations in countries where *Prosopis* was introduced previously. However, the original sources of seed and dates for introductions to many countries are poorly documented. Seed introduced to Hawaii came from a tree in France with a speculated provenance in Brazil (Pasiecznik et al. 2001) and *P. pallida* introduced to Australia came from Hawaii (Pasiecznik et al. 2001). South Africa had multiple introductions of many species and seed was most likely introduced from native ranges in Chile, Honduras, Mexico and USA (Zimmerman, 1991). Seed from naturalised populations in South Africa was introduced into Egypt and seed introduced into Sudan came from South Africa and Egypt (Pasiecznik et al. 2001). The provenance of early *Prosopis* introductions to India is uncertain (likely Mexico or Jamaica); later introductions came from Argentina, Australia, Mexico, Peru and Uruguay (Pasiecznik et al. 2001).

Reasons for introduction: Most introductions of *Prosopis* were intentional, although there have been accidental cross-border introductions between neighbouring counties. *Prosopis* was introduced for many reasons, including: to provide fodder and shade in the arid areas of South Africa and Australia; for dune stabilization, afforestation and fuel wood supply in Sudan; for live fencing in Malawi; initially to rehabilitate old quarries and later for afforestation and the provision of fuelwood and fodder in Kenya; for fuelwood production and rehabilitating degraded soil in India; for local greening, ornamental cultivation and soil stabilization in many Middle Eastern countries and for vegetation trials in Spain (Zimmermann, 1991; Ghazanfar, 1996; Pasiecznik et al. 2001; Choge et al. 2002; Chikuni et al. 2004; Elfadl and Luukkaen 2006; van Klinken et al. 2006; Laxén, 2007; N. Pasiecznik and E. Peñalvo López, unpubl. data). *Prosopis* was possibly first introduced unintentionally into Botswana, Nigeria and Yemen through livestock trading with neighbouring countries (Pasiecznik et al. 2001; Geesing et al. 2004).

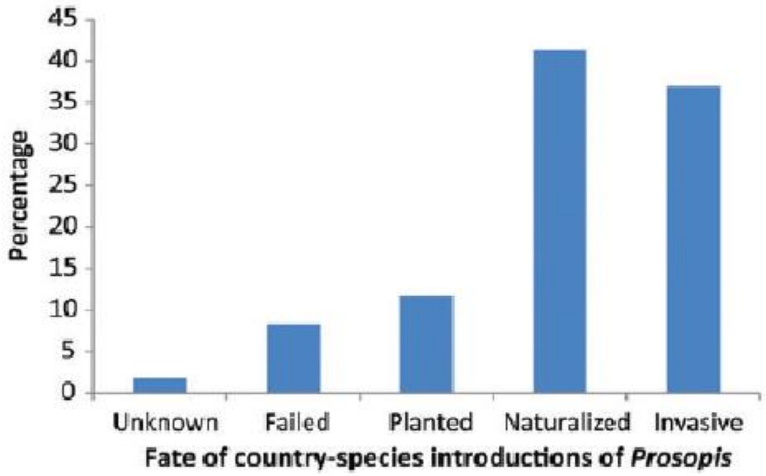

Figure 1.4: Classification of all records of introduced *Prosopis* species (236 introductions in 103 countries); classification of "naturalised" and "invasive" follow the criteria of Pyšek et al. (2004).

Fate of introductions: Of all the introductions of *Prosopis* species reviewed here, 79% have led to naturalisation, of which 38% have become invasive (Figure 1.4). No information on naturalisation is available for 8% of records, and 2% of introductions are known to have failed (i.e. did not survive planting). Currently 12% of introductions are only recorded as "planted".

1.3.2 Distribution

Prosopis currently occurs naturally or as an introduced species in at least 129 mainland and island countries and territories (Figure 1.5; [SUPPORTING INFORMATION - File 2]). This includes the Caribbean islands (18) and mainland counties (19) in the Americas (excluding Canada, Suriname and Guyana), 40 countries in Africa, 26 in Asia, 4 in Europe, 24 island/atolls countries in the Pacific, Atlantic and Indian Oceans and Australia.

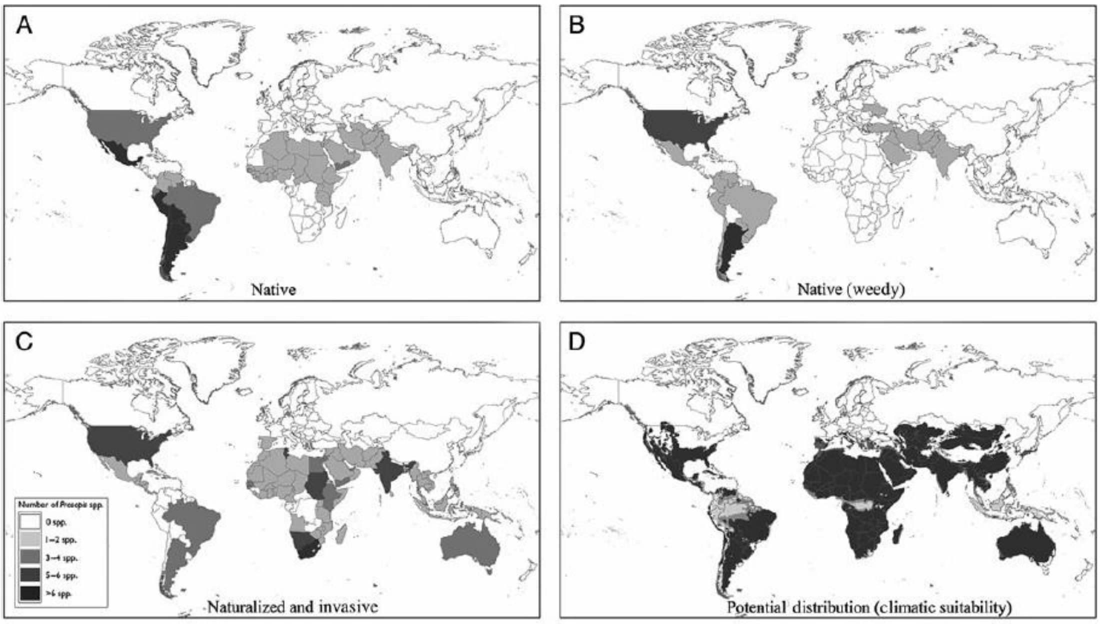

Figure 1.5: The global distribution of *Prosopis* species: a) species diversity in countries with native taxa; b) species diversity of taxa recognized as being weedy within their native ranges; c) species richness of naturalised and invasive *Prosopis* taxa (following the criteria of Pyšek et al. 2004) and (d) potential *Prosopis* species richness based on climatic suitability.

The last comprehensive global review of *Prosopis* distribution listed the presence of taxa in 93 mainland and island/atoll countries (Pasiecznik et al. 2001). It is unlikely that *Prosopis* has been potentially introduced into more places in the 13 years since that review was undertaken, but rather that data availability has increased in the intervening period or that there has been unintentional spread e.g. into Tanzania. Of the 129 countries, 26 have only native species, 64 have only introduced *Prosopis* species, and 39 have both native and introduced species. *Prosopis* is weedy in 38% of countries where it occurs naturally and 38% of species in the genus are currently categorised as weedy in their native ranges. The distribution and scale of invasions in countries with invasive *Prosopis* are not well known, with only 13 % of countries having detailed distribution or percentage cover data and not just records of occurrence.

1.3.3 Potential Distribution

Climate matching was used to assess areas of potential naturalisation and invasion (Peel, 2007). We identified many regions that are climatically suitable for *Prosopis* where there are currently no records of any taxa (Figure 1.5(d)).This includes in countries in Europe (Greece, Italy, Portugal, Romania etc.), South America (Guyana and Suriname), Asia (China, Japan, Nepal and South Korea etc.) and numerous island/atoll countries and overseas territories (Comoros, Malta, Solomon Islands, Timor-Leste etc.) (Figure 1.5(d); [SUPPORTING INFORMATION – File 3]). All countries where at least one *Prosopis* species has been introduced and has established have the potential for the naturalisation of additional *Prosopis* species. For example, there are currently seven naturalised and invasive *Prosopis* species recorded in South Africa, but the country is climatically suitable for many more species [SUPPORTING INFORMATION File 2 and 3]. Maundu et al. (2009) also illustrated a high climatic suitability for *Prosopis* in southern and eastern Africa and showed there are many areas that could have invasions but currently do not.

1.4 Management of *Prosopis*

Naturalised and/or weedy *Prosopis* are reported in 112 countries. Currently 23 countries with weedy or invasive *Prosopis* (21%) implement some form of formal management. No countries rely exclusively on biological control, six (26%) use only mechanical or chemical control, five (22%) use control through utilisation, and 11 (48%) apply an integrated approach (three or more methods, including biological control, mechanical control, chemical control, control through utilisation and cultural control) (Table 1.1 and 1.2).

Table 1.1: Logistic regression highlighting the importance of different ecological, economic and social factors in determining management of *Prosopis* within a country.

Explanatory variable	Nagelkerke R Square	Predictions- % correct	Wald Stat	p-value
No. introduced Prosopis spp.	0.540	84.3	13.04	0.000
Source of introduction known	0.234	70.0	4.815	0.999
Time since introduction	0.009	47.1	0.275	0.626
Use level	0.103	67.1	4.19	0.242
Distribution and extent of Prosopis cover known	0.616	81.4	7.087	0.069
Level of Prosopis impacts	0.685	87.1	19.638	0.000
No. of publications relating to Prosopis	0.960	88.6	20.765	0.000
Overall knowledge of Prosopis invasions	0.686	92.9	16.993	0.005
GDP per capita	0.013	65.7	0.680	0.410
Human development index	0.041	68.6	0.324	0.569

Countries that use only chemical and mechanical control are mainly found in the Middle East and have small isolated invasions and are usually wealthier nations, whereas control through utilisation is applied in poorer countries such as Kenya and Ethiopia. Biological control is driven by Australia and South Africa, however, there are also areas where ‘biological control agents’ are present but were not deliberately introduced, for example, Egypt (seed feeding beetles -Coleoptera and Burchidae), Sudan and Yemen (*Algarobis prosopis*) (Delobel and Fediere, 2002; Al-shurai and Labrada, 2006; Babiker, 2006). In Yemen there is no evidence that the non-native A. *prosopis* feeds on the native *Prosopis* cineraria (Al-shurai and Labrada, 2006). There are concerns, however, that introduced insects could affect less invasive *P. pallida* populations in these areas which are utilised by local communities (Pasiecznik et al. 2006). Another view is that any effect of such insects could improve the usefulness of less invasive taxa by reducing seed production and therefore potential invasiveness and could lead to less dense stands with larger trees and greater pod production (Zachariades et al. 2011).

Logistic regressions were run to determine what factors underpin whether a country has formal management of *Prosopis* taking place or not. The degree of understanding of *Prosopis* invasions impacts and ecology (besides residence time - the time since introduction) is a better determinant of whether or not a country will manage *Prosopis*, than the socio-economic conditions of the country (Table 1.1). The stepwise regression reviled that level of impacts and overall knowledge on *Prosopis* invasions are key determinates of the presence of management within a country or not. Having knowledge on invasion potential/risk either allows countries to act timeously or to develop protocols to guide management based on an overall understanding of impacts, ecology, uses and special scales. Having a good understanding surrounding *Prosopis* invasions also helps to highlight the need for management, and subsequent management also stimulates the accumulation of further knowledge on invasions. Residence time might not be a significant predictor, because in wetter areas invasions tend to establish much faster than in drier areas (Table 1.1). Also, all countries have had *Prosopis* long enough to have naturalised and invasive populations (Zimmermann et al. 2006).Simple socio-economic variables are poor predictors of the existence of management strategies as there is evidence of management in countries at all levels development (Table 1.1). Many of the poorer countries receive foreign aid to implement and run management programs, at least at the outset.

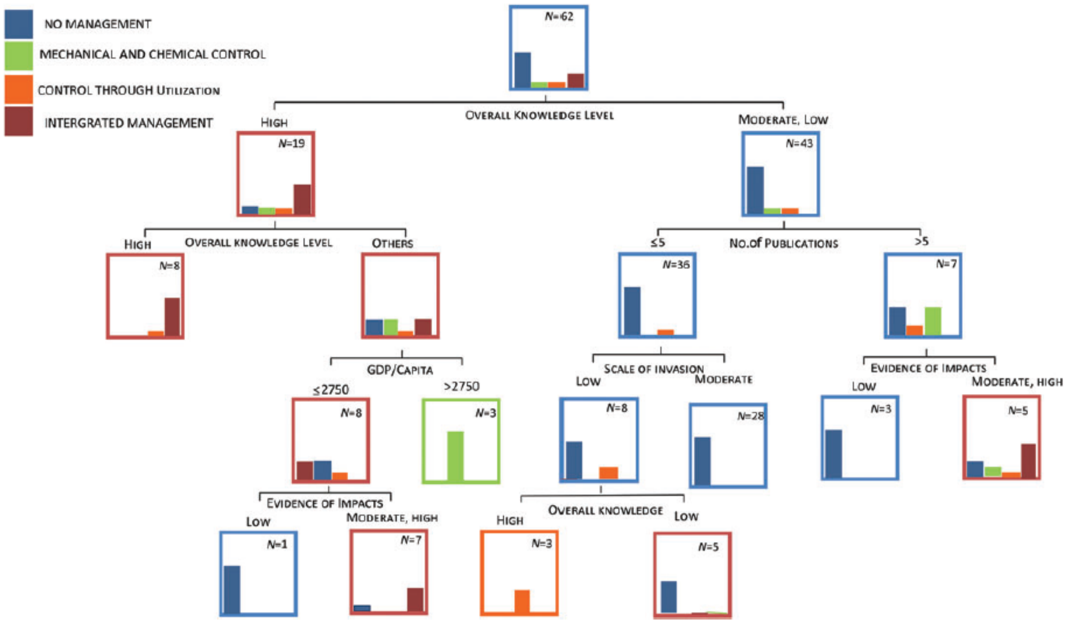

Figure 1.6: A classification and regression tree model using social, ecological and social variables to explore the drivers of different types of *Prosopis* management globally.

The findings of this review contradict previous publications that have argued that less developed countries have conducted less research and management of invasive alien species (McNeely et al. 2005; Pyšek et al. 2008; Nuñez and Pauchard, 2009; McGeoch, et al. 2010). Some developing countries are at the forefront of *Prosopis* research and management such as Kenya (control through utilisation, social impacts) and South Africa (biological control), along with developed countries such as Australia and the USA. Witt (2010) noted that the prominence and severity of the impacts of *Prosopis* in developing countries has motivated this investment in research and understanding. However, there may be a lack of research for less prominent invasive alien species in poorer regions of the world.

The classification and regression model highlights the factors that underpin what management approaches counties are likely to adopt (Figure 1.6). Similar to the regression output, the overall level of knowledge of *Prosopis* is an important factor when predicting what management approach or technique a country will adopt (Figure 1.6). Countries with a good understanding of *Prosopis* based on the number of publications and the diversity of published materials have a higher chance of having some form of management and in general this takes the form of integrated management. The level of development of a county, indicated by GDP per capita, also influences the type of management approach a country is likely adopt. Wealthier countries are more likely to implement mechanical and chemical control methods which are the most costly but also currently the most effective options. Middle-income countries most commonly implement integrated management, whereas poor countries predominantly adopt control through utilisation for managing *Prosopis*.

Table 1.2: A comparison of techniques for managing *Prosopis* and their advantages and disadvantages.

Control type	**Advantages**	**Disadvantages**
Biological control	*Relative inexpensive once implemented *Works over large areas, including areas that are inaccessible for mechanical control * Minimal associated costs after biocontrol is released (monitoring is required)	*Biocontrol agents have not yet had substantial impacts on reducing stand density or extent of invasions and rates of spread in some areas such as (South Africa) but have been more successful in places like Australia *Initial research is costly *Potential to spread across borders unintentionally *Inapplicable in areas where native *Prosopis* is weedy *Conflicts of interest around the use of biological control in areas where *Prosopis* invasion are seen as beneficial (e.g. South Africa; Kenya)
Mechanical control	* Efficient at removing *Prosopis* over large areas	*Costly technique * Labour and capital intensive
Chemical control	* Efficient at removing *Prosopis* over large areas	*Costly technique * Labour and capital intensive
Utilisation	* Maximize on benefits to be had from biological invasions * Promote rural social-economic development * Reduces overexploitation of native spp. * Profits counteract management costs	Encouraging utilization may create dependency on the species, thereby exacerbating conflicts of interest Some areas have lower value *Prosopis* spp. (more thorny, bitter pods, shrubby forms) making utilization more difficult Many *Prosopis* invasions are in remote areas making large scale utilisation difficult
Cultural control/Other control (e.g. fire, grazing and livestock transport management)	* Low costs *Can also prevent other types of degradation	*Requires people to change perceptions * Large scale education programmers are needed * Does not always work for all *Prosopis* spp. – e.g. *fire tolerant hybrids* * Not applicable in all areas e.g. *places with low biomass and fire tolerant hybrids*

The advantages and disadvantages of these approaches differ (Table 1.2), and are closely linked to the costs of the control method. For example, countries with limited invasions are more likely to use mechanical and chemical control, whereas those with large-scale invasions are more likely to adopt an integrated approach, as purely mechanical and chemical control becomes too costly (van Klinken et al. 2006). Control through utilisation aims to aid local development while simultaneously controlling *Prosopis* impacts and is therefore promoted in poorer parts of the world.

1.4.1 Contentious issues surrounding invasive Prosopis taxa and their management

The benefits and impacts and choice of different management approaches of *Prosopis* have led to contentious issues regarding management. Control through utilisation is advocated by some to enable benefit supply of invasive *Prosopis* while simultaneously reducing the negative impacts of invasions (Choge and Chikami, 2004). However, many believe that this approach is inefficient at reducing invasions and leads to other problems such as dependencies (Table 1.2) (van Wilgen et al. 2011) and that other approach such as chemical and mechanical clearing should be prioritised, although they are costly (Witt, 2010). To date there is no evidence of the success of control through utilisation as a management technique (Table 1.2). The control through utilisation approach is motivated around local development (which is needed) more so than managing invasions at large spatial and temporal scales.

There are conflicting views on best management approaches (eradication vs. control through utilisation) in different villages in Kenya (Mwangi and Swallow, 2005; Njoroge et al. 2012). Similar cases of contentious issues and conflicts of interest have been seen for other management approaches such as biological control. In South Africa only seed-feeding beetles were introduced so that neither the *Prosopis* trees themselves nor the production of pods would be harmed (Richardson 1998a) - even though better biological control agents have been identified that would harm trees and be more effective in reducing invasions (Zachariades et al. 2011).

1.4.2 Case studies comparing different management approaches

Despite the growing body of research on management options for weedy and invasive *Prosopis* stands (van Klinken et al. 2006), there is an ongoing debate about how to effectively manage large-scale invasions. Different approaches are currently being used to manage *Prosopis*, each with their own set of advantages and disadvantages (Table 1.2). The following case studies were selected as being representative of different management strategies and also encompass the approaches most commonly employed in countries with different levels of socio-economic development (developed - Australia; emerging economies - South Africa; developing - Kenya). The case studies are also characteristic of management strategies driven and implemented by different stakeholders, e.g. government driven with mainly private implementation (Australia), mainly government driven and implemented (South Africa) and government driven with some NGO and international support (Kenya).

Australia: *Prosopis* has invaded over one million hectares and could potentially spread over 70% of Australia's land area (Osmond, 2003). *Prosopis* taxa are considered as one of the 20 worst invasives in Australia, and in accordance with the Weeds Management Act 2001, a strategic plan has been developed to guide management (Australian Weeds Committee, 2012). *Prosopis* is a declared weed in all the mainland states and 1 territory in Australia and have been categorised in accordance to the threats they pose and the corresponding management responses that need to be implemented (van Klinken and Campbell, 2009). This includes preventing introductions, trade, sale or movements of *Prosopis* taxa and the eradication of small populations and control of large populations (Australian Weeds Committee, 2012). In general, most landowners use mechanical and chemical control measures to manage *Prosopis*. Although control and eradication programmes are primarily funded by the state, many private land owners also fund management operations. For example, in Queensland $A 4 million was allocated for *Prosopis* management by the government which was supplemented further by over $A 600 000 by landholders between 1995 and 1999 and over $A 2 million was spent on clearing between 2001 and 2005 (Martin and van Klinken, 2006).

Control of *Prosopis* first started in 1954 at Mardie Station, Western Australia, and by 1962 a major reduction in *Prosopis* density had been achieved. Populations increased again when funding diminished but in the mid-1970s the allocation of government funding led to substantial progress with clearing (van Klinken and Campbell, 2009). In other areas of Western Australia control was improving but after funding lapsed many infestations returned in 1990s with exceptions of some areas such as Yeeda Station where control has been successful due to annual monitoring and clearing (van Klinken and Campbell, 2009). In Queensland substantial funding was invested for clearing in the area around Comongin Station and by 2005 over 4 000 ha of dense *Prosopis* stands had been removed (van Klinken and Campbell, 2009). In northern Queensland research concluded that eradication was feasible in the region and significant steps have been made towards this goal (van Klinken and Campbell, 2009). New South Wales and South Australia have similar examples of good control efforts and others that have had limited success due to a laps in control and monitoring (van Klinken and Campbell, 2009).

Four biological control agents have been released in Australia: *Algarobius bottimeri* and *A. prosopis* (seed-feeding bruchids), *Evippe* species (a leaf-tying moth) and *Prosopidopsylla flava* (a sap sucker) (van Klinken et al. 2003; van Klinken, 2012). Two have established widely (*A. Prosopis, Evippe* species) and the latter has had noticeable impacts on *Prosopis* populations through reducing long-term growth rates (van Klinken, 2012). Biological control in Australia has been more successful than other places like South Africa and the benefit to cost ratios are positive (0.5), with expectations to increases in the future (Page and Lacy, 2006). The release of more agents is recommended to further improve control (van Klinken et al. 2003; van Klinken, 2012).

Experiments have shown that some species are highly fire tolerant (especially the hybrids) which reduces the potential for using fire as a control method in many areas (van Klinken, 2006). Grazing control has also been advised to help prevent establishment and further spread of *Prosopis* (Csurhes, 1996), although this approach has had limited success in Argentina and the USA (Brown and Archer, 1989; Dussart et al. 1998). There are also regulations on the transport of livestock in areas infested with *Prosopis* to prevent its spread and accidental introduction elsewhere in Australia (Australian Weeds committee, 2012). Management policy is backed up by good legislation; Australia is one of two countries with a national management strategy. The government has also published many easily accessible documents on *Prosopis* management methods to inform landowners regarding control measures, and the *Prosopis* strategic plan places a lot of emphasis on educating and making stakeholders aware of *Prosopis* invasions and how to manage them (Australian Weeds Committee, 2012). There have been rewarding examples of control success (van Klinken and Campbell 2009); although *Prosopis* populations continue to spread and in many areas and further management is needed.

South Africa: *Prosopis* invasions in South Africa cover an estimated 1.8 million ha, are increasing at 8% per annum (Versfeld et al. 1998; Van den Berg, 2010). They have the potential to invade between 5 and 32 million ha of South Africa based on climatic suitability - about a third of the area of the country (Rouget et al. 2004). *Prosopis* is declared as a category 3 invasive alien species because it provides benefits and causes harm; this status means that it is legal to grow *Prosopis* in demarcated areas once a permit has been issued. A combination of mechanical, chemical and biological control methods are used to control *Prosopis*, mainly by the government-managed Working for Water programme. Three seed-feeding beetles (*Algarobius Prosopis*, *A. bottimeri* and *Neltumius arizonensis*) were introduced as biological control agents to try and reduce spread while maintaining its benefits – with *A. bottimeri* failing to establish (Zimmermann, 1991; Coetzer and Hoffmann, 1997; Zachariades et al. 2011). Although biological control is considered the most cost effective way of managing large-scale invasions of many species, there are many cases where the agents fail to make a significant impact and *Prosopis* is one of them (van Wilgen et al. 2012). The overall return on investment is low compared to biological control programmes for Opuntia species and Australian acacia species in South Africa (van Wilgen et al. 2012). There is potential to release more agents, such as the *Evippe* species which is already successful in Australia (see above), should the contentious issues surrounding the benefits and costs of *Prosopis* be resolved (Zachariades et al. 2011). *Prosopis* cover increased by approximately 35% between 1996 and 2008, despite the expenditure of R 435.5 million (US$ 42.7 million) on control over this period. Only 15,100 ha were cleared using mechanical and chemical control with this substantial budget (van Wilgen et al. 2012), which makes the cost/ha very expensive (US$ 2,828). The limited success to date may be due to lack of a management strategy and of prioritisation of management projects (Forsyth et al. 2012). There is need for researchers, managers and policy makers to agree on new strategies for prioritising areas for interventions to curb the spread of *Prosopis* and to ensure that the limited resources are used effectively (Forsyth et al. 2012). There have been some attempts at controlling *Prosopis* through utilisation, but they had no noticeable impacts on invasions, and these initiatives failed as input and transport costs were too high and financial returns were low (Zimmermann et al. 2006). South Africa also has many particularly aggressive hybrids that form dense shrub-dominated stands, which makes the utilisation approach difficult (Zimmermann et al. 2006).

Kenya: *Prosopis* is estimated to have invaded one million hectares and has the potential to invade nearly half of Kenya's surface (Maundu et al. 2009; Witt, 2010). It was declared a noxious weed in 2008 (Low, 2012). Biological and mechanical control were initially proposed as the management approach to combat *Prosopis* invasions, but the government later opted for a control-by-utilisation approach (Pasiecznik and Felker, 2006b; FAO, 2006). The Food and Agricultural Organization (FAO), with support from several NGOs, initiated programmes to manage *Prosopis* through utilisation. These efforts were continued by the government's forestry department and forestry research organisation (KEFRI) following the end of these projects. Considerable time and effort was taken to build capacity, formulate good policies, and educate communities to utilise the goods and services from *Prosopis* (Pasiecznik et al. 2006a). For example, small-scale utilisation projects were established and a cookbook using *Prosopis* flour was created and supplied to communities to promote its use (Choge et al. 2006; Pasiecznik et al. 2006a). Although there are initial costs for training and purchasing appropriate small-scale processing machinery are high, they are considered to be lower than other control approaches (Pasiecznik et al. 2006a). In 2002, trade in *Prosopis* goods and services was worth US$ 2,122 per household per year in some villages (Choge et al. 2002). Ten years later, trade in *Prosopis* products in four selected areas was estimated to exceed US1.5 million (Choge et al. 2012). Each tonne of pods that are collected and milled into flour is estimated to remove approximately two million viable seeds (Pasiecznik et al. 2006a). Changes in legislation, and the promotion of *Prosopis* use, helped drive the substantial rise in use and led to 100% of the locals in one village supporting control through utilisation to as the most preferred management method to adopt in Kenya (Njoroge et al. 2012). However, in other villages 85-90 % of people surveyed considered complete eradication of *Prosopis* to be the best option (Mwangi and Swallow, 2005). There are still however, contentious issues surrounding the benefits and costs of the species and management approaches in Kenya (Pasiecznik et al. 2006a). There are many publications on the profits that are being made through utilisation, but there is no evidence that these utilisation programs have contained, or reduced the extent of *Prosopis* invasions. There is therefore, need for further investigation of the successes and failure of control through utilisation programmes (Geesing et al. 2004). A common problem with trying to promote *Prosopis* utilisation is that it is seen as an inferior resource in many communities, with people preferring to use native species (Geesing et al. 2004). Recently, a new utilisation approach to increase invasive *Prosopis* use has been adopted in Kenya - a power station (based on technology from India) is currently being built in the Kenyan Rift Valley which aims to produce electricity for the local area from burning *Prosopis* biomass (S. Choge, pers. comm.).

1.4.3 Research and management needs

This section highlights key management and research issues that need to be addressed to improve *Prosopis* control and the factors that currently constrain progress in these areas (Figure 1.7). There is great need for countries to develop national and even regional strategies, to provide guidelines for research and management in a targeted way as each country has unique requirements and needs. Australia and Ascension Island are the only counties/territories to have strategic plans for *Prosopis* management and countries with long-standing *Prosopis* control programs such as South Africa and Kenya still do not. Some broad scale factors that need to be considered are suggested below.

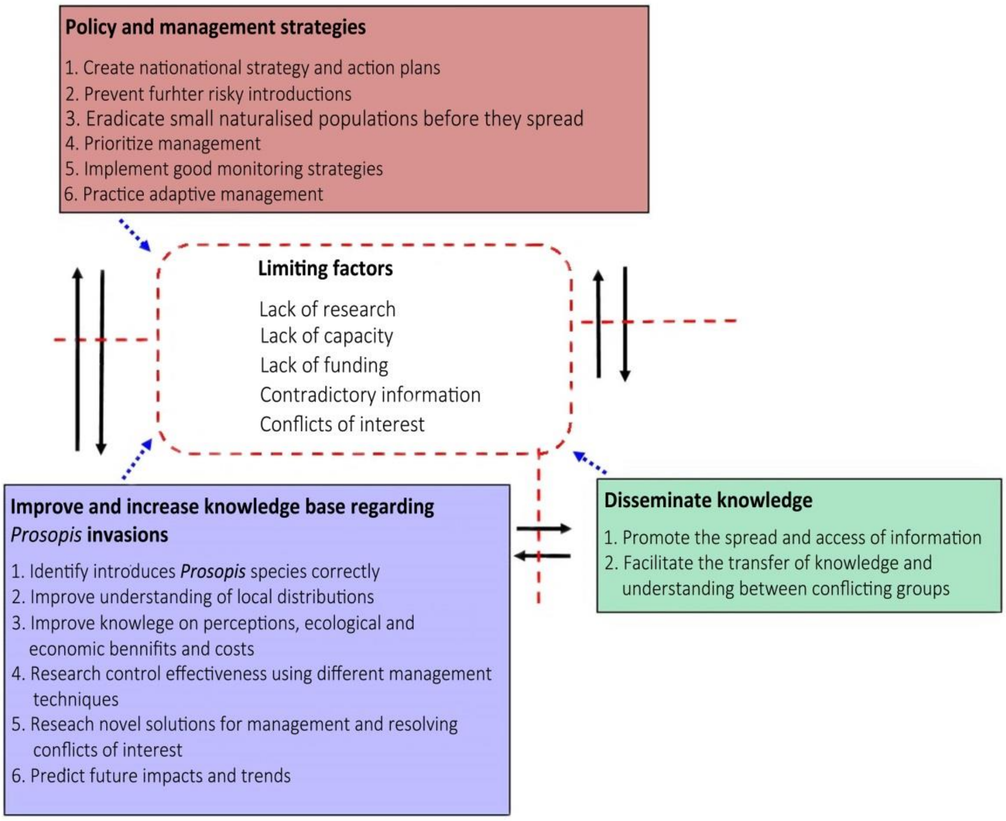

Figure 1.7: Requirements for research and management needs regarding *Prosopis* and factors limiting success to date.

Policy and management: National strategies and management/action plans need to be created and adopted to guide the coordinated control of *Prosopis* (Figure 1.7). Such national strategies and plans are important to set up frameworks on how to guide *Prosopis* management and research. Numerous organizations and national governments globally have undertaken projects to control *Prosopis* and planning and prioritisation from the outset would ensure greater success. Country-specific strategic plans need to be created as there are large differences in invasions rates and scales and social-economic situations within different areas of the world.

Introductions of known invasive *Prosopis* species to climatically suitable countries where it does not already exist should be undertaken such as in (China, European countries along the Mediterranean and North East Asia), and spread of *Prosopis* into new areas within countries where it is invasive should be prevented. Risk assessments for purposeful introductions need to be conducted in the future. Pathways of accidental introductions between neighbouring countries and into new areas in countries with invasive *Prosopis* need to be managed. This could include regulations on livestock and fodder transport which is currently implemented in Australia (Australian Weeds Committee, 2012). This is done by holding livestock in feed lots for a week before they are transported to ensure that all *Prosopis* seeds have excreted.

Countries need to eradicate small naturalised populations before they become invasive. Early detection and rapid response is a cost-effective way of preventing invasive species from getting out of hand and causing devastating, irreversible impacts in the future. For example, in Spain, *Prosopis* has started to show signs of naturalisation at a single location where it was planted for experiments and eradication attempts now would be most cost effective in the long run (N. Pasiecznik and E. Peñalvo López, unpubl. data).

There is also an urgent need for managers and researchers to monitor the effectiveness of control measures. Adaptive management needs to be promoted and applied for controlling *Prosopis* invasions where operational success is so far limited, so that the causes of the failures can be identified and addressed to improve overall control. Managers and researchers need to collaborate in research to design from the outset successful adaptive management strategies to be implemented.

Improve knowledge: There are many research questions regarding *Prosopis* invasions in many parts of the world that need to be answered to improve management (Figure 1.7). These include correctly identifying *Prosopis* species present and gaining consensus on the status of introduced and weedy species (e.g. following the criteria proposed by Pyšek et al. 2013). There have been numerous misidentifications of introduced *Prosopis* species, especially in Africa. This has caused much taxonomic confusion and contradictions between different sources of information that are only starting to be clarified. There are also hybridised populations in many areas where *Prosopis* been introduced further hindering identification (Zimmermann, 1991; Pasiecznik et al. 2004). It was recently recognised that *P. pallida*, which was seen as not being as invasive as other species, is more widespread than originally thought as it was misidentified as *P. juliflora* in Africa (Pasiecznik et al. 2006c). Most species introduced to Africa were described as *P. chilensis*, but this is not the case, and accurate species lists are not available for many African countries like Angola (Pasiecznik et al., 2004). Molecular methods are useful for clarifying taxonomic issues, especially in areas where hybridization has taken place. It is important to know what taxa are present for management, e.g. when looking for biological control agents and understanding ecology and rates of spread (Pyšek et al. 2013).

There is a need to improve the understanding of *Prosopis* distribution and population sizes in introduced ranges to guide management planning (Wilson et al. 2014). As indicated earlier, only 13% of countries with naturalised and invasive *Prosopis* have maps or detailed records of occurrence and scale of invasion. No information is available on the scale of *Prosopis* invasions on any of the Pacific (besides Hawaii), Indian Ocean or Caribbean Islands. Only a few African countries have a good understanding of the scale of invasions and, in Asia, information on the distribution of invasive *Prosopis* are only available for India and Pakistan. Such knowledge is essential for planning and implementing management. Bioclimatic mapping at board local scales is useful for understanding potential spread and occurrence of invasive species. However, bioclimatic models can be of limited value at very local scales as other biotic and abiotic factors come into play (Robinson et al. 2011). On a global scale, bioclimatic modelling is useful for highlighting which countries and species need risk assessments for purposeful introductions, and where introduction pathways need to be monitored to prevent unintentional introductions e.g. between India and China or Iran and Turkmenistan.

Further knowledge on the ecology, local perceptions, and the ecological, economic and social benefits and impacts of *Prosopis* are needed to guide management (Wilson et al. 2014). Our study has highlighted that knowledge on *Prosopis* invasions is essential for management (Table 1.1; Figure 1.6). Most of the literature comes from a handful of countries (Australia, India, Kenya, South Africa, USA), and research in other areas is needed since each region has its own set of factors that drive invasions and complicate management. There is also need for research to better predict trends such as future densities, extent and impacts which is particularly important when it comes down to developing strategic responses. Drivers of weediness in areas where it is native - such as Argentina, Mexico, Middle East, and the USA - require further study to improve understanding of what drives native plants to become invasive and provide insight in how to manage them.

The issue of the lack of knowledge is also present for research on the effectiveness of controlling populations using different methods. Utilisation as a control method is becoming popular in many areas such as Djibouti, Ethiopia, and Kenya. However, despite many reports showing how much monetary benefit *Prosopis* has provided, there is no information on how successful this approach is for controlling *Prosopis* invasions. There are also conflicting ideas on the role and success of biological control in Australia and South Africa and further work is needed (Zachariades et al. 2011). There is scope for identifying and potentially releasing additional biological control agents to improve control success in areas where this has been limited until now, such as in South Africa (Zachariades et al. 2011).Research is needed to identify novel solutions to aid the dilemma of management and contentious issues regarding invasive *Prosopis* globally. These include methods that retain the benefits, but reduce the impacts substantially. Risk assessments need to be run for *Prosopis* species that have not been introduced yet to determine whether they might be better candidates for introduction, by providing benefits with fewer costs associated with invasiveness.

Dissemination of knowledge: Organisations involved in addressing land degradation and invasions should promote the dissemination of knowledge and awareness of both the impacts and benefits of *Prosopis* to prevent unwise introductions and promote management (Figure 1.7) Some people still advocate the introduction of *Prosopis* species long after the severe impacts caused by invasions of these species were widely publicised; this has been described as ‘dangerous aid’ (Low, 2012). Having regular multidisciplinary international meetings or workshops on *Prosopis* invasions may help to spread knowledge and create dialog between parties which could help to reduce contentious issues surrounding many invasive *Prosopis* species. The creation of management strategies using transdisciplinary approaches would also help to provide solutions acceptable to all stakeholders in situations where conflicting goals exist.

1.5 Conclusions

Prosopis species are among the most widespread and damaging invasive woody plants in semi-arid and arid regions of the world and there is much potential for taxa to spread further. The detrimental effects on the environment and human livelihoods are escalating rapidly and there is an urgent need to devise more effective management approaches to drastically reduce adverse impacts and enhance benefits. However, there are still critical gaps in our knowledge of its ecology, impacts and how to retain benefits and reduce costs, and a lack of management capacity in many countries. Clearly focussed research and strategic planning is needed to improve management reduce costs and improve benefit flows.

Supporting information (Appendices)

File 1: Methods for literature review, climate matching, regression analysis, classification and regression tree**.**

File 2. Global distribution of *Prosopis* species. Status codes (*sensu* Pyšek *et al*. 2004) are given in brackets: N = naturalised; I = invasive; NA = native; W = weedy; U = unknown. Countries partaking in management of *Prosopis* species are marked with an asterisk.

File 3. Climate matching output – list of climatically suitable countries and the associated species (excluding known native species).

File 4. Underlying information on *Prosopis* invasions worldwide.

Acknowledgements

We thank the many researchers and managers that were consulted about the occurrence and management of *Prosopis* and the DST-NRF Centre of Excellence for Invasion Biology and Working for Water Programme through their collaborative research project on “Integrated management of invasive alien species in South Africa” – National Research Foundation (grant 85417) for funding.

Chapter 2: The impact of invasive alien *Prosopis* species (mesquite) on native plants in different environments in South Africa

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Abstract

Many *Prosopis* species have been introduced to South Africa; some taxa and their hybrids have naturalised and become widespread invasive trees. These invasions have detrimental effects on biodiversity, ecosystem services and human livelihoods. Although several studies have documented these impacts, the studies have been limited to single sites or restricted areas. This study assessed the *Prosopis* population across the full invasive range of the genus in South Africa, and quantified the effects of invasions on native woody and herbaceous species. Basal areas of invasive *Prosopis* stands reached 9 m2/ha, and were on average higher along perennial rivers than along ephemeral rivers (mean basal areas of 3.2 vs. 1.4 m2/ha). Native woody species density, basal area, richness and diversity all decreased significantly as the basal area of *Prosopis* stands increased. For example, up to eight native woody species occurred at basal area < 2 m²/ha, this decreased to three native species or fewer at basal areas > 4 m²/ha. The cover of native perennial grasses and herbaceous plants declined from 15 – 20% where the basal area of *Prosopis* was < 2 m2/ha to zero where the basal area of *Prosopis* was > 4.5 m2/ha. The results highlight the widespread nature of the impacts across all invaded biomes. Current control of *Prosopis* has had limited success, and alternative, potentially more effective, options are controversial. In the light of the widespread impacts, we recommend that a thorough assessment of the problem be undertaken to inform policy.

2.1 Introduction

Many 'multi-purpose' trees have been transported around the world and several have subsequently become naturalised and invasive (Rejmánek and Richardson, 2013). Tree invasions have become much more widespread in recent decades in many parts of the world and several invasive alien trees are key drivers of biodiversity loss and disruption of ecosystem functioning (Richardson et al. 2014). *Prosopis* (mesquite) taxa are widespread invaders in semi-arid and arid areas across the world (Pasiecznik et al. 2001). These invasions have detrimental impacts on the environment, society and local economies (Shackleton et al. 2014). Negative impacts of *Prosopis* invasions on a wide range of native organisms have been documented in many parts of the world. These include reductions in plant species richness, density and diversity in Hawaii, India, Kenya and the United Arab Emirates (El-Keblawy and Al-Rawai, 2007; Kaur et al. 2012; Muturi et al. 2013), increased native tree mortality in Brazil and South Africa (Schachtschneider and February, 2013; de Souza Nascimento et al. 2014; Shackleton et al. 2015), negative impacts on bird and insect community composition in South Africa (Steenkamp and Chown 1996; Dean et al. 2002) and reductions in turtle and bird recruitment on Atlantic islands (Belton, 2008). Ecosystem services such as soil quality, grazing and water supply are affected by *Prosopis* invasions, leading to a range of negative consequences for local human communities (Geesing et al. 2004; Mwangi and Swallow, 2005; Ndhlovu et al 2011; Wise et al. 2012; Dzikiti et al. 2013; Ayanu et al. 2014; Shackleton et al. 2014).

Prosopis species were introduced to South Africa in the late 1800s and were widely distributed and planted up to the 1960s for shade and fodder during a time of severe drought (Harding and Bate, 1991; Zimmermann, 1991; Poynton, 2009). Invasive *Prosopis* stands (comprising several species and their hybrids) now cover very large areas of arid and semiarid parts of the country, with extensive invasions in the Northern Cape and Western Cape provinces (Poynton, 2009). *Prosopis* is estimated to have invaded 1.8 million ha (1.5 %) of South Africa and has been estimated to spread between 3.5 and 8 % per annum (Voster, 1977; Coetsee, 1993; Harding and Bate, 1991; Versfeld et al. 1998). This implies that invaded areas can double every 5-8 years. In the Northern Cape province *Prosopis* invasions increased by almost 1 million ha between 2002 and 2007, which is equivalent to 27.5 % per year (Van Den Berg, 2010). In terms of land area invaded, *Prosopis* is ranked as the second worst invasive alien plant taxon in South Africa after Australian acacia species (Henderson, 2007). The genus also ranks highly for its negative impacts on biodiversity and ecosystem services (Le Maitre et al. 2000). Invasive *Prosopis* species are being managed by the Working for Water programme in South Africa, using mechanical and chemical and biological control (three seed-feeding beetle species) but with limited success in reducing the overall extent of invasions and their impacts (Zachariades et al. 2011; van Wilgen et al. 2012).

Ecosystem services such as water supply and grazing potential are clearly affected by *Prosopis* invasions in South Africa (Ndhlovu et al. 2011; Wise et al. 2012; Dzikiti et al. 2013). Further negative effects are noted on bird and insect species richness and composition in the Kalahari (Steenkamp and Chown, 1996; Dean et al. 2002). *Prosopis* also increases the mortality of a keystone tree species (*Acacia* erioloba) in the Kalahari Desert (Schachtschneider and February, 2013). All of these studies have been limited to small areas or single sites, and there is a need for more extensive surveys to establish both the nature of the invasions, and the degree of impact that they are having in different biomes and habitats. Such information would be necessary for estimating the impacts of *Prosopis* over large spatial areas, and for informing large-scale management strategies.

This study aimed (1) to quantify the basal areas of *Prosopis* invasions in different biomes and river types across South Africa; and (2) to assess the impacts of *Prosopis* invasion on native plant species richness, diversity, basal area, density and cover over a wide area representative of the invasive range of the genus in South Africa.

2.2 Methods

2.2.1 Scope of investigation and study sites

We investigated the degree of variation in the basal area of invasive *Prosopis* trees at 11 sites across three biomes (Nama Karoo, Savanna and Succulent Karoo, see Mucina and Rutherford, 2006) and three river classes (see below). We used the same sites to investigate the effects of *Prosopis* invasion on the composition and structure of indigenous plant communities. These sites covered most of the range of invasive alien *Prosopis* trees in South Africa. Mean annual rainfall varied between 150 and 450 mm, and the seasonality of rainfall differed, with rain falling either predominantly in winter or summer, or evenly distributed across seasons (Dent et al, 1989) (Figure 2.1). Rainfall was higher in the Succulent Karoo and Savanna study sites and lowest in the Nama Karoo study sites (Figure 2.1). The underlying geology of the area included shales of the Dwyka and Ecca Group, granites of the Namaqua group in the east, gneiss of the Namaqua and Natal Metamorphic Provinces, deep sands of the Kalahari Group in the central and northern sites, shales of the Transvaal Supergroup in the east, and shales of the Beaufort group in the south (Voster, 2003). Altitudes ranged from 700 to 1300 m above sea level.

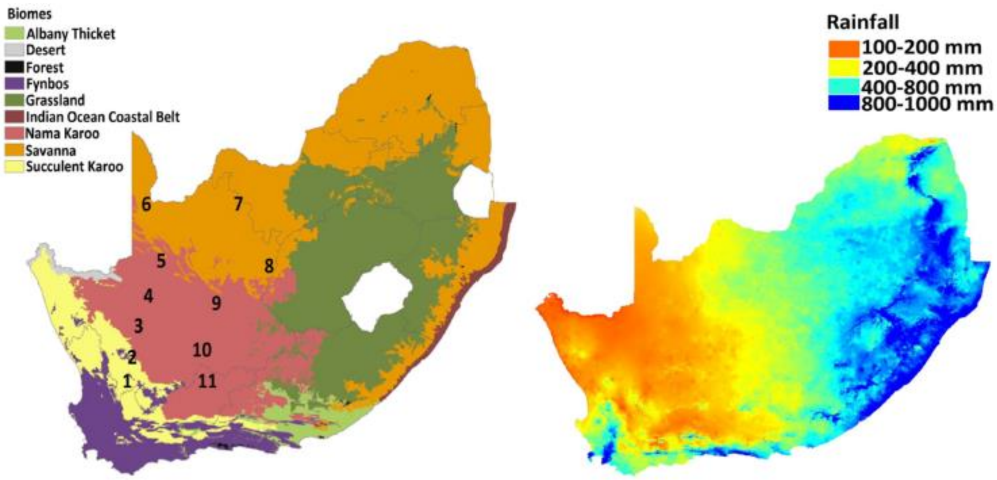

Figure 2.1: Study area showing biomes, mean annual precipitation and data collection sites across South Africa: (1) Calvinia; (2) Loeriesfontein; (3) Brandvlei; (4) Kenhardt; (5) Upington; (6); Mier (7) Seven; (8) Kimberley; (9) Prieska; (10) Carnavon (11) Beaufort West.

2.2.2 Data collection

At each of the 11 sites, we set out transects on farms that had un-invaded vegetation, as well as areas invaded by different densities of *Prosopis*. Along each transect, three plots of 10 x 10 m were placed at 50 m intervals. In total, we evaluated 894 plots, selected to cover a gradient from uninvaded to heavily-invaded sites. Care was taken not to place transects in disturbed areas so as to exclude, as far as possible, the influence of past land practices but also to place transects where trees were always present. This was done through consultation with farmers. On each plot, we measured the stem diameters of all trees and shrubs with stems >1cm diameter at 30 cm above the ground. Diameters were measured at 30 cm, and not at breast height, as the trees in the study site often branched below breast height. In the first plot of each transect the percentage cover of perennial grass, annual grass, perennial herbaceous plants, annual herbaceous plants, organic litter and bare ground was visually estimated by averaging estimated cover on four 1x1 m quadrats placed in the centre of each quarter of the plot. Individual herbaceous species were not identified. *Prosopis* trees were not recorded at species level as most stands comprised complex hybrid mixtures that are difficult to identify (Mazibuko, 2012).

We also classified the habitat type for each transect into one of three categories: floodplains of perennial rivers (the Orange River, with permanent flow year-round); floodplains of larger ephemeral rivers (drainage lines with seasonal flow, listed by the Water Institute of South Africa (WISA, www.ewisa.co.za/misc/riverssa/defaultb.htm); and smaller (tributary) ephemeral rivers (those not listed by WISA). Data were collected in the austral winter between June and September 2013.

2.2.3 Data analysis

2.2.3.1 Prosopis density and basal area across different environments

We investigated whether the basal area of *Prosopis* invasions differed between the river categories (perennial, large ephemeral, or small ephemeral) and between ephemeral rivers in the three biomes (Nama Karoo, Savanna and Succulent Karoo). In each river category, and in each biome, plots were ranked from the lowest to highest basal area, and divided into three groups of equal size, representing low, moderate and high basal area classes. Welch ANOVAs and Games-Howell Post-Hoc tests were used to compare *Prosopis* in the different basal area classes across biomes and river categories. Welch ANOVAs and Games-Howell tests were used because the assumption of homogeneity of variances was not met.

2.2.3.2 Impacts of Prosopis invasions on native species

The effects of *Prosopis* basal area on the relative abundance of native woody species was investigated using the Shannon-Wiener index (a measure of relative dominance, Magurran, 2004). Regressions were run to compare the relationship between the basal area of *Prosopis* invasions and the density, basal area, species richness and diversity of native woody species. Regressions were also used to examine the effect of *Prosopis* basal area on the cover of grasses, herbaceous plants, organic litter and bare ground cover.

2.3 Results

2.3.1 Effects of biome and habitat type on Prosopis basal area

Of the 894 plots enumerated, 220 plots were free of *Prosopis* trees. When the remaining dataset (plots with *Prosopis* trees of varying basal area) were ranked from the lowest to the highest basal area of *Prosopis* trees, the plots in the first third (low basal area) had a mean basal area of 0.57±0.97 m^2/ha for all sites across South Africa. Corresponding values for moderate and high basal area plots were, 1.14±1.12 m²/ha in the middle range and 2.17±1.31 m²/ha in the high range (Figure 2.2).

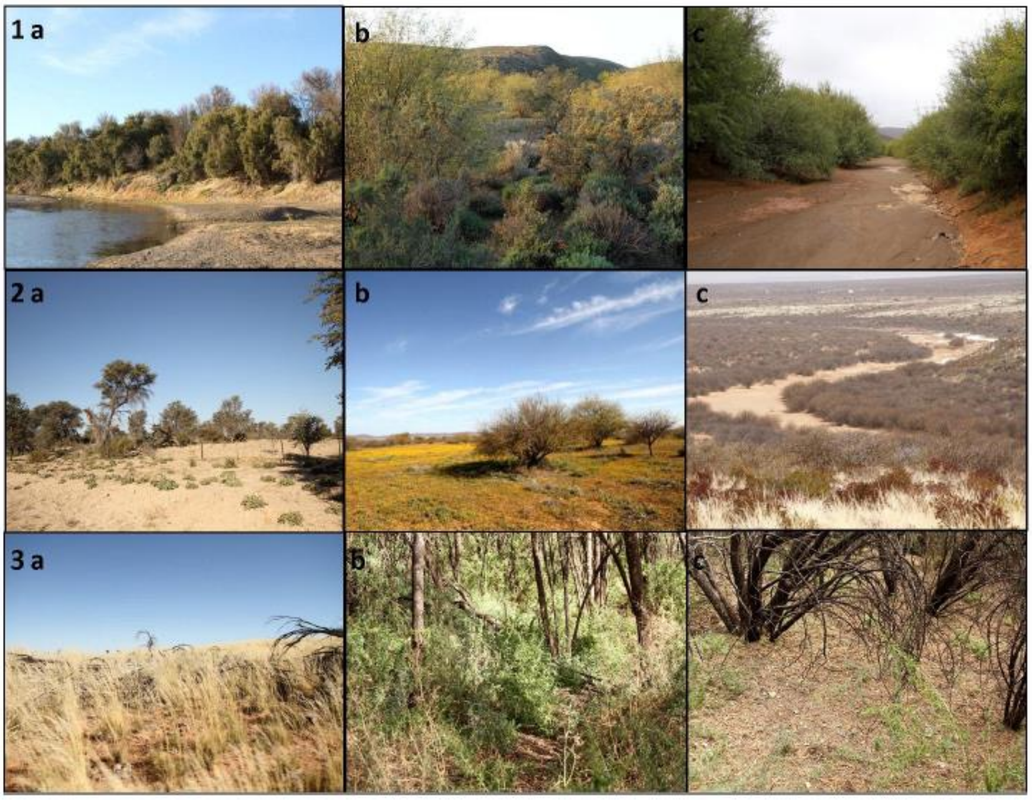

Figure 2.2: Images of *Prosopis* and native vegetation in South Africa: Panel 1 - (a) Non- invaded riverine forest; (b) Low *Prosopis* invasion; (c) Dense *Prosopis* invasion; Panel 2 – (a) Non-invaded Savanna vegetation; (b) sparse *Prosopis* invasion; (c) Landscape scale, dense *Prosopis* invasion; Panel 3 – (a) Grass cover 5 years after clearing *Prosopis*; (b) Ground cover under native *Acacia* karroo riverine forest; (c) Ground cover under a *Prosopis* invasion. Photos: R T. Shackleton.

Habitat type (river categories) had significant effects on the basal area of *Prosopis* stands. (Figure 2.3a, Table 2.1). On average, the plots in the high-range class had more than double the basal area along perennial rivers than along both categories of ephemeral rivers (3.2 vs. 1.43 m2/ha). Small ephemeral rivers also tended to have lower mean basal areas in the medium and low ranges, compared to large ephemeral or perennial rivers.

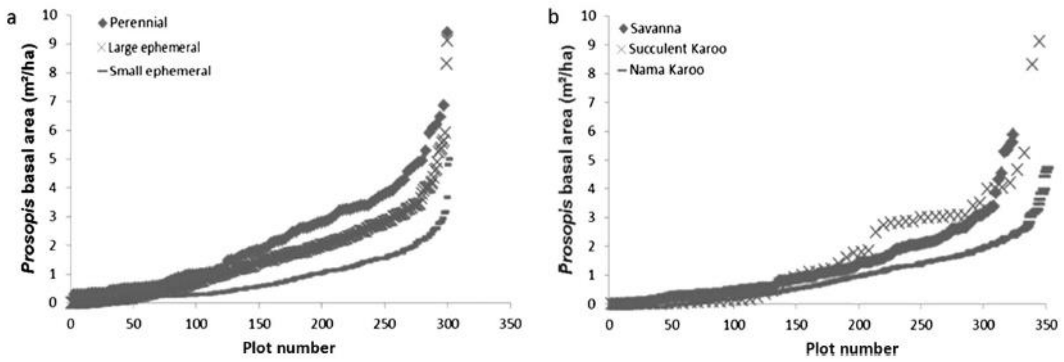

Figure 2.3: A comparison of *Prosopis* basal area across: (a) three river size classes; and (b) three biomes. Data points are for individual plots ranked from low to high in terms of basal area. As the number of plots differed between river classes and biomes, the horizontal axis was scaled to facilitate comparison.

Table 2.1: Mean (± standard error) basal area (m^2/ha) of invasive *Prosopis* species in three habitat types (river categories). Basal area values were ranked and divided into three data sets of equal size representing low, moderate and high basal areas respectively. Basal area estimates with different superscript letters are significantly different across river categories (Games-Howell Post-Hoc tests).

Basal area class		**River category**		**P-value**
	Perennial	**Large ephemeral**	**Small ephemeral**	
Low	1.01 ± 1.25^a	0.69 ± 0.94^a	0.25 ± 0.32^b	F = 78.5, df=2, $p < 0.0001$
Moderate	1.69 ± 1.75^a	1.71 ± 1.23^a	0.83 ± 0.79^b	F = 86.33, df=2, $p < 0.0001$
High	3.2 ± 1.58^a	2.41 ± 1.44^b	1.43 ± 0.71^c	F =79.77, df=2, $p < 0.0001$

The effects of biome type on the basal area of *Prosopis* invasion were less clear (Figure 2.3b, Table 2.2). On average, the high range plots differed significantly between all three biomes. The Succulent Karoo (wetter) had more than double the basal area in of the Nama Karoo (3.84 vs. 1.87 m2/ha), while the value for the Savanna biome was intermediate (2.04 m^2/ha).

Table 2.2: Mean (± standard error) basal area (m²/ha) of invasive *Prosopis* species in three biomes. Basal area values were ranked and divided into three data sets of equal size representing low, moderate and high basal areas respectively. Basal area estimates with different superscript letters are significantly different across river categories (Games-Howell Post-Hoc tests).

Basal area class	**Biome**			**P-value**
	Nama Karoo	**Savanna**	**Succulent Karoo**	
Low	0.34±0.41[a]	0.40±0.47[b]	0.16±0.29[c]	F = 39.9, df=2, p < 0.0001
Moderate	1.15±0.82[a]	1.47±1.17[a]	1.55±1.10[a]	F = 45.22, df=2, p < 0.095
High	1.87±0.89[a]	2.04±1.40[b]	3.84±2.00[c]	F = 29.95, df=2, p < 0.0001

3.3.2 Effects of invasion by Prosopis on native woody plants

Invasion by *Prosopis* reduced the density, basal area, richness and diversity of native woody plants (Figure 2.4). Native woody species density, basal area, richness and diversity all decreased significantly ($p < 0.000$) as the basal area of *Prosopis* stands increased. Where *Prosopis* trees were either absent or present at basal areas of less than 4 m2/ha, native woody trees were able to persist at densities above 4000 stems/ha; as invasions increased above basal areas of greater than 4 m2/ha, the maximum density of native woody species fell rapidly to between 2000 and zero trees per ha. The number of native woody species present on the plots also declined, from five - eight species where *Prosopis* was at basal areas below 2 m2/ha, to one – three species when the basal area of invasions exceeded 4 m2/ha. As the basal area of invasions increased, stands were correspondingly more dominated by *Prosopis*, as indicated by Shannon-Wiener indices as low as zero (indicating total dominance by a single species) in highly invaded stands. The scatter plots (Figure 2 4) suggest two thresholds, one of *Prosopis* basal area of invasions between0-2m^2/ha (after which native tree populations drop substantially but are still present), and a second at where the basal area reaches 6 m^2/ha (after which native trees are largely eliminated).

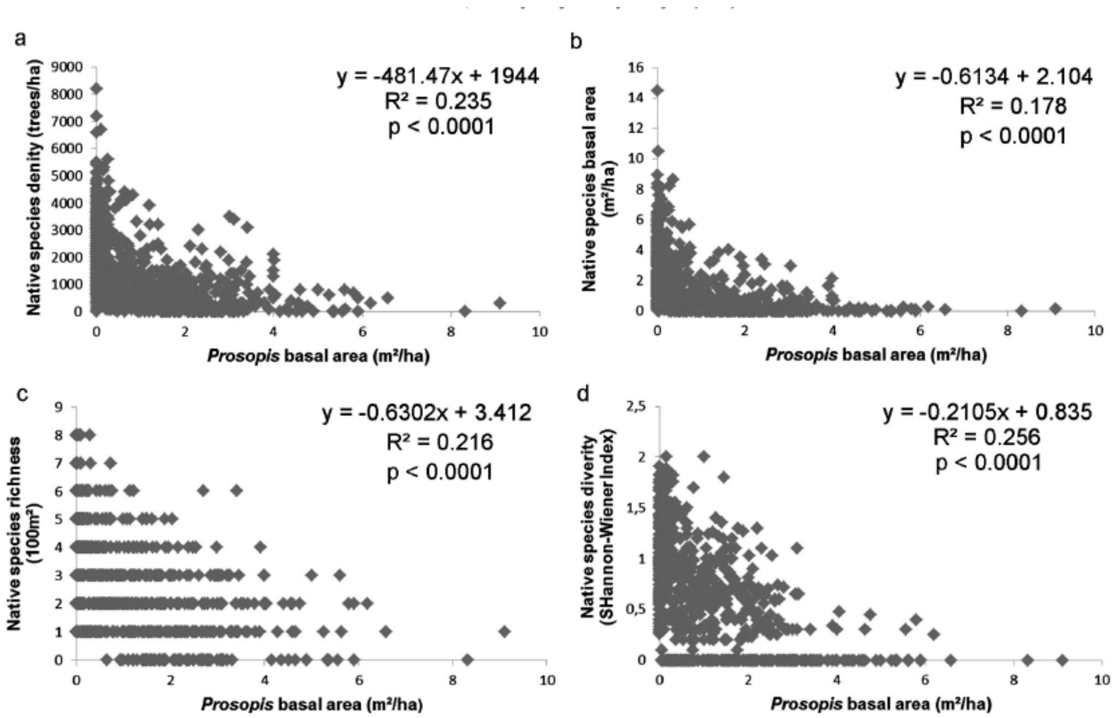

Figure 2.4: Scatter plots and regression analyses showing the effects of *Prosopis* basal area on: (a) native woody species density; (b) basal area; (c) species richness; and (d) Shannon-Wiener species diversity index.

2.3.3 Effects of Prosopis invasion on native herbaceous plant and abiotic ground cover

Invasion by *Prosopis* reduced the cover of perennial grasses and herbaceous plants (Figure 2.5). As was the case with native woody plants, the cover of perennial grasses dropped from above 15% where the basal area of *Prosopis* was below two m2/ha, to zero where the *Prosopis* basal area was above 4.5 m2/ha. Similarly, the cover of native perennial herbaceous plants dropped from above 20% where the basal area of *Prosopis* was below 2 m2/ha, to zero where the *Prosopis* basal area was above 4.5 m2/ha. On the other hand, we were not able to detect any meaningful impacts of invasion by *Prosopis* on the cover of annual grasses and annual herbaceous plants. Native annual plants persisted at quite high levels of invasion by *Prosopis*. Organic litter cover and bare ground cover was also not significantly influenced by *Prosopis* invasion (Figure 2.6).

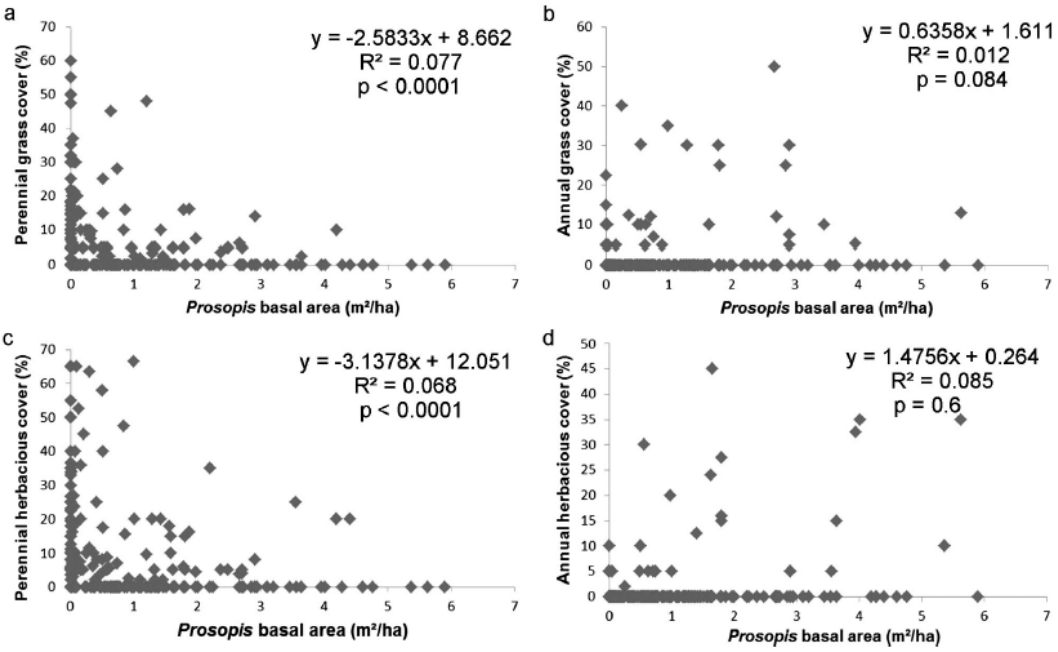

Figure 2.5: Scatter plots and regression analysis assessing the effect of *Prosopis* basal area on non-woody plant cover: (a) perennial grass cover; (b) annual grass cover; (c) perennial herbaceous plant cover (100m²); and (d) annual herbaceous plant cover.

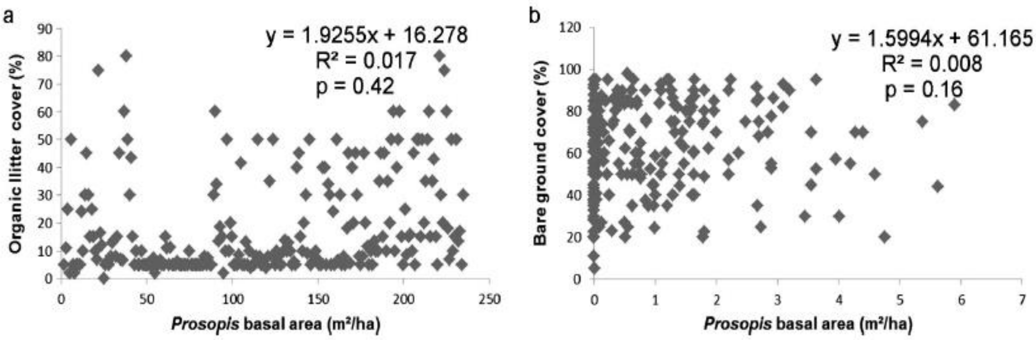

Figure 2. 6: Scatter plots and regression analyses showing the effect of *Prosopis* basal area on (a) organic litter cover; and (b) bare ground cover.

2.4 Discussion

2.4.1 International comparisons

The findings of our study are similar in many ways to those made for *Prosopis* invasions in other parts of the world. *Prosopis* forms dense invasive thickets across much of South Africa's interior. These invasive thickets are influenced by abiotic factors, and areas with higher water availability have higher invasions with higher basal areas (Figure 2.3). Similarly, densities of invasive *P. pallida* were 5.3 times greater in relatively moist lowlands in Hawaii, compared to drier upland plots (Dudley et al. 2014). Dudley et al. (2014) also showed that greater water accessibility increased nitrogen fixation, which was linked to increased growth and productivity of these *Prosopis* invasions. This trend is mirrored in findings by Stromberg et al. (1993) who showed that weedy (native invasive) *P. velutina* invasions in the Sonoran Desert have higher basal areas in perennial-riparian compared to xero-riparian (ephemeral rivers) and upland areas. These findings show that *Prosopis* responds in a similar way, whether as a weed in its native range or where it is an invasive alien tree.

Our findings showing the negative impacts of *Prosopis* invasions on native plants (Figures 2.4 and 2.5) are supported by other studies internationally. *Prosopis* invasions also negatively affected native species richness in Hawaii, India, Kenya and the United Arab Emirates (El-Keblawy and Al-Rawai, 2007; Kaur et al. 2012; Muturi et al. 2013). In the United Arab Emirates, native species richness and densities under *Prosopis* tree canopies were lower than at canopy margins and away from *Prosopis* canopies (El-Keblawy and Al-Rawai, 2007). This suggests that *Prosopis* was able to outcompete native plants for limited resources, such as light and water (Garcia-Serrano et al. 2007; El-Keblawy and Al-Rawai, 2007). The allelopathic effects of *Prosopis* have also been shown to reduce native tree germination and survival (de Souza Nascimento et al. 2014; El-Keblawy and Abdelfetha, 2014). Our results for woody plants differed from those in Australia where it was found that *Prosopis* invasions had a positive effect on the density of native tree species but a negative effect on density of native shrub species (van Klinken et al. 2006). The only trees found in areas with *Prosopis* invasion in Australia (*Eucalyptus* spp.) showed higher densities in dense and moderate *Prosopis* invasions than in areas with low-density invasions (van Klinken et al. 2006). A similar trend of *Prosopis* presence increasing native species richness and diversity was also found in India, however, the increase was in weedy, economically unimportant native species and there were negative impacts on endangered *Commiphora wightii* and other important climax native species (Kumar and Mathur, 2014). Percentage cover of native grass and herbaceous plant species is also reduced by *Prosopis* invasions (Figure 2.5). Similar shifts were seen in Australia, with far fewer shrubs and grasses found in densely invaded areas (van Klinken et al. 2006). Denser *Prosopis* invasions tended to an increase in bare ground cover (Figure 2.6). Loss of ground cover under *Prosopis* invasions has been seen to facilitate soil erosion in some areas (Bedunah and Sosebee, 1986).

2.4.2 Implications of findings

Our study has added to the growing body of evidence (Steenkamp and Chown, 1996; Dean et al 2002; Ndhlovu et al. 2011; Dzikiti et al. 2013; Schachtschneider and February, 2013) that invasion by *Prosopis* has negative impacts on South Africa's natural ecosystems and the services that they deliver. We have further demonstrated that these impacts occur across a wide area, in all biomes invaded by *Prosopis* trees. While *Prosopis* trees were originally introduced to provide fodder, and for other benefits, recent studies suggest that these benefits are rapidly being eroded by negative impacts (Wise et al. 2012). Loss of native plants due to *Prosopis* invasions not only decreases biodiversity in the area, but also has negative implications for local livelihoods. Many people in the rural areas of South Africa rely on natural resources from plants for incomes and subsistence (Shackleton et al. 2007). *Prosopis* reduces the densities of native species like *Acacia erioloba* and *A. karroo* which are highly valued and commonly used for firewood and fodder in South Africa (Powell, 2001; Pote et al.

2006). This is of particular importance as many communities dislike *Prosopis* for fuelwood (Geesing et al. 2004). The loss of native grass and herbaceous plant cover due to *Prosopis* invasion is common across South Africa (Ndhlovu et al. 2011). This has serious repercussions for the local economy of these arid and semiarid parts of the country, considering that livestock agriculture is the primary land use and one of the key factors driving the economy and employment in these areas.

Wise et al. (2012) noted that, while the estimated net economic value of mesquite was substantial, this value was being eroded as invasions grow, with net negative values expected within 4 – 22 years, depending on the rate of spread. In response to the growing threat, the South African government has spent R 435 million (between 1996 and 2008) on mechanical control operations aimed at clearing stands of invasive *Prosopis* trees in arid areas (van Wilgen et al. 2012). In addition, biological control agents were released between 1983 and 1997 in attempts to control *Prosopis* (Zachariades et al. 2011). However, because of the perceived value of *Prosopis* trees, biological control attempts were confined to seed-feeding insects that would not damage the trees. As a result, the degree of control achieved by these insects is currently inadequate to stem the spread. Other biological control agents that have been deemed safe to release in South Africa have showed success in limiting *Prosopis* invasions in Australia (van Klinken, 2012). The mechanical control programme has been equally ineffective at a broad scale, as evidenced by the rapid population growth over the past two decades (Van den Berg 2010). Despite substantial investment, mechanical control efforts were only able to treat about 0.6% of the estimated invaded area each year (van Wilgen et al. 2012), which is way below the spread rate of the species.

It is clear that *Prosopis* invasions will continue to spread despite intensive attempts at control and the impacts will grow accordingly, unless more effective ways can be found to control the genus in South Africa. One obvious solution would be to explore the feasibility of introducing more damaging biological control agents that would be more effective at curtailing spread, such *Evippe* spp. (van Klinken, 2012). There is some resistance to this idea (particularly further north in Africa), because there is a risk that biological control agents could attack indigenous African species of *Prosopis*, or other alien *Prosopis* species that are not invasive, and that are useful (Zachariades et al. 2011). Other proposals include the notion of utilization as a control method (Pasiecznik et al. 2006; Shackleton et al., 2014). For example, many people rely on *Prosopis* for their livelihoods in India, where it has been suggested that increased use of products from *Prosopis* through proper silviculture would be a feasible way of managing costs and improving benefits relating to these invasions (Walter et al. 2014). However, use in South Africa is lower and the silviculture option would not be feasible (Shackleton et al. in press). These suggestions are also controversial as their effectiveness is disputed and they create a dependence on the resource which provides justification for further distribution of the invasive species (Geesing et al. 2004; van Wilgen and Richardson, 2014). The growing evidence, presented in this study and elsewhere, of the widespread negative impacts of *Prosopis* invasions will continue to increase unless a solution can be found. We recommend that a full assessment of the costs and benefits be carried out to inform policy decisions. The creation of national strategic plans such as those in Australia would also help to guide management and aid in efficiency in the future. Such an assessment would have to be carried out with a political mandate (for legitimacy), involve all of the stakeholders, and use experts and peer review to address all of the issues.

Acknowledgements

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Chapter 3: *Prosopis* invasions in South Africa: Populations structures and impacts on native tree population stability

This chapter was published in the *Journal of Arid Environments*

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Abstract
Several *Prosopis* taxa are widespread invaders that have negative impacts on biodiversity and human livelihoods globally. Better knowledge of the impacts and ecology of invasive *Prosopis* species is required to support and inform management interventions. *Prosopis* was introduced to South Africa and has become the second most widespread invasive alien plant taxon in the country. We compare population structures of invasive *Prosopis* populations in different part of South Africa, and quantify the effects of *Prosopis* invasions on native tree populations using size-class distribution (SCD) curves. Kolmogorov-Smirnov tests, regressions, quotients, and Permutation Indices were used to compare size-class distributions and assess population stability. *Prosopis* population structures differed across South Africa. Those along perennial rivers and areas in the Succulent Karoo biome had fewer juvenile plants. *Prosopis* in South Africa also has higher recruitment (% juvenile plants) than in other areas like Australia. *Prosopis* invasions are having a negative effect on the stability of native tree populations in South Africa, and are linked to increased mortality of native trees. Improved management of *Prosopis* is needed.

3.1 Introduction

Invasive alien species are a key driver of biodiversity loss and ecosystem function disruption globally (Wilcove et al., 1998). They are a major cause of mammal, bird and fish species extinctions, and also threaten plant diversity in many regions (Gaertner et al., 2009). Biological invasions lead to the suppression of native plants by competing for limited resources (Richardson et al., 1989). The understanding of the impacts of invasive alien species at a community levels is, however, rather limited and further research is needed especially over large spatial and temporal scales (Tickner et al., 2001). Taxa in the genus *Prosopis* (mesquite) have been introduced and become naturalized or invasive in many of the world's arid and semi-arid areas (Rejmánek and Richardson, 2013). *Prosopis* has been highlighted as a serious invasive alien taxon globally and poses threats to biodiversity and human activities, but further research on impacts and ecology is needed (Shackleton et al., 2014). These *Prosopis* invasions have been shown to have a negative impact on native plant, bird and turtle populations in many countries (Belton, 2008; Kaur et al. 2012; Muturi et al., 2013).

Prosopis taxa were introduced to South Africa in the late 19th century and were actively distributed and planted in the semi-arid and arid parts of the country, especially in the 1960s and 1970s (Zimmermann, 1991). Several species and their hybrids are now major invaders across large parts of the arid interior of South Africa. Common species include *Prosopis chilensis, P. glandulosa* and *P. velutina*, and their many freely inter-breeding hybrids (Zimmermann, 1991; Poynton, 2009; Mazibuko, 2012). There is also evidence that *P. alba, P. juliflora, P. laevigata P. pallida P. pubescens* are also present but not as common (Mazibuko, 2012). *Prosopis* invasions now cover at least 1.8 million ha of South Africa (Versfeld et al., 1998) and are expanding at around 8 % per annum (Van den Berg, 2010). Invasions have had severe negative impacts on ecosystem services such as water and grazing supply (Ndhlovu et al., 2011; Dzikiti et al., 2013) and are adversely affecting native plant, bird and insect species richness and diversity (Steenkamp and Chown, 1996; Dean et al. 2002, Ndhlovu et al., 2011; Shachtschneider and February, 2013).

An integrated approach to managing *Prosopis* is being implemented in South Africa to reduce the impacts of invasions. This includes biological control using seed-feeding beetles (*Algarobius Prosopis, A. bottimeri* and *Neltumius arizonensis*) (Zimmermann, 1991) and mechanical and chemical control implemented mainly by the government-run Working for Water programme, but also by private land owners. There is the potential for the release of more biological control agents if the conflicts of interest surrounding *Prosopis* are resolved (Zachariades et al., 2011). Between 1996 and 2008 *Prosopis* cover has increased by 35 % despite R 435.5 million (US$ 42.7 million) being spent on controlling its spread (van Wilgen et al., 2012). Approximately 15 100 ha were cleared with this budget (van Wilgen et al., 2012). There is potential to look into other control mechanisms to improve management further, such as the control-by-utilisation approach applied in Kenya (Pasiecznik and Felker 2006). These different methods each have advantages and disadvantages and management approaches are often are based on the population structure of invasive populations, the level of understanding of invasion, and development level of the country (van Wilgen et al., 2011; Shackleton et al., 2014). Baseline data on the population structures and impacts of *Prosopis* are needed to guide effective management in South Africa. This is particularly needed over large spatial scales, since previous studies have been site specific (Steenkamp and Chown, 1996; Dean et al. 2002, Ndhlovu et al., 2011; Schachtschneider and February, 2013).

Little attention has been given to determining the effects of invasive species on the recruitment, mortality and population stability of native plants across a representative range of environments. The use of size-class distributions (SCDs) provides a convenient method for assessing population trends in plants, and has been widely used in studies of rare, threatened and heavily utilised plants to guide in their management (Shackleton, 1993; Botha et al., 2004; Venter and Witkowski, 2010; Cousins et al., 2014). Few studies have used SCD curves to investigate the population structure of invasive alien populations, and even fewer have applied this method to assess impacts of invasive plants on native species – most studies that have been done deal with *Prosopis* (van Klinken et al., 2006; de Oliveira et al., 2012; Muturi et al., 2013). SCD curves have the potential to provide important insights into the effects of invasive alien plants on native species population stability, and can inform management strategies based on population structures, recruitment and impacts.

3.2 Aims and objectives

a) Compare size-class distributions and population stability of *Prosopis* populations within different biomes in South Africa and with differing water availability. b) Determine whether invasive *Prosopis* populations are having an impact on the stability, population structure and mortality of native tree species.

3.3 Study site

The study was conducted at 11 sites in an area that covered three of South Africa's terrestrial biomes: the Succulent Karoo, the Nama Karoo and the Arid Savanna (Figure 3.1). Mean annual rainfall across the study area ranges from 150-450 mm (increasing towards the west); rainfall seasonality ranged from winter in the west to summer in the east with bimodal rainfall where they overlap (Dent et al, 1989). Rainfall across these sites has been highly variable over the last 10 years, but has tended to be close to the yearly average to slightly higher in the past three years at most sites (Agricultural Research Council, unpublished data). Altitudes range from 700 to 1300 m a.s.l. The most common land use in the area is livestock ranching and game farming.

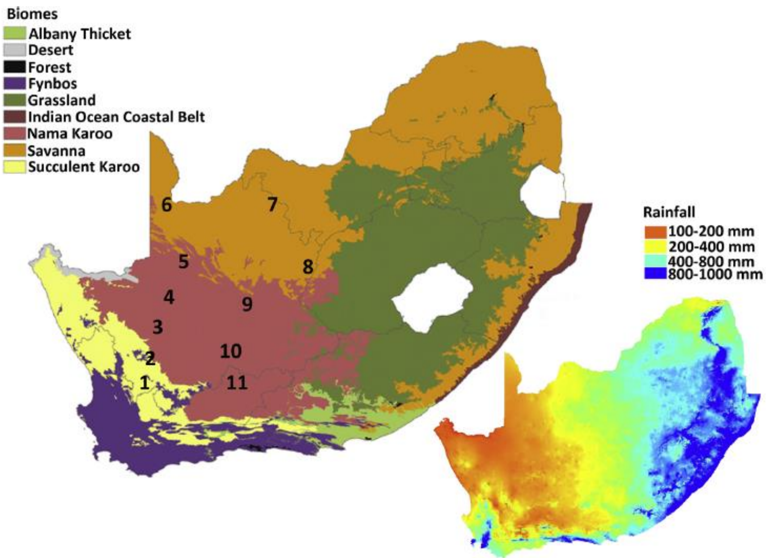

Figure 3.1: The study area, showing biomes, mean annual precipitation and data collection points across South Africa: (1) Calvinia; (2) Loeriesfontein; (3) Brandvlei; (4) Kenhardt; (5) Upington; (6); Mier (7) Seven; (8) Kimberley; (9) Prieska; (10) Carnavon (11) Beaufort West

3.4 Methods

3.4.1 Data collection

Data were collected between June and September 2013. At each site transects were established along rivers and alluvial plains where natural riverine forests were found in areas with varying levels of *Prosopis* stand density. Transects comprised three plots (10 x 10 m) placed every 50 m. Farmers were consulted on the past land practices on their farms to prevent placing transects in areas that were previously disturbed e.g. old flood irrigation fields or areas that were dammed or where no native trees were present. We also only worked on farms that had both invaded and non-invaded areas to ensure that major differences in land-use history did not confound our results.

In total 894 plots were surveyed across the 11 sites. In each plot all tree diameters were measured 30 cm above the ground and all trees were identified to species level (except *Prosopis*). This height was chosen because *Prosopis* and other native species often branch below breast height. For trees with multiple stems, all stem diameters were measured and summed to give a single tree diameter for the SCD analysis. Trees with diameters < 1 cm were simply identified and counted. Diameters of all dead native tree species were measured and identified to species level based mainly on bark textures. *Prosopis* species were not identified to species level because most invasive stands in South Africa comprise hybrids that can only be accurately identified using molecular methods (Mazibuko, 2012). Expert taxonomic advice was sought for identification of some of the native species. The different biomes and different river classes (Small Ephemeral, Large Ephemeral and Perennial) - indicative of water availability - were included to assess abiotic effects on *Prosopis* invasion structures.

3.4.2 Data analysis

Size-class distributions were constructed for *Prosopis* populations in different biomes and river classes. SCDs were also constructed for native tree species, and invasive alien *Tamarix ramosissima*, and were separated into two groups: (a) those with zero to low (ZL) *Prosopis* invasion (basal areas of < 2 m^2/ha); and (b) those with moderate to high (MH) *Prosopis* invasion (basal areas of > 2 m^2/ha). The value of 2 m^2/ha was chosen because it formed a thresholds beyond which native species densities, basal areas, species richness and diversity decreased considerably (Shackleton et al., under review). 723 plots (220 with no *Prosopis*) plots fell into the ZL class and 171 plots fell into the MH class. Only tree species with 10 or more records were included in the analyses. Kolmogorov-Smirnov tests were used to compare size-class distributions between trees found in the two *Prosopis*-density categories and to compare *Prosopis* SCDs in different biomes and river classes (Botha et al., 2002 and 2004; Venter and Witkowski, 2010). Regressions were also run to assess the fit (R^2) of the SCD.

Prosopis and native tree population stability in areas with ZL invasion and MH *Prosopis* invasion were investigated by calculating the quotients between the numbers in successive size-classes (Harper, 1977). Quotients for the whole *Prosopis* population and populations in different biomes and along different river types were also calculated. Constant quotients indicate population stability and fluctuating quotients indicate unstable or episodically recruiting populations (Botha et al., 2002; Venter and Witkowski, 2010).

Population structures and stability of native trees found in ZL, and MH density invasions, and *Prosopis* populations in different biomes and on rivers in different types were further investigated using the Permutation Index (P-index) (Wiegand et al., 2000; Botha et al., 2004;

Venter and Witkowski, 2010). The P-index compares the degree of deviation from a monotonic decline (Wiegand et al., 2000). Populations with monotonically declining populations will have a low P-index and those with discontinuous population structures will have a large P-index value (Wiegand et al., 2000; Venter and Witkowski, 2010).

Regression analyses were used to assess the relationship between the basal area of dead trees, density of dead trees and mean number of dead species in relation to different *Prosopis* invasion's basal areas.

3.5 Results

3.5.1. Prosopis populations

The overall *Prosopis* population in South Africa (Figure 3.2) shows a positively skewed distribution with quotients fluctuating in the juvenile and large tree size-classes.

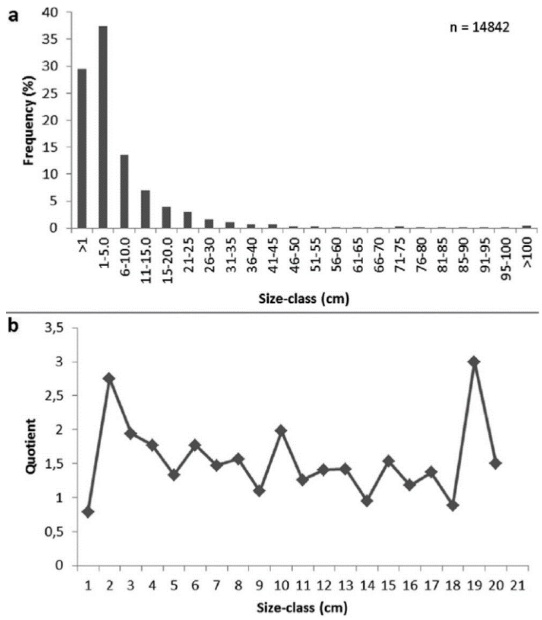

Figure 3.2: Population structure of *Prosopis* spp. in South Africa: (a) Size-class distributions (diameter at 30 cm above ground) and (b) quotients (ratios) of the numbers in different size classes

The shape of the SCD of *Prosopis* populations differed significantly between the three biomes (Succulent Karoo, Nama Karoo, Arid Savanna) and along different types of rivers (small ephemeral, large ephemeral and perennial) (Kolmogorov-Smirnov test, $p < 0.001$) (Table 3.1 and 3.2).

The Succulent Karoo biome had a higher proportion of trees in larger size classes, and the Nama-Karoo Arid Savanna had a higher proportion of juvenile trees and fewer in larger size classes (Figure 3.3 and Table 3.1). The Nama Karoo has the smallest proportion of large trees. Perennial rivers had a much smaller percentage of juveniles in their populations than the two other river types and more trees in larger size classes (Figure 3.3) which indicates less recruitment.

In areas with lower water availability the SCDs are dominated by smaller trees with a lack of larger trees in larger size-classes, whereas *Prosopis* populations with greater water availability show fewer trees in smaller size-classes and more in larger size-classes.

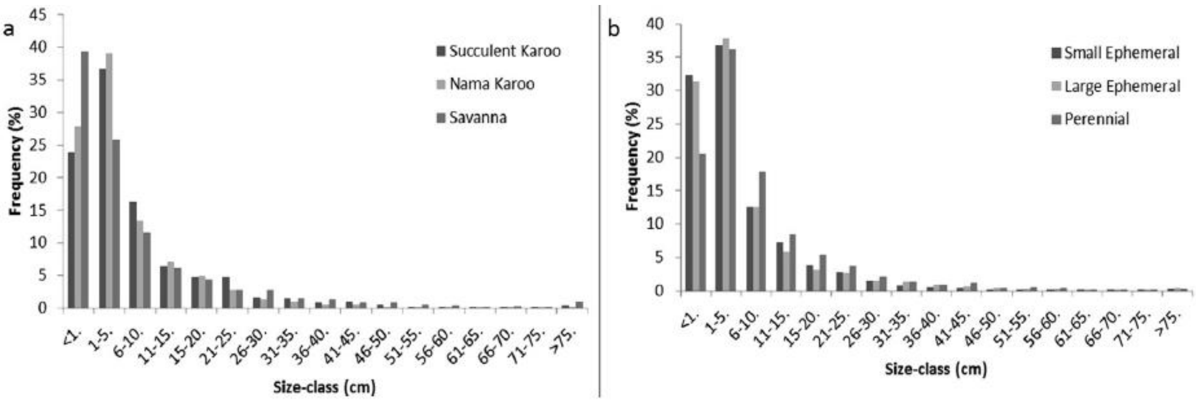

Figure 3.3: Size-class distributions of *Prosopis* (diameter at 30 cm above ground) in different biomes (a) and river types (b).

Table 3.1: A comparison between the overall population structure of *Prosopis* spp. at the 11 sites across three different biomes and river types.

	% juvenile	**R²**	**P- index**	**Kolmogorov-Smirnov against whole population**
Total population	66	0.944	4	-
Biome				
Succulent Karoo	60.6	0.881	6	0.001
Nama Karoo	67.1	0.926	7	0.001
Arid Savanna	65.7	0.850	5	0.001
River type				
Small Ephemeral	69.3	0.906	4	0.001
Large Ephemeral	69.5	0.926	5	0.001
Perennial	56.7	0.934	8	0.001

Table 3.2: Results of Kolmogorov-Smirnov tests comparing the size class distributions of *Prosopis* populations in different biomes and river types.

Biome	*Succulent Karoo*	*Nama Karoo*	*Arid Savanna*	**River Type**	*Small Ephemeral*	*Large Ephemeral*	*Perennial*
Succulent Karoo	-	0.001	0.001	*Tributary*	-	0.013	0.001
Nama Karoo	0.001	-	0.001	*Ephemeral*	0.013	-	0.001
Arid Savanna	0.001	0.001	-	*Perennial*	0.001	0.001	-

The percentage of juvenile plants in the whole *Prosopis* population was 66 % which is indicative of high recruitment rates (Table 3.1). The Succulent Karoo and perennial rivers had slightly lower percentages of juvenile plants (Table 3.1). The high R^2 values illustrate that *Prosopis* populations fit the reverse J-shape in the SCD curve very well, indicating a stable populations with high recruitment (Table 3.1). Populations of *Prosopis* in the Nama Karoo fitted the revers J-shape in the SCD curve better than populations in the other biomes. Quotients between successive size-classes show an unevenly distributed population, with high variation in small and large size-classes with more stability in the middle size-classes (Figure 3.1 and 3.4). The Succulent Karoo and Nama Karoo showed low fluctuating quotients, whereas *Prosopis* populations in the Arid-Savanna were stable except when it came to the larger size-classes.

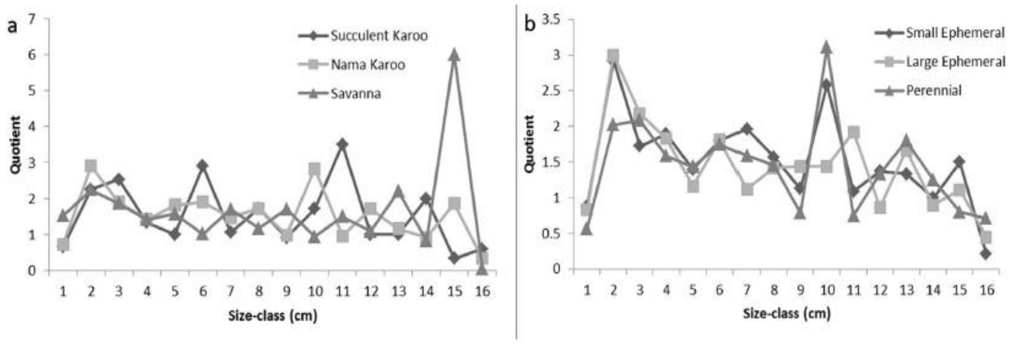

Figure 3.4: Quotients indicating population stability between successive size-classes for *Prosopis* populations in different biomes and river types.

The P-index was fairly similar for the different biomes (Table 3.1). Populations in perennial rivers (high water availability) showed the highest amount of discontinuity. This may be because there were more large trees and fewer juveniles in these areas. Populations in small ephemeral rivers had the lowest P-index, meaning that they had the most stable monotonically declining population size structures. The fact that P-values in all areas are very low suggests that these *Prosopis* populations are undergoing regular recruitment (i.e. SCD monotonically declining) areas across their range in South Africa.

3.5.2 Tree population trends under Prosopis invasion

All populations had positively skewed SCD curves (Figure 3.5) with the native trees populations in ZL invasions fitting the reverse J-shape in the SCD better than tree populations in MH-density invasions highlighted by the R^2 values (Figure 3.5; Table 3.3). Native tree populations under MH density invasions often had similar populations in the juvenile and adult populations but had lower numbers of trees in the middle size-classes (Figure 3.5). About 60 % of the native tree species found under ZL *Prosopis* invasion densities had significantly different SCDs population shapes compared to those under MH invasions (Kolmogorov-Smirnov $p < 0.05$) (Table 3.3). *Prosopis* is also having a negative impact on the population stability of another alien invasive tree in South Africa, *Tamarix ramosissima* (Table 3.3).

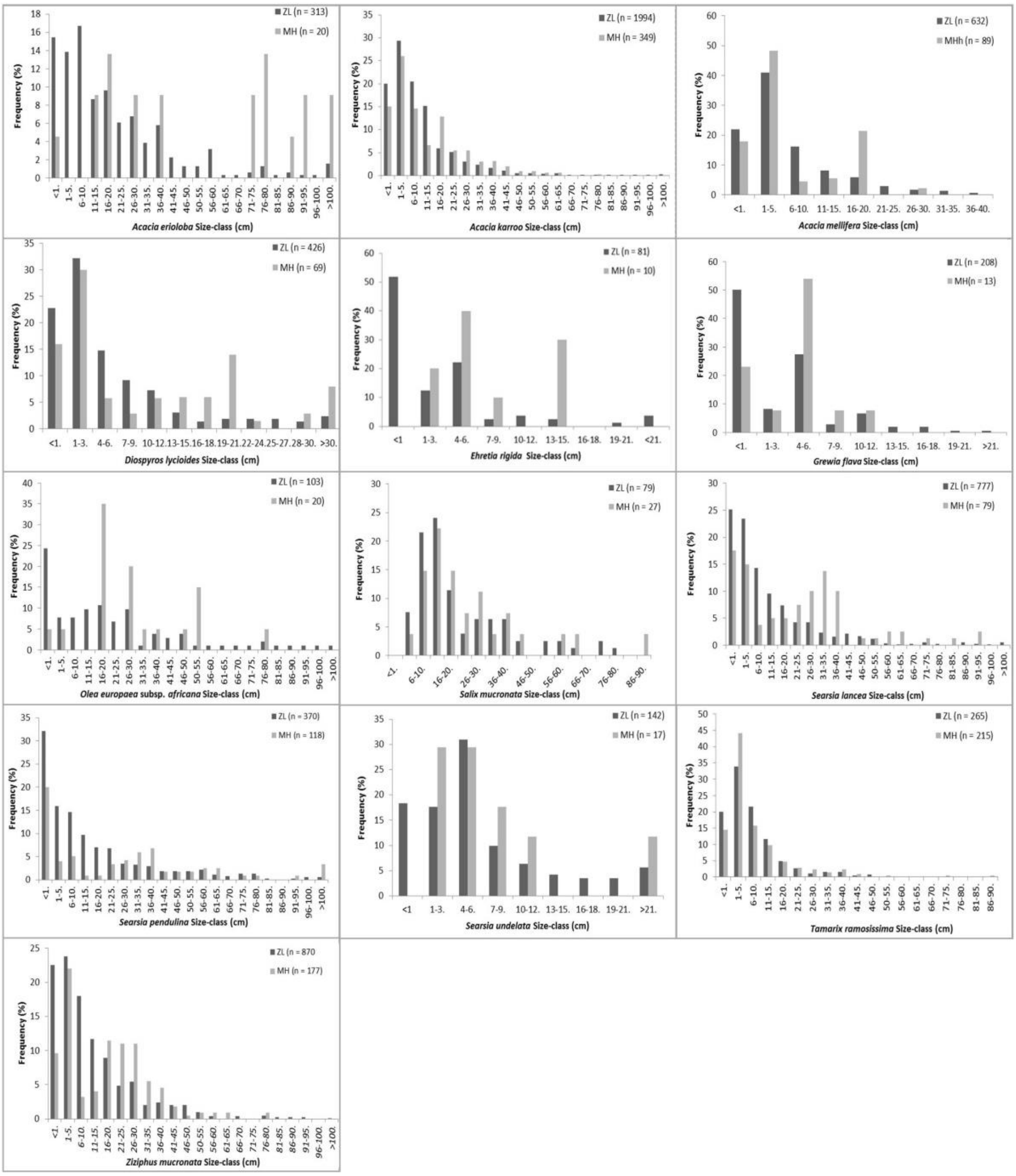

Figure 3.5: Population structures of native and alien invasive trees found in areas with zero-low (ZL) and moderate to high (MH) levels of *Prosopis* invasion based on stem diameters 30 cm above the ground.

Table 3.3: Population parameters for native trees and the alien *Tamarix ramosissima* at sites with (zero to low) ZL and (moderate to high) MH levels of *Prosopis* invasion.

Species	**ZL invasion**		**MH invasion**		**Kolmogorov-Smirnov**
	R^2	P-index	R^2	P-index	p-value
Acacia erioloba	0.780	40	0.006	138	0.01
Acacia karroo	0.886	18	0.856	23	0.007
Acacia mellifera	0.964	2	0.417	10	0.946
Diospyros lycioides	0.794	12	0.239	30	0.005
Ehretia rigida	0.723	12	0.181	12	0.640
Grewia flava	0.853	4	0.154	4	0.264
Olea europaea subsp. africana	0.735	32	0.139	66	0.01
Salix mucronata	0.217	50	0.231	54	0.9
Searsia lancea	0.831	37	0.596	58	0.002
Searsia pendulina	0.873	26	0.341	74	0.001
Searsia undulata	0.709	6	0.057	16	0.643
Tamarix ramosissima	0.898	10	0.786	28	0.001
Ziziphus mucronata	0.891	33	0.631	40	0.009

Quotients fluctuated for all species but were generally more stable for areas with ZL density *Prosopis* invasion compared to MH density invasion (Figure 3.6). The higher P-index for all species (except *Ehretia rigida* and *Grewia Flava* which were the same) in sites with MH density invasions compared to ZL *Prosopis* invasion density indicates a higher level of discontinuity within populations (Table 3.3) and, therefore, a less stable population structure.

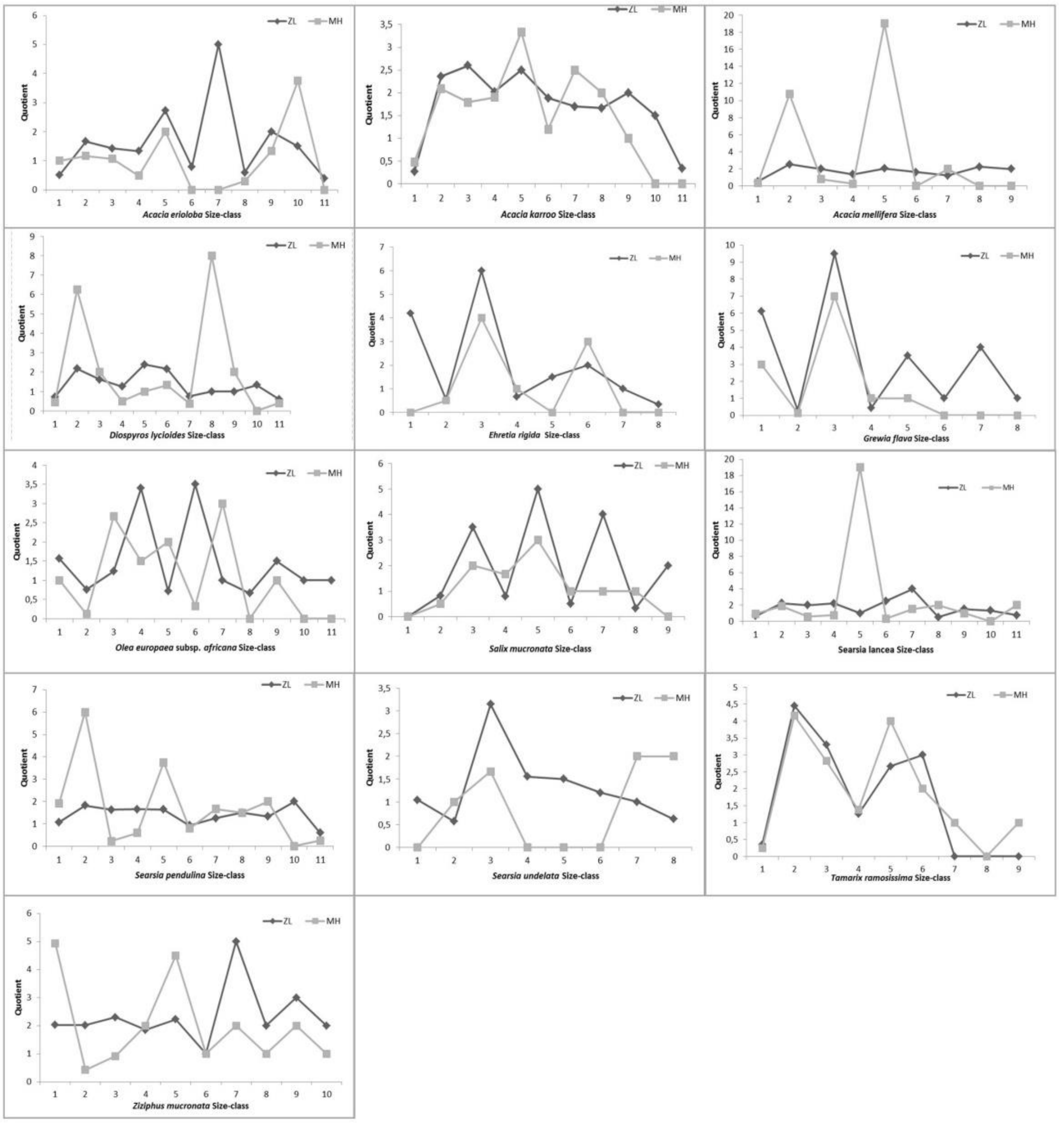

Figure 3.6: Quotients comparing native tree population stability between successive size-classes in areas of zero-low (ZL) and moderate to high (MH) levels of *Prosopis* invasion.

5.3. Effects of Prosopis invasion tree species mortality

As *Prosopis* basal area increased the basal area of dead native trees increased significantly ($p < 0.001$) (Figure 3.7). Approximately 36 % of the basal area mortality of woody plants is explained by *Prosopis* invasion. Larger *Prosopis* basal areas were also related to a significant increase in the number of dead trees/ha and the mean number of dead plant species per 100 m^2 at different *Prosopis* basal areas ($P < 0.001$).

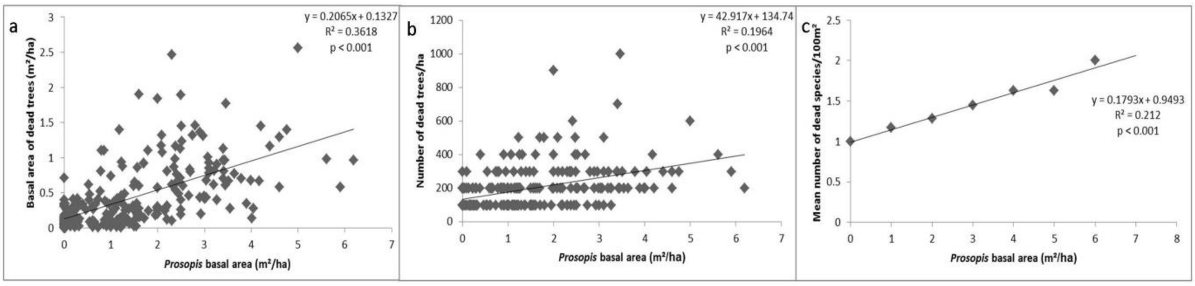

Figure 3.7: Scatter plot and regression analysis showing the effect (a) *Prosopis* basal area on dead tree basal area (b) *Prosopis* basal area and number of dead trees (c) mean number of dead species at different *Prosopis* basal areas.

3.6 Discussion

3.6.1 Prosopis population structures

The data on population structure of invasive *Prosopis* stands in South Africa illustrates strong and sustained recruitment, with stable reverse J-shaped SCD structures (Table 3.1, Figure 3.2 and 3.3). However, there are differences between biomes and river classes which show that abiotic factors are influencing *Prosopis* population structure in South Africa. Interestingly, *Prosopis* populations in areas with perennial rivers (Orange River) and with readily available water show lower proportions of juveniles in their population. This may be because *Prosopis* trees are larger on average in these areas and have higher mean basal areas populations, due to high water availability, which leads to greater intraspecific competition (Shackleton et al., under review). The Succulent Karoo also had higher basal area *Prosopis* populations and showed lower percentage juvenile populations (Shackleton et al., under review). Populations with lower densities had a higher percentage of juvenile in their populations, and were often found in more arid areas.

Prosopis populations structures in this study show greater percentage juveniles than Australia, which is indicative of higher recruitment rates (van Klinken et al., 2006), but similar to that of invasive populations in Kenya (Muturi et al., 2013) and those at early stages of invasion in Brazil (de Oliveira et al., 2012). Other studies in South Africa (at Riemvasmaak, to the west of Upington - outside our study area) found *Prosopis* populations to be lacking larger individuals (SDC of >1 to 7) but showing good reverse J-shaped population structures (Hoffman et al., 1995). The Riemvasmaak population was thought to be in the early stages of invasion which would account for the lack of larger trees (Hoffman et al., 1995). These findings confirm Van den Berg's (2010) conclusions that there has been a rapid recruitment and significant increases in the extent of *Prosopis* invasions between 1974 and 2007.

The findings also suggest that *Prosopis* populations are not undergoing self-thinning and that intraspecific competition is limiting trees in larger size-classes from being more dominant in South Africa (all the invasive stands were over 15 years old and many of them over 50 years old) (Figure 3.2). This leads to highly positively skewed population structure with a lack of larger individuals. Muturi et al. (2013) also noted a lack of self-thinning in invasive *Prosopis* stands in Kenya. However, in Australia, *Prosopis* population structures represent more of a normal curve shape, illustrating slower recruitment with moderate sized trees being dominant but continued population growth (van Klinken, 2006). The same thinning of native 'weedy' *Prosopis* has been found in populations in the USA and is also a common successional phenomenon in other semi-arid native 'weedy' tree species (Archer, 1995; Shackleton et al., 2013).

We do not understand the mechanism behind this self-regulation, and why it does not seem to apply to places like South Africa. Our findings highlight the need for improved control methods as *Prosopis* in South Africa shows high recruitment rates and rapid spread (Figure 3.2; Table 3.1; van den Berg 2010). There is also a need to understand the ecology of the species by adding a temporal component to guide management decisions

3.6.2 The impacts of Prosopis on native tree populations

The analysis of population SCDs suggests that *Prosopis* invasions are having a negative effect on native tree population structures and stability. In most cases native tree species recruitment is higher in non-invaded areas and indicators of population stability (P-index and quotients) were better in areas with low invasion densities relative to areas with moderate-high invasion (Figure 3.5 and 3.6; Table 3.3). However, it must be noted that recruitment in arid ecosystems is stochastic, and is highly dependent on above-average annual precipitation over a few seasons (Chesson et al. 2004). In most of the Northern Cape rainfall has been slightly above average in the three years preceding the study which may account for the high number of *Prosopis* juveniles and high juvenile populations for many native species (Agricultural Research Council, unpublished data). However, there has been high rainfall variability over the last 10 years, which may be contributing to the stochastic population's structures. There is seedling establishment for most native species and the larger native trees are present in invaded areas. However, the middle size classes for most native tree populations were lower in MH density *Prosopis* invasions (Figure 3.5). *Acacia erioloba*, *Ehretia rigida* and *Olea europaea subsp. africana* showed very little to no recruitment in areas invaded with *Prosopis* but did juveniles in areas with lower invasion (Figure 3.5). Salix mucronata was the only species with no juveniles in areas with both low and moderate to high invasion. This suggests that most native tree seedlings can initially establish in invasive *Prosopis* stands but are soon outcompeted. It also shows that large well-established trees can compete with *Prosopis*, although they are likely to die back eventually (Figure 3.5 and Figure 3.7). Native tree seedlings were also found in invasive *Prosopis* stands in Kenya, with a lack of native trees in the middle and large size-classes (Muturi et al., 2013). This illustrates the negative impacts of *Prosopis* on native species population stability in South Africa and also in other parts of Africa (Maturi et al., 2013). The results suggest that interspecific competition for limited resources between *Prosopis* and native trees is causing increased native tree mortality (Figure 3.7). Mascaro et al. (2008) also show many more dead stems in areas with tree invasions as opposed to uninvaded areas, as well as an overall lower recruitment in Hawai'i. In Brazil, *P. juliflora* invasions reduce native seedling growth rates by half and cause increased seedling mortality of native woody plants (de Souza Nascimento et al., 2014). The increased native tree mortality and negative impact on population structure is of particular concern for protected and keystone species in South Africa like *Acacia erioloba* (Milton and Dean, 1995; Seymour et al., 2003) (Figure 3.5). *Prosopis* invasions also negatively impact *A. erioloba* populations due to increased competition for ground water, as they have deeper root systems and are causing substantial dieback of this species (Schachtschneider and February, 2013). Interestingly, *Prosopis* also seems to be slowly out-competing another invasive alien tree species - *Tamarix ramosissima*.

The formation of these dense monospecific stands of *Prosopis* dominated by small to moderate sized trees in invaded areas as seen in South Africa is particularly problematic (Figure 3.2). This is because these *Prosopis* thickets reduce grazing potential, access to land, and produce small shrubby trees that provide no little or no goods and services for human use (Mwangi and Swallow, 2005; Shackleton et al., 2014). The loss of native trees due to *Prosopis* invasion also has negative effects on other species like birds, due to reduction of suitable nesting sites and food availability (Dean et al., 2002). *Prosopis* invasion also affects local human communities who rely on many specific natural resources from native trees, for example *A. erioloba* is extremely popular for fuelwood and fodder (Powell 2001; Stave et al., 2007).

3.6.3 Prosopis management

Our findings illustrate the need for the management of *Prosopis*, as it is impacting native biodiversity and recruiting rapidly. The insights on *Prosopis* population structures discussed here will be useful for guiding management. *Prosopis* is often managed using a control-through-utilisation approach in developing countries, as this provides valuable resources (Pasiecznik and Felker, 2006; Kazmi, 2009; Choge et al., 2012). Having an understanding of the SCD of *Prosopis* populations is essential when considering this approach as it can inform managers how many trees can be harvested and allow for the calculation of potential profits. One suggestion is to produce timber products such as furniture and flooring using invasive *Prosopis* trees in Africa, which is commonly done with *Prosopis* in its native range. However, trees need to be greater than 20 cm in diameter for this (Felker, 2002). The *Prosopis* SCD (Figure 3.2) shows that trees of this size-class are uncommon in invasive stands in South Africa. Areas in Kenya also lack larger trees (Muturi et al., 2013). This suggests that management of *Prosopis* through timber extraction is not a viable option in South Africa and possibly in other parts of Africa such as Kenya. However, there is potential for the use and management of *Prosopis* to create charcoal, bio-char and ethanol, which can be made from smaller trees (Kazmi, 2009). Localised small-scale power generation is also viable for these smaller sized trees and power plants are currently being built in Kenya to aid local development and try and reduce *Prosopis* invasion cover (Shackleton et al., 2014).

At a local level, having information of invasive species population structures can greatly aid management. Currently, planning for clearing projects conducted by the Working for Water programme is based on ad hoc estimates of population structure based on crude visual estimation. Knowledge of the SCDs of populations and having this baseline data will enable Working for Water to better calculate clearing costs. Information on invasive *Prosopis* population structure is also needed for monitoring, to assess the effectiveness of management strategies. This baseline information is also needed if adaptive management is going to be implemented to track project success.

3.7 Conclusions and priorities for future research

Prosopis invasions in South Africa are impacting the population stability of many native tree species. These trees provide important ecosystem services in the arid and semi-arid parts of South Africa and therefore *Prosopis* invasions need to be managed to mitigate against the loss of these services. This research can be taken further by adding a temporal component; this will involve re-visiting sites to collect data to facilitate population growth modelling and elasticity analysis which would allow for more detailed comparisons between different populations and for the calculation of population growth rates (Golubov et al., 1999). There is also a need for further research on the impacts of *Prosopis* invasions on species - especially, rare, endemic and endangered species, such as the Riverine rabbit (*Bunolagus monticularis*). A national strategy is needed to guide the management of invasive populations of *Prosopis* in South Africa and in other regions where it is invasive, and an understanding *Prosopis* population structure and the impacts of invasion on native tree species will help to facilitate this.

Acknowledgments

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Chapter 4: Stakeholder perceptions and practices regarding *Prosopis* (mesquite) invasions and management in South Africa

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Abstract

Invasive alien trees impact the environment and human livelihoods. The human dimensions of such invasions are less well understood than the ecological aspects, and this is hindering the development of effective management strategies. Semi-structured interviews were undertaken to investigate the knowledge and perceptions *Prosopis* between different stakeholder groups. Chi-squared tests, Welch ANOVAs and Principle Component Analyses were run. Factors such as land tenure and proximity to invasions were especially important for explaining differences in perceptions and practices relating to *Prosopis* among different stakeholder groups. Most respondents were aware of *Prosopis* and considered it to be invasive (i.e., spreading). Costs associated with *Prosopis* were perceived to exceed benefits, and most stakeholders wanted to see a reduction in the abundance of *Prosopis* stands. The mean total cost for the management of *Prosopis* was US$ 1 914 yr-1 per farm, where costs ranged from under US$ 10 to over UD$ 500 per ha based on invasion densities and objectives for control. The findings highlight the need for more effective management interventions.

4.1 Introduction

Biological invasions impact biodiversity, ecosystem services and human well-being globally and further research on invasion dynamics, impacts and options for management is needed to identify options for sustainable management (Pimentel, 2002; Pyšek and Richardson, 2010). Research on invasive species is normally approached from the domain of ecology, and more recently economics. Far less attention has been given to understanding the wider social dimensions of invasions (McNeely, 2001; García-Llorente et al. 2008; 2011). Insights on the human dimensions of invasive alien species are essential for effective decision making; in many cases complex social issues delineate the full suite of benefits and costs associated with invasions (García-Llorente et al. 2008). Research is needed to evaluate stakeholder knowledge, perceptions, practices, awareness and wants and needs relating to biological invasions (Shackleton et al. 2007; Eiswerth et al. 2011; Kull, 2011; Rai and Scarborough, 2014). This is particularly important for invasive species that were introduced for specific purposes and where complex conflicts of interest now exist due to the provision of valuable consumptive and non-consumptive services (Shackleton et al. 2007; Low, 2012a; Dickie et al. 2014; van Wilgen and Richardson 2014).

Many invasive alien species such as Australian acacias, *Opuntia ficus-indica* and *Prosopis* provide services such as fuelwood, medicine and edible products to local communities (de Neergard et al. 2005; Pasiecznik et al. 2006; Shackleton et al. 2007; Shackleton et al. 2011).

In the semi-arid parts of Brazil the direct-use services provided by invasive species were seen as more important for local communities than native species (Dos Santos et al. 2014). *Pinus* spp., *Prosopis* and other invasive trees are also exploited commercially on a large scale by private companies (Moran et al. 2002; Shackleton et al. 2014). Additionally, species like *Acer platanoides*, *Jacaranda mimosifolia* and *Pinus* are valued for aesthetic and cultural reasons by communities (Foster and Sandberg, 2004; Dickie et al. 2014). However, these species also have negative impacts on biodiversity, ecosystem services and local livelihoods.

Prosopis taxa have been introduced to many parts of the world over past centuries to curb desertification, stabilise soils and to provide services such as fuelwood, fodder and shade to aid local communities (Pasiecznik et al. 2001; Low, 2012b; Shackleton et al. 2014). As with most invasive alien woody plants around the world (Richardson et al. 2014), *Prosopis* introductions were initially seen as only beneficial to most stakeholders. However, negative perceptions of *Prosopis* grew as its abundance increased and adverse effects of invasions emerged (Pasiecznik et al. 2001; Mwangi and Swallow, 2005; Maundu et al. 2009; Shackleton et al. 2014).

There is growing evidence of the costs of *Prosopis* invasions on biodiversity, ecosystem services and the economy in South Africa (Shackleton et al. 2014). This includes reductions in bird and insect species richness and diversity (Steenkamp and Chown, 1996; Dean et al. 2002), *Prosopis* causing increased mortality of *Acacia erioloba* due to competition for limited resources (Schachtschneider and February, 2013), loss of grazing potential (Ndhlovu et al. 2011), impacts on water resources (Dzikiti et al. 2013) and negative impacts on the South African economy (Wise et al. 2012). On the other hand it is still used for fodder and fuelwood in its invasive range (Wise et al. 2012). However, understanding of the social dimensions of *Prosopis* invasions is poor, and this is thwarting attempts to implement effective management to reduce the costs while, where possible, maintaining some or all of the benefits (Richardson, 1998). Key factors that influence human perceptions of invasive alien species generally relate to the abundance of the invader, the services it provides, the time since introduction, the mode of introduction and many socio-political features of human societies (Binggeli, 2001; Donlan and Martin, 2004; Shackleton et al. 2007; Kull et al. 2011; Rai and Scarborough, 2014).

Current management interventions for *Prosopis* in South Africa focus on an integrated approach involving mechanical control and chemical control by the national Working for Water Programme, and biological control (Zachariades et al. 2011; van Wilgen et al. 2012). Although success has been achieved in reducing the density and impacts of invasive stands on a small scale in some areas, the extent and magnitude of impacts is increasing rapidly (Wise et al 2012). Between 1996 and 2008 the cover of *Prosopis* in South Africa increased by 35%, despite the expenditure of R 435.5 million (US$ 42.7 million) on management (van Wilgen et al. 2012). The release of further biological control agents may be the only cost effective way of managing *Prosopis* invasions. However, further work in this area has been put on hold due to the conflicts of interest surrounding *Prosopis* use (Zachariades et al. 2011; Wise et al. 2012). A national strategy for tackling invasive *Prosopis*, along the lines of one proposed for Australian acacia species in South Africa (van Wilgen et al. 2011), is urgently needed. A key prerequisite for such a strategy is a much improved understanding of the social dimensions of the problem.

In many cases management strategies have been implemented without due consultation with stakeholders about their perceptions and needs. This has in some cases resulted in conflicts of interest issues relating to livelihood vulnerability and has led to wastage of limited funding (Davis et al. 2011; McNeely, 2011; Rai et al. 2012). Focussed social studies can provide valuable insights that are helpful for developing shared goals for management and the means for achieving such goals (Kreuter et al. 2005). However, some social studies on invasive species have only focused on benefits (de Neergard et al. 2005; Shackleton et al. 2011). Although this is clearly important, costs also need to be considered to provide comprehensive guidelines to inform management interventions. Social studies can also build platforms for improving communication between scientists, managers and the public (Dangles et al. 2010; Heger et al. 2013). In the case of *Prosopis* invasions in South Africa, better knowledge of the human dimensions could certainly help to highlight benefits vs. costs, explore new opportunities for effective management, and justify contentious interventions.

The aims of this study are to: (1) elucidate the factors that determine the understanding and perceptions of a woody invasive plant that has both benefits and costs, using *Prosopis* invasions in South Africa as a case study; and (2) compare and contrast the knowledge, perceptions and practices relating to *Prosopis* among different stakeholders (3) use the information gained to suggest management interventions in the future.

4.2 Study sites

The study was conducted at 10 locations across the invasive range of *Prosopis* in South Africa (Figure 4.1 and 4.2). The area covers the Succulent Karoo, Nama Karoo and Savanna biomes in the Northern Cape province. The area included sites with private and communal land tenure systems, and towns and villages of different sizes. Kimberly and Upington are the two largest towns in the study area with populations of over 200 000 and 50 000 people respectively. Calvinia, Prieska and Carnavon are small towns with populations of 10 000 to 20 000 people. The other towns and villages have fewer than 5000 people.

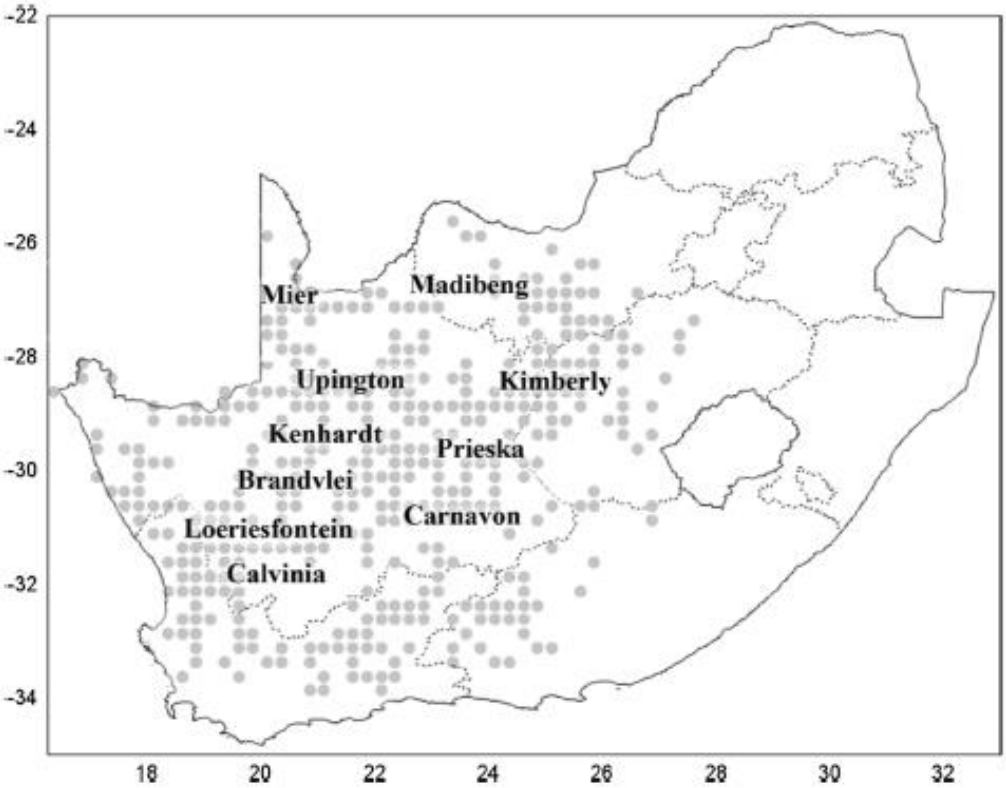

Figure 4.1: Towns in the Northern Cape province, South Africa, where surveys were conducted to determine human perceptions relating to *Prosopis* invasions. The dots represent the distribution of *Prosopis* in South Africa (Source of Map – Henderson, SAPIA database, ARC-Plant Protection Research Institute, Pretoria).

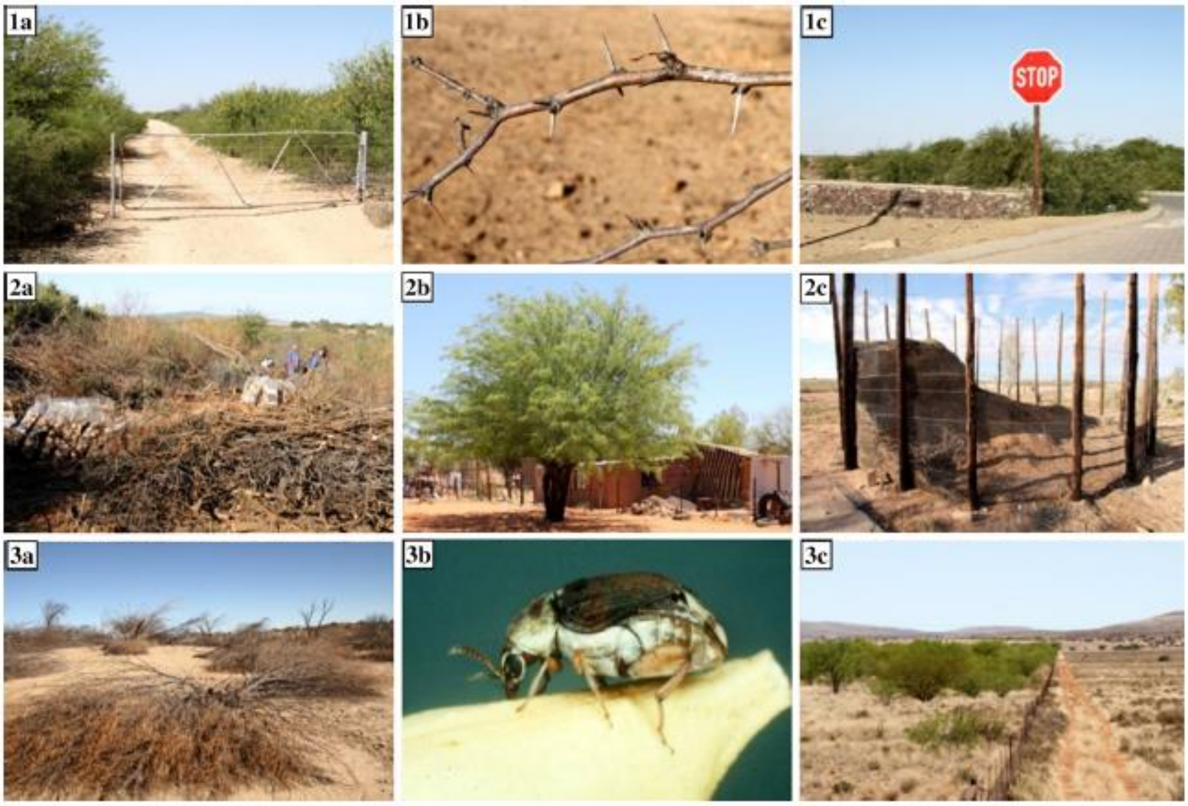

Figure 4.2: Invasive *Prosopis* species in South Africa: costs, benefits and management options. Panel 1 shows costs: (1a) *Prosopis* encroachment on livestock rangelands; (1b) *Prosopis* thorns that injure humans and animals and damage tyres; (1c) *Prosopis* encroaching on urban infrastructure. Panel two shows benefits: (2a) Workers making fuelwood from *Prosopis*; (2b) *Prosopis* being used as a shade and ornamental tree in a rural village; (2c) *Prosopis* pods collected to be milled and fed to livestock. Panel three shows management options: (3a) Mechanical and chemical clearing of *Prosopis* invasions; (3b) *Algarobius prosopis* (Bruchidae; a seed-attacking insect introduced for biological control); (3c) Fence-line contrast of a farmer who clears annually and one who does not manage *Prosopis.* Photos: R.T. Shackleton and J.H. Hoffmann (3b).

Twenty years after the first democratic elections in South Africa, the legacy of apartheid is still strongly reflected in the distribution of different racial groups across the country. Most rural land belongs to Whites and is managed as privately-owned commercial farms. There are smaller areas of communal land (including some areas that were demarcated as "homelands" before 1994); these are populated mainly by Black and Coloured (mixed race) groups. The primary land use in these areas is subsistence farming. In urban settings, towns are still divided by social-economic status and racial group, with moderately affluent suburbs (comprising mostly Whites) and informal settlements (populated mainly by Black and Coloured groups). Sharp contrasts in social and economic status exist between these four main stakeholder groups over the study area (Table 4.1). The economy of the province is dominated by mining, tourism and agriculture: fruit and vegetables along perennial rivers and extensive livestock farming in rangeland areas. The sites provide a representative cross-section of the prevailing environmental and socio-political conditions across the invasive range of *Prosopis* in South Africa.

Table 4.1: Demographics of sample population (mean±sd) of the different stakeholders interviewed [n = (farmers – 133; urban informal – 236; urban affluent – 130; rural 100). Hh = household

Stakeholder category	Mean age (yrs)	Gender (% male)	Race group (%)	Mean education of hh head (no. years)	Mean no. people in hh	Mean no. wage earners per hh	Mean no. state grants per hh	Mean no. state pensions per hh	Modal income bracket (Thousands of R/month)
Farmers	53±134	81	Coloured (12) White (88)	13±3	3±1	2±0	0±0	0±0	30-40
Communal rural	47±16	47	Black (25) Coloured (75)	7±4	5±3	1±1	2±1	1±1	0-5
Urban - Affluent	48±13	57	Black (8) Coloured (4) White (88)	14±2	3±1	2±1	0±0	0±0	<40
Urban - Informal	48±33	38	Black (28) Coloured (72)	8±4	5±3	1±1	1±1	1±1	0-5

4.3 Methods

Four key stakeholder groups were identified in the study area: two in rural areas (farmers and villagers living on communal lands) and two in urban areas (people living in poor informal settlements and those living in affluent suburbs). Semi-structured household interviews were administered with these stakeholder groups to ensure that the views of different population groups were considered, but also to explore differences in perceptions, practices and knowledge regarding *Prosopis* invasions among stakeholder groups. The interviews comprised a mix of closed-ended, open-ended and ranking questions and had two primary parts: (1) demographic data; and (2) an assessment of perceptions, understanding, practices and local knowledge relating to *Prosopis* invasions. The latter included questions relating to knowledge of *Prosopis* (e.g. whether it is invasive or not, its benefits and costs), issues relating to management and the sources of knowledge (if any) regarding *Prosopis* invasions. Household interviews were conducted in a random manner in the home language of the respondents (Afrikaans, English, Tswana or Xhosa). A translator was used where the respondents were not fully conversant in English. Interviews were directed at the oldest person present at the house.

In total 639 interviews were conducted across 10 sites within the invasive range of *Prosopis* in South Africa (Figure 4.1). This included; 130 household interviews with commercial farmers, 409 interviews in urban areas – (276 in informal settlements, 133 in affluent town suburbs), and 100 in rural villages situated on communal land. Interviews with farmers were conducted at all 10 sites, respondents from urban areas were not included in Mier and Madibeng sites as these areas only had small rural communal land villages. Mier and Madibeng were the only sites where household interviews were administered with people living in rural communal land areas. Sampling numbers differed between different stakeholder groups because of logistical issues of reaching respondents at their homes as well as being based on the population demographics of the different groups. For most areas there were a very limited number of farmers in the area based on their large farm sizes. Villages occurring in the communal rural land areas were very small, so sample sizes were very limited. More interviews than were initially planned were conducted with people in urban informal settlements as the interviews at these sites went faster than planned because unemployment was high and most households had someone present throughout the day. Interview times in these communities were therefore not restricted to early evenings.

Chi-squared tests (χ^2) and Welch ANOVAs were used to compare responses between the four different stakeholder groups. Principal Component Analyses were run to assess the relationship between respondents' demographic variables and understanding and perceptions relating to *Prosopis* invasions in South Africa.

4.4 Results

4.4.1 Knowledge and perceptions on Prosopis invasions

The majority of the sample population were aware of *Prosopis* (Table 4.2). However, a significantly poorer knowledge of *Prosopis* was found in urban suburbs where 35 % of respondents did not know what *Prosopis* was (Table 4.2). Knowledge of *Prosopis* was related to town size and proximity to invasions, with people in urban informal settlements and affluent areas in large towns (Kimberly and Upington) having a significantly poorer knowledge of *Prosopis* (informal settlements: 78.2 %; affluent areas: 33.7 % of people had no knowledge) compared to a much lower percentage in smaller towns (informal settlements: 2.1 %; affluent areas: 6.0 % not knowing) (χ^2 96.8; df = 1; p < 0.001).

Table 4.2: Stakeholder responses (mean) to questions relating to knowledge and perceptions of *Prosopis* in South Africa.

Questions	Farmers	Urban - Informal	Urban - Affluent	Communal land	χ^2, df, p-value
Do you know what *Prosopis* is? (also accepted and used local names mentioned above) (% people responding yes)	100	93.5	65.4	100	123.8; 3; 0.001
Do you have *Prosopis* on your property? (% yes)	94	29.6	13.5	61	224.1; 3; 0.001
Did you plant the *Prosopis* on your property? (% yes)	1.5	3.5	4.8	3.6	6.4; 3; 0.1
Is *Prosopis* spreading on your property? (% yes)	96.7	78.2	83.5	98.4	14.1; 3; 0.003
Is *Prosopis* spreading in the environment around you? (% yes)	100	87.3	74.4	100	149.7; 6; 0.001
If you don't have *Prosopis* trees on your property would you like to it? (% yes)	0	9.8	0.9	2.1	42.4; 6; 0.001
Did you know *Prosopis* is an invasive alien tree?	100	37.1	58.3	53	146.0; 3; 0.001

Prosopis invasions were much more prevalent on farms and rural communal areas compared to urban properties. Ninety-four percent of farmers had *Prosopis* on their land, and on average more people in rural communal areas (61 %) than people in urban areas (29.6 % in informal settlements and 13.45 in affluent suburbs) had *Prosopis* in their gardens. Fifty percent of farmers categorized *Prosopis* as being common on their properties, 22 % had moderate invasions and 28 % had small *Prosopis* invasions on their farms. On a household level, there were on average 2.4±3.8 *Prosopis* trees in the gardens of people that had *Prosopis* on their land. A small minority of stakeholders had planted *Prosopis* themselves on their property (Table 4.2). Most respondents said that *Prosopis* had been on their properties when they arrived there (farmers 45.7 %; informal settlements 40 %; affluent suburbs 68.8 %; and rural communal households 34 %). Approximately a quarter of farmers (27.6 %), and approximately half of households in informal settlements (46.6 %), and rural villages (52 %) reported that *Prosopis* had spread naturally onto their land, but only 6.2 % of households in affluent suburbs held this view. Despite a dislike for *Prosopis* in most stakeholder groups, some urban dwellers (9.8% informal; 0.9% affluent) reported a desire to plant *Prosopis* trees on their properties. The most cited reasons for this were to provide shade and greenery which is lacking in informal settlements. However, many people said any easy-to-grow tree would be acceptable; it did not have to be *Prosopis*.

Prosopis was seen to be spreading on people's properties and in the local environment (Table 4.2; Figure 4.2). People from farms and in rural communal areas supported the notion of *Prosopis* as an invasive species significantly more than people from urban areas. Many people in urban areas did not know whether or not *Prosopis* was invasive or spreading (10.5 % in informal settlements and 23.6 % in affluent suburbs).

There were contrasts between different stakeholder groups regarding the knowledge of *Prosopis* being invasive. All the farmers (100 %) knew that *Prosopis* is an invasive alien tree. Other stakeholder groups were significantly less aware of this, and people in informal settlements had the least knowledge of this fact (37.1 %) (Table 4.2).

4.4.2 Benefits and costs of Prosopis

All stakeholder groups considered the costs of *Prosopis* to be greater than the benefits (Figures 4.3 and 4.4). Although this sentiment was present across stakeholder groups (Figure 4.3), there were significantly different views between different stakeholders. More than 90 % of farmers and people in rural communal areas viewed *Prosopis* as harmful – much more so than people in urban areas (informal 64.2 % and affluent 50.6 %). Significantly more people from urban informal settlements viewed *Prosopis* as beneficial as compared to other stakeholder groups, most likely because invasion densities close to towns and within towns are much lower than in rangelands. Some respondents did not know whether *Prosopis* was beneficial or not (9.7 %) – a substantial proportion of respondents (33.1 %) who held this view resided in urban affluent areas, where awareness of *Prosopis* was lower (Figure 4.3). Few respondents recognized any effects of *Prosopis* on their livelihood (6.3 %), with significantly more urban people reporting this compared to other stakeholder groups, largely because urban people lacked first-hand experience/observation of *Prosopis* invasions.

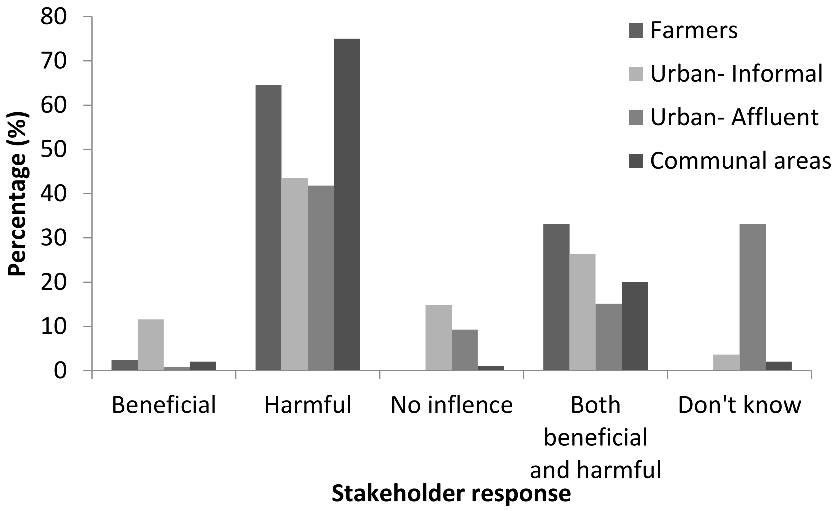

Figure 4.3: Stakeholder views of the benefits and costs of *Prosopis* in South Africa (χ^2 = 205.1; df = 12; p < 0.001).

Prosopis was recognized as beneficial to some people in the study area (Figure 4.3). In total, 13 types of benefits were reported, the most common being fodder, fuelwood and shade (Table 4.3). A small minority of respondents (< 5 %) also mentioned other direct and indirect benefits of *Prosopis*, such as honey, local greenery, aesthetic value in towns and gardens, acting as wind breaks, creating privacy for households, and as an ingredient for the brewing of beer/alcohol.

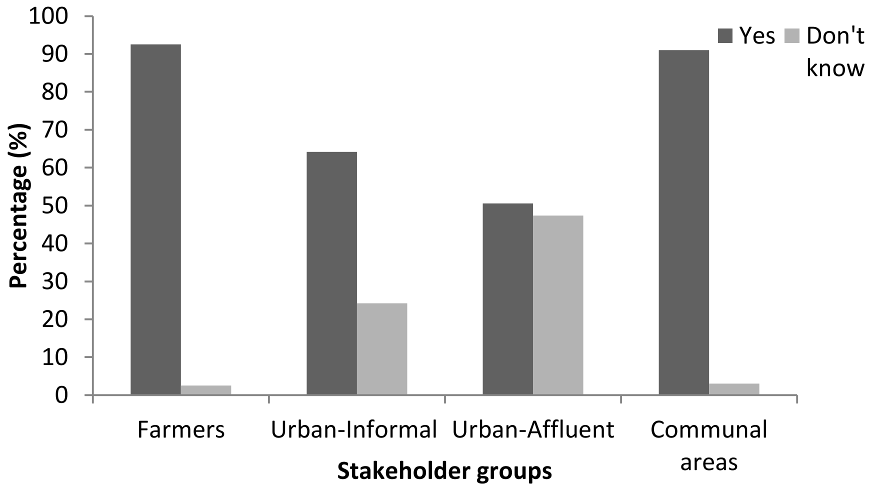

Figure 4.4: Different views of stakeholder groups on whether costs associated with *Prosopis* are greater than the benefits? (χ^2 = 135.8; df = 6; p < 0.001).

Many farmers mentioned that despite the use of *Prosopis* as a fodder source for livestock, the consumption of pods by livestock facilitated the spread of *Prosopis* on their properties. Some farmers (3.8 %) reported using an alternate feeding strategy that maximizes *Prosopis* fodder benefits while reducing spread. This involved milling pods to powder (breaking up the seeds) prior to providing them as a supplement to livestock (Figure 4.2). This is, however, labour intensive and expensive. In the affluent suburbs *Prosopis* was seen as having medicinal benefits. Many respondents reported its use for stabilizing blood-sugar levels in the form of a South African product called “Manna”. This is manufactured from *Prosopis* pods and is popular in affluent communities. Many people in informal settlements highlighted the use of *Prosopis* pods for food, predominantly as snack eaten by children. Eating *Prosopis* pods as an adult carries a negative stigma of being poor. *Prosopis* was seen as promoting local job creation, particularly by respondents in urban informal and affluent suburbs. These jobs included the collection of pods in the Prieska area for the company that produces ‘Manna’, as well clearing *Prosopis* as part of the Working for Water programme. Although not specifically mentioned by respondents as a form of job creation, there were people in most communities who sold fuelwood made from *Prosopis*, and many farmers sold wood to try and recover the costs of clearing – which also led to job creation.

Table 4.3: Stakeholder views of benefits (mean) provided by *Prosopis* (5% and above) ($\chi^2 = 221.5$; df = 15; $p < 0.001$).

Benefits	Farmers	Urban-Informal	Urban-Affluent	Communal areas
Fodder	63.1	21.7	23.3	25
Fuelwood	16.2	17	21.8	19
Medicine	1.5	1.1	7.5	0
Shade	16.9	29.3	12.9	26
Children eat pods	0	6.2	0.8	0
Provides jobs	0	6.2	3.8	0

The types and the average number of benefits listed differed significantly between the various stakeholders groups. ($p < 0.001$) (Table 4.3). Only fuelwood and shade were commonly mentioned across all stakeholder groups. Fodder was mentioned on average three times more by farmers than other stakeholders, and the fact that *Prosopis* invasions led to job creation and that *Prosopis* provides edible products was mentioned most by respondents from informal settlements. The use of *Prosopis* to produce the blood sugar medicine was mentioned mainly by people residing in urban affluent areas. The provision of jobs for collectors selling pods to make Manna in Prieska and jobs provided by WfW are important in these rural areas where other employment is low.

In total, 28 different costs associated with *Prosopis* were mentioned (Table 4.4; Figure 4.2 and 4.3). The most common costs mentioned were negative impacts on water supply and grazing potential, loss of native species (including grass, shrubs and trees), problems with encroachment, and transformation of land (Table 4.4). Further complaints (less than 5%) relating to *Prosopis* included; death of livestock, increased livestock illness, allergies and asthma, changing of the taste of water, a reduction in wool quality, flooding caused by it blocking river systems, and damage to electrical lines. *Prosopis* was also seen as aesthetically unpleasing, responsible for giving children stomach problems (after pod ingestion), providing refuge for criminal activities, and killing of garden plants. The high costs associated with managing invasions, and the difficulty of removing *Prosopis* trees (as they coppice profusely) were also seen as problematic costs associated with the tree.

Table 4.4: Stakeholder views of the costs/harm (mean) caused by *Prosopis* (5% and above) ($\chi^2 = 575.4$; df = 45; $p < 0.001$).

Negative impacts	Farmers	Urban- Informal	Urban- Affluent	Communal areas
Reduced Water	75.2	38.4	42	75
Reduces grazing	73.7	11.6	24.8	29
Kills native plant spp.	69.5	11.6	17.3	49
Encroachment and loss of access of land	65.4	23.1	27.1	44
Roots break foundations/houses	3	25	6.8	30
Expensive to control	19.5	0.7	0	0
Makes town/garden dirty	0	14.9	3	1
Reduces property value	13.5	0	0	0
Thorns cause injury to animals and people	5.3	13.8	1.5	45
Roots block bore holes	12	0	0	11
Supports pest animals	9.7	0	0.8	0
Reduces profits	5.3	0	0	0
Thorns cause tyre damage	3.8	0	0	8
Blocks pipes	2.3	5.1	5.2	7
Reduces supply of native wood	2.3	2.2	0	11
Impacts farming	0	0	5.2	0

One farmer grew up with *Prosopis* invasions along a small river on their farm, and mentioned the first time he ever saw the river flow was after *Prosopis* stands were cleared from along its banks after he inherited the farm. Many different stakeholders noted that dense thickets caused loss of access to recreational areas in urban areas and loss of access to rivers and grazing areas in rangelands. *Prosopis* thorns were seen as problematic across all stakeholder groups as they injure livestock and people and puncture car tires. Many people mentioned that the thorns were poisonous and caused infections. All stakeholders mentioned problems associated with the deep-penetrating root systems of *Prosopis* trees; these block bore holes, block and burst underground water pipes and cause buildings to crack and break when the roots shift foundations.

Prosopis had negative economic impacts for farmers, including high costs for control, loss of profits and decreased in the value of farms. The costs of clearing can exceed the purchase price of the land. One farmer mentioned that it costs R 5000 per ha to clear *Prosopis* on land that he purchased for R 1500 per ha.

Farmers mentioned that *Prosopis* thickets benefitted problem animal species such as jackals (which eat lambs), aardvarks and porcupines (which break water pipes), baboons and feral pigs (which cause general damage). On the other hand, one farmer noted an increase in populations of the native kudu *Tragelaphus strepsiceros* due to *Prosopis* invasions, which he considered a benefit. *Prosopis* was seen to reduce the abundance of native tree species such as *Acacia erioloba* and *A. karroo* (both important fuelwood species). The grazing potential of land has also been reduced by *Prosopis* through the reduction of grasses and Karoo shrubs. In urban areas *Prosopis* caused gardens and the city streets to become 'dirty' due to leaf and podfall in the dry season.

The reported cost categories ranged from those associated with single trees causing problems at a household level (blocking water pipes, cracking foundations, growing into electricity liens, making gardens dirty) to those at a landscape level (biodiversity loss, encroachment of land, loss of grazing, water uptake). Chi-squared tests revealed that the types of costs and number of costs listed differed significantly between different stakeholder groups ($p < 0.001$). People in rural areas, farms and communal areas were able to identify more costs (3.8 and 3.3 per interviewee) compared with people in urban informal settlements (1.6) and people in affluent urban areas (1.4).

4.4.3 Prosopis management

The majority of farmers (88 %) implemented some form of management to control invasions (Table 4.5; Figure 4.2). The most common techniques included manual cutting and herbicide application to stumps. However, some farmers rented earth-moving machinery to dig up invasive *Prosopis* trees, while others applied only a foliar herbicide and burnt the bases of large trees. Despite the presence of biological control agents (seed-feeding beetles), many farmers regarded the control method as ineffective. No respondents purposefully used the control-through-utilization approach, although many farmers did use the wood from felled trees to partly cover the costs of clearing. Others collected pods to add to feed. Some suggested that creating large-scale industries to produce paper or bio-energy could improve control as it would introduce a large-scale demand for *Prosopis*. However, high transport costs to and from remote areas was viewed as a potential problem for rolling out such enterprises.

Table 4.5: Stakeholder perceptions, views and practices (mean ± sd) relation to the management of *Prosopis* invasions in South Africa.

Questions	**Stakeholder groups**				
	Farmers	**Urban-Informal**	**Urban-Affluent**	**Communal areas**	**χ^2, df, p-value**
Do you control *Prosopis* on your property? (% yes)	87.8	21.3	17.6	46.6	103,9; 3; 0.001
Average annual cost of control? (Rand)	20 667±12024	0	50±22	0	8.3; 3; 0.001
Would you like to see a decrease in *Prosopis* population densities in your area (environment)?	100	92.8	100	99	4.3; 3; 0.23
Would you be happy for the Working for Water programme to clear *Prosopis* on your property? (% yes)	73.4	73.9	67.4	94	90.7; 6; 0.001

Expenditure on the management of *Prosopis* was highly variable and was based on invasion densities and goals of management. Expenditure to prevent establishment of invasions in uninvaded camps was in some cases lower than R 100 per ha and for the removal of moderate to dense invasions farmers estimated they were paying R 600-2500 per ha using manual cutting and poisoning and over R 5000 per ha using excavators. The annual average costs of control implemented by farmers was high with a mean of expenditure of R 20 667±12 024 (R1 = US$ 11.3 – November 2014) per farm per annum. Annual expenditure on the management of *Prosopis* was also highly variable, ranging from R 750 – 2000 per farm per annum, and was spent either on maintaining access roads and water points on densely invaded farms, or doing annual clearing to prevent the establishment of *Prosopis* on farms with sparse invasions. Attempts to achieve local eradication of moderate and dense *Prosopis* invasions resulted in expenditure ranging from R 40 000 to R 180 000 per farm per annum. One farmer mentioned that the South African National Roads Agency offered to clear *Prosopis* on his farm in return for road-building material from his farm. They had spent almost R 500 000 clearing approximately 20 ha of dense invasion using earth-moving machinery (this figure was not included in the average cost of control calculation).

The proportion of respondents controlling *Prosopis* in other stakeholder groups was significantly lower than for farmers. Respondents from the other stakeholder groups mainly uprooted *Prosopis* seedlings and some trimmed or felled trees when they got too big. Most people uprooted and trimmed trees themselves. People in the affluent group employed gardeners to do this, with costs averaging R 50 per annum.

The majority of respondents from all stakeholder groups wanted to see a decrease in the abundance of *Prosopis* in their area (Table 4.5). Most people wanted Working for Water to clear their land; this view enjoyed significantly more support from people from rural communal areas than other groups. Their main reasons being that this reduced the negative impacts of *Prosopis* and helped reduce the personal costs of clearing. However, many farmers objected to letting Working for Water teams on their land as they saw them as ineffective. Examples included the late application of herbicides after cutting, over-dilution of herbicides, and clearing outside the growing season which results in the herbicide not being taken up by the *Prosopis* trees. These trees then coppiced which led to increased density of invasions. Farmers also noted that the piecemeal clearing technique employed by Working for Water often left patches of *Prosopis* between cleared areas and was ineffective in the long term, as there was a source of seed to reinvade cleared areas. Furthermore, many farmers expressed concerns about theft of stock and equipment, apparently by Working for Water teams. The mistrust in the efficiency of the Working for Water program from farmers has resulted in many landowners preferring to clear *Prosopis* invasions themselves. A number of respondents in urban areas did not want *Prosopis* trees to be removed from their properties, although they were happy to see them removed from rangelands. Many respondents reported they would only be happy for *Prosopis* trees to be removed from urban areas if these were replaced with other trees by the government.

4.4.5 Factors relating to the knowledge of Prosopis

The majority of respondents observed the benefits and costs of *Prosopis* first hand. However, various other knowledge resources were reported by the respondents. Most people who did not gain knowledge from personal experience, gained knowledge on *Prosopis* through interacting with local farmers, and people employed by Working for Water. Others learned about *Prosopis* at their places of work and at school. A small percentage of people also mentioned that they have learned about *Prosopis* invasions via the media. Prominent sources were a short documentary on the national environmental TV show “50:50” and adverts for “Manna” as a blood-sugar stabilizing product. Farmers who do not have *Prosopis* on their land said they have observed and heard about the benefits and costs at quarterly meetings of farmers associations. The origin of the knowledge on the benefits and impacts of *Prosopis* differs significantly between the stakeholder groups ($P < 0.001$) (Table 4.6). Generally, farmers and people in rural communal areas experienced benefits and costs first hand, whereas people in urban areas learned about the benefits and costs from other people (farmers and Working for Water staff) and the media. Those who lived nearer to invasions also had a better knowledge of the benefits and costs relating to the invasions.

Table 4.6: Where people gained their knowledge on the benefits and costs (mean) of *Prosopis* (Benefits; $\chi^2 = 306.1$; df, = 14; $p < 0.001$) (Costs; $\chi^2 = 203.2$; df = 18; $p < 0.001$)

	Stakeholder groups			
How you gained knowledge on *Prosopis*	**Farmers**	**Urban - Informal**	**Urban – Affluent**	**Communal areas**
		Benefits		
Observed	97	88.7	47.7	89.4
Farmers association	3	0	0	0
Farmers	0	11.4	45.3	10.6
Work place	0	0	4	0
Media	0	0	3	0
		Costs		
Observed	93	59.4	49	70.8
Farmers	5.3	20.9	39	10
Farmers association	1	0	0	0
Media	0.8	2.4	10.2	0.8
Work place	0	0.8	3.8	0
Working for Water	0	16.5	0	17.5
School	0	0	2.8	0.8

The Principal Component Analysis revealed that there were no strong relationships between demographic variables (age, education level and gender) and people’s knowledge and perceptions of *Prosopis*. There are, however, strong relationships between knowing what *Prosopis* is and knowing whether it is spreading, knowing that it causes impacts, and wanting *Prosopis* to be managed better.

4.5 Discussion

4.5.1 Factors shaping knowledge, perceptions and practices of Prosopis invasions

There is still much to be learned about factors that influence knowledge, perceptions and practices relating to biological invasions (García-Llorente et al. 2008). One framework suggests that the abundance of invasions is the dominant factor influencing perceptions (Shackleton et al. 2007). Other factors such as biophysical characteristics of the local environment, potential uses, growth form of the plant, mode of introduction, social context of the area (socio-economic status, local policies and land tenure), and familiarity with the invasive species clearly also shape perceptions and use of invasive aliens (Kull et al. 2011;

Rai and Scarborough, 2014). Aesthetic values relating to invasive species have also been found to influence the perceptions of invasions (Dickie et al 2014), and were highlighted to a limited extent in our results. Using *Prosopis* invasions as a case study has highlighted that there are substantial differences in knowledge, perceptions and attitudes towards *Prosopis* between different stakeholders in South Africa

Knowledge of *Prosopis* is more superficial in urban areas where impacts of invasions do not directly influence people's livelihoods and where there is less first-hand experience of invasions. Many people in urban areas only knew about *Prosopis* through engaging with people who have first-hand experience (farmers and farm workers) and via the media (Table 4.6). This highlights that proximity to invasions played an important role, with people in urban areas away from large scale invasion being less knowledgeable. Town size played a role regarding knowledge of *Prosopis* invasions - individuals in smaller towns were more knowledgeable. This is most likely due to these communities being closer knit, allowing people to gain knowledge of *Prosopis* by interacting with farmers; such interactions are less common in larger cities like Kimberly and Upington.

Population demographics had no clear influence on knowledge and perceptions of *Prosopis*. However, other social-context factors such as land tenure led to differences in perceptions and practices regarding the management of *Prosopis*. A significantly higher percentage of private land owners actively managed *Prosopis* compared with respondents living in communal areas (Table 4.5). Although 75 % of people in rural communal areas considered *Prosopis* to be harmful, and 99 % of people would like to see populations controlled, no one was involved in any form of management besides clearing seedlings from their gardens. This may be because they are very poor and cannot afford to clear *Prosopis* themselves, but also because people are not sufficiently strongly motivated to manage invasions as they feel that such interventions should be undertaken by government. Tenure rights - where people did not want to invest in clearing land they did not own – were also important. In Kenya many people in communal areas cleared *Prosopis* in small agricultural fields that were considered their "own" and most respondent's viewed that it was their duty to do it, although many mentioned government assistance would be appreciated (Mwangi and Swallow, 2005). The majority of respondents in Kenya (60 %) believed that it was the government's responsibility to remove *Prosopis* from communal land (rangelands) but 40 % believed that it should be a combined effort involving government, NGOs and local communities (Mwangi and Swallow, 2005).

4.5.2 Knowledge, perceptions and practices relating to Prosopis invasions in South Africa

All stakeholder groups felt that *Prosopis* had more negative impacts/costs than benefits in the study area (Table 4.4). The key benefits of *Prosopis* that are recognized are its provision of fodder, shade and fuelwood. Some benefits listed by respondents were not commonly mentioned in the literature on *Prosopis* from other parts of the world, including: making beer, job creation, medicinal value, and aesthetic beauty. On the other hand, communities in other parts of the world highlighted uses of *Prosopis* that were not mentioned in our survey. These included its use for construction poles, charcoal, fencing, improving soils, wood carving/timber, bio-char and making ropes (Chikuni, 2004; Mwangi and Swallow, 2005;

Kazmi et al. 2009). Many noted that the benefits were less in dense invasions because the trees in dense stands produce fewer pods and remain in a shrub form, making utilisation difficult because people and livestock are unable to penetrate these thickets (Shackleton et al. 2014). Most of these benefits can be substituted by native species such as *Acacia karroo*, *Searsia* spp. (used for fuelwood and shade), *A. erioloba* and *A. mellifera* (used for fuelwood, shade and fodder). The production of the blood sugar pills is an exception to this, although a decrease in tree densities could allow for greater pod yields. Job creation was also important though trade of pods to make Manna and through WfW. For example, benefits from the sale of fruits from the cactus *Opuntia ficus-indica* in the semi-arid thicket region of the Eastern Cape provided a cash injection for local traders which accounted for 9.2 % of total household yearly income (Shackleton et al., 2011). In Kenya the loss of native species due to encroachment by *Prosopis* has led to the loss of many specific services provided by these species such as palms that are used for thatching and weaving (Stave et al. 2007).

Some novel issues relating to costs/negative impacts were also raised. These included factors such as *Prosopis* roots breaking infrastructure, the fact that the presence of *Prosopis* invasions reduces the property values of farms, and that leaf and pod fall in the dry season makes gardens and town streets untidy and "dirty". Communities in other parts of the world have mentioned that *Prosopis* invasions caused cracks in the ground, increased the prevalence of malaria, and reduced crop yields (Mwangi and Swallow, 2005).

Most respondents believed *Prosopis* to be spreading. This is in agreement with other sources that have shown that *Prosopis* invasions in the Northern Cape Province increased from approximately 128 000 ha in 1974 to 1.5 million ha in 2007, and that the extent increased by around 8 % per annum from 1974-2007 (Van den Berg 2010; van Wilgen et al. 2012). This will increase costs and reduce benefits, thereby increasing human vulnerability in the future (Shackleton et al., 2007; Wise et al., 2012). Most people (98 %) would like to see *Prosopis* populations reduced in the study area (Table 4.5). This is slightly higher than in Kenya where 85-90 % of the respondents would like *Prosopis* to be eradicated (Mwangi and Swallow, 2005). Although, some people with *Prosopis* in their gardens did not want *Prosopis* removed. There were also numerous issues raised regarding the efficiency and reliability of the government run programme that co-ordinates invasive plant clearing – Working for Water. Farmers are making substantial investments every year to manage *Prosopis* on their land (Table 4.5). The average costs of manual cutting and poisoning when done by farmers were generally lower than those of the Working for Water programme which range from R 130 per ha in sparsely invaded areas to R 5 340 per ha under dense invasions (Wise et al. 2012).

4.5.3 Implications for management

The results have highlighted that there is demand for increased and improved control of *Prosopis* in South Africa and that the conflicts of interest are not as pronounced as was previously thought. Local respondents considered the costs of *Prosopis* to outweigh the benefits. This is because of the obvious negative effects that the invasions have on livelihoods, and because the benefits from utilisation are low when *Prosopis* forms dense thickets (Shackleton et al. 2014).

Respondents identified the need to monitor Working for Water operations more closely and to prioritise management interventions to improve management success and effectiveness in the long term. Farmers suggested that tax subsidies or subsidies on herbicides would help them to manage *Prosopis* better. This suggestion is being implemented in other areas of South Africa (Gamtoos Water, 2013).

The results from our study shown that there is need for more cost effective methods to reduce the costs of *Prosopis* invasions and to reduce the financial burden of control for farmers and the Working for Water programme. This need could be met through the use of biological control (Zachariades et al. 2011; van Wilgen et al. 2012; Wise et al. 2012). Research into biological control was halted in the past due to conflicts of interest around the use of *Prosopis*. However, the substantial rates of spread and high levels of costs from *Prosopis* invasions warrant resumption of research on this topic (Zachariades et al. 2011). To date biological control of *Prosopis* in South Africa has been poor, with one agent falling to establish, and the other two having minimal effects on the rate of spread of *Prosopis* (Zachariades et al. 2011).There are other biological control agents, such as an *Evippe* species, that have reduced *Prosopis* invasion densities in Australia (van Klinken, 2012) which could also be effective in South Africa (Zachariades et al. 2011). Effective biological control agents could reduce stand densities (and the rate of spread), which would make utilisation easier and thus raise the benefits of *Prosopis* in the long run (Zachariades et al. 2011).

Further research is also needed to explore the feasibility of promoting large-scale use of *Prosopis* to utilise benefits from *Prosopis* and increase employment, while at the same time reducing the costs and spread of invasions (Choge and Chikamai, 2004; Kazmi et al. 2009). For example, Kenya is in the process of setting up regional power plants that will be fuelled with *Prosopis* biomass and there is scope for large scale charcoal production (Shackleton et al. 2014). Many respondents suggested *Prosopis* invasions are important for job creation.

Improving awareness and encouraging farmers with sparse *Prosopis* invasions to control them before they become dense could also help these land owners to save money and prevent the spread of *Prosopis* in the long term. There is also need for targeted awareness programmes in urban areas, where knowledge about *Prosopis* is lacking. Information on local invasive species should be incorporated in the school syllabus. A key requirement for reducing the costs of *Prosopis* invasions and more effective and improve management is a national strategy – similar to the one implemented in Australia or suggested for invasive Australian acacia species in South Africa (van Wilgen et al. 2011; Australian Weeds Committee, 2012). Using multiple-stakeholder participatory approaches to create this strategy would help to reduce the conflicts and help to develop a holistic plan that considers all the needs and concerns of all stakeholders.

4.6 Conclusions

Citizens in rural areas – living on commercial farms and in villages situated on rural communal lands - had greater knowledge on aspects relating to *Prosopis* invasions than people living in towns and cities. Perceptions, knowledge and practices relating to *Prosopis* differed between stakeholders and were linked to the social context of the stakeholder groups such as land tenure, economic status and town/city size. No clear link was found between knowledge and perceptions of *Prosopis* and demographic variables such as age, gender and education level. Most people believed that *Prosopis* invasions in South Africa were causing more harm than benefit and numerous negative impacts were mentioned. Most stakeholders viewed that *Prosopis* is spreading and that densities in South African need to decrease to reduce costs. The costs of control are currently high for farmers and the Working for Water programme, and there is need to look into new methods of management but also to make current management more effective. Biological control or mass scale utilisation could help to improve control in the future.

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Chapter 5: Use of non-timber forest products from invasive alien *Prosopis* species (mesquite) and native trees in South Africa: Implications for management

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Abstract

Prosopis species have been introduced to many areas outside their native range to provide benefits to local communities. Several *Prosopis* species and their hybrids (hereafter "mesquite") have, however, become naturalised and invasive and now generate substantial costs. Management options are limited because of the complex conflicts of interest regarding benefits and costs. Management policies and strategies must take account of such conflicts, but further insights are needed on the dimensions of uses and impacts before such information can be usefully applied. Current policy in South Africa allows for the growth and use of mesquite in one province, but not in others where its control is mandatory. We report on a study to quantify the direct use and perceptions of non-timber forest products (NTFPs) from mesquite and native trees in South Africa. Semi-structures household interviews were conducted with various stakeholder groups to identify what tree products are used, to ascertain amounts used as well as to gauge perceptions of natural resource use between different tree species and use over time. The direct household use value of native trees was higher than that of mesquite, and local stakeholders attached greater value to products from native trees than from mesquite. Therefore, native trees are and will still be preferentially harvested, and mesquite is unlikely to offer protection to native species by providing an alternative source of products. Mesquite pods do, however, provide valuable additional resources (fodder and medicinal products). The use of both native trees and mesquite is decreasing as the incomes of poorer households rise and as alternative energy sources become available. The benefits and reliance on mesquite are not as high as previously assumed and the impacts from mesquite invasions create large problems for local communities. This study provides further evidence that the impacts of mesquite exceed the benefits, lending support for a policy to reduce negative impacts.

5.1 Introduction

Thousands of plant species have been introduced to new locations by humans, especially during the last three centuries, to serve many purposes (Richardson, 2011). Many have naturalised and some have become invasive (Rejmánek and Richardson, 2013). Invasive plants often supply benefits to societies in their new ranges, but costs associated with these invasions often increase as the plants spread (Shackleton et al., 2007a; Kull et al. 2011). This typically results in the emergence of complex conflicts of interest, with some stakeholders calling for eradication or control of the invaders, while others promote their continued use (Shaanker et al. 2010; Kannan et al. 2014; Shackleton et al. 2014; van Wilgen and Richardson, 2014). Some invasive plant taxa (e.g. *Acacia* and *Pinus* species) are commercially important for forestry and agroforestry (Richardson, 2011), while many others (e.g. *Acacia mearnsii*, *Opuntia ficus-indica* and *Prosopis* species) provide useful resources such as fuelwood, fodder and fruit, and are important for local livelihoods (Pasiecznik et al. 2001; de Neergaard et al., 2005; Shackleton et al. 2007a, 2011; Richardson et al. 2015). However, these same species also cause substantial costs to local livelihoods and the environment (Shackleton et al. 2014; van Wilgen and Richardson, 2014).

Non-timber forest products (NTFPs) are all biological materials other than timber that are harvested from trees for use and sale at the household level (De Beer and McDermott, 1989). These include native and introduced species (Cunningham, 2001). NTFPs are utilised for subsistence and commercial gain all over the world (Shackleton and Shackleton, 2004) and account for 20 % of the incomes of rural poor communities on average and are used by more than 85 % of households in urban areas of southern Africa (Shackleton et al., 2007b; Davenport et al. 2012). Use and trade of NTFPs has potential to aid poverty alleviation and provide social upliftment in developing countries in a sustainable way (Shackleton and Shackleton, 2004); this includes various initiatives to promote the utilisation of invasive alien species of *Acacia* and *Prosopis* (Choge and Chikami, 2004; Pasiecznik et al. 2006; Shackleton et al. 2007). The introduction of invasive species can bring benefits by supplying more NTFPs or novel NTFPs, but can simultaneously be detrimental to natural resources, changing traditional patterns of resource use in a positive or negative way (Shackleton et al. 2007a). For example, in South Africa's Eastern Cape province, 90 % of households used invasive alien *Acacia* species (wattles) as their primary heat source, and 19 % of households relied on wattles for cash incomes (de Neergaard et al., 2005). The sale of fruit from invasive stands of *Opuntia ficus-indica* in the Eastern Cape amounted to 9 % of the yearly income of collector's households (Shackleton et al., 2011). In Malawi, *Prosopis* (thereafter "mesquite") provided 44 % of households with an income source (Chikuni et al., 2004), and in India mesquite provided up to 70 % of fuelwood needs for households in arid regions (Pasiecznik et al., 2001; Walter, 2011). NTFPs from mesquite such as medicine, fodder, flour alternatives and charcoal, are sold commercially on a large scale worldwide (Shackleton et al., 2014). However, mesquite also generates numerous costs in the same areas, which negatively affect local biodiversity, ecosystem services, economies and local livelihoods (Shackleton et al. 2014).

The services that these invasive alien species provide and the costs that they generate have resulted in conflicts regarding their use and management in many developing countries (Low 2012; van Wilgen and Richardson 2014). The introduction of new plants has been labelled as "dangerous aid" as many of these invasive non-native species harm the same communities that were targeted for assistance in the long term (Low 2012). The presumed benefits of these species limit management options and lead to contradictory policies in many developing countries, while costs associated with the invasions continue to rise. For example, in the Northern Cape province, South Africa, mesquite is listed as a "Category 3" invasive "species" which means that the genus may remain in the prescribed area/province, but further planting, propagation or trade is prohibited – expect for the pods from mesquite which are exempted, and may be used on private land. In other South African provinces, mesquite is a "Category 1" invader which means that invasive populations must be controlled (although the regulations do allow for ongoing use of pods) (NEM:BA, 2004; Act No. 10 of 2004: Alien and Invasive Lists 2014) (Department of Environmental Affairs, 2014). This means that any trading of products derived from mesquite is illegal in South Africa. Similarly, policy in Kenya states that mesquite should be managed though utilisation to reduce rates of spread and impacts while at the same time benefitting local communities. This policy is controversial as it limits control options; for example biological control is excluded (Shackleton et al. 2014). Such policies that seek to reduce impacts while seeking to benefit communities are widespread in developing countries. The situation is very different in developed countries, where social upliftment does not feature in strategies for dealing with invasive species. In Australia, for example, mesquite is listed as a weed of national significance and legislation does not allow for utilisation (Australian Weeds Committee, 2012). Similarly, European regulations issued in 2015 do not make it easy to utilise products from any invasive species (European Union, 2014). Utilisation of natural resources is crucial for local livelihoods and social upliftment in developing countries (Shackleton and Shackleton 2004). Sustainable strategies for dealing with "conflict of interest" invasive species must address the relative value of useful invasive species, like mesquite.

The systematic study of the use and perceptions of invasive species relative to native species has been limited (Kull et al. 2011). People use many invasive species simply because they are there, and not to use them would be to forego an opportunity. This is exacerbated if the species provides a resource that is not available from native species (Shackleton et al. 2007a). However, the use and perceptions of conflict invasive species such as Australian acacias differ considerably in different areas (Kull et al. 2011). People often use both native and alien species for the same purposes, and it would be useful to understand the drivers and levels of such usage to develop policies that will minimise harm and maximise benefit. Both native and alien species must be considered when formulating broad conservation aims in rangelands (Milton et al. 2003). On the one hand the alien species could relieve pressure on native species, thus benefiting conservation. On the other hand, however, on-going invasion by the alien species could be very detrimental to native species and to ecosystem services. Furthermore, if the alien species is perceived to be useful, then there would be resistance to the implementation of control from those who benefit from the resource. A better understanding of the level of use, value and dynamics of NTPF uses and perceptions of invasive species is clearly important for formulating effective responses and to guide policy formation and management. The use of NTFPs is usually assumed to be sustainable, allowing for biodiversity conservation and economic development to co-exist (Negi et al. 2011), and this has been proposed for invasive species (Choge and Chikamai, 2004). Sustainable outcomes are, however, rare. The situation is dynamic, with the net benefits being high shortly after introduction but steadily reduce as the species invades, resulting later in net harm (van Wilgen and Richardson 2014). One needs to consider that even beneficial invasive species can also lead to negative externalities whereas native species do not. Therefore, it is crucial to ensure that the use and perceptions on NTFPs from native and invasive species are incorporated in strategies dealing with invasive species to ensure that the needs of local communities are met while ensuring the conservation of biodiversity and ecosystem services. Mesquite invasions in South Africa provide a good case study for gaining further insights on these issues.

5.1.1 *Mesquite in South Africa*

Several *Prosopis* species were introduced to a few localities in South Africa in the late 1800s. In the mid-1900s mesquite was widely promoted and planted by the Department of Agriculture as a fodder, fuelwood and shade resource to aid farmers who were struggling with a two-decade long drought in the arid parts of the country (Zimmermann, 1999; Poynton, 2009). *Prosopis* has since become the second most widespread invasive plant genus in South Africa after Australian acacias (van Wilgen et al. 2012). There is growing evidence that mesquite invasions in South Africa are having profound negative impacts on biodiversity (Dean et al 2002; Steenkamp and Chown 1996; Schachtschneider and February, 2013; Shackleton et al. 2015a, 2015b), ecosystem services (Ndhlovu et al. 2011; Dzikiti et al. 2013) and local livelihoods and economies (Wise et al. 2012; Shackleton et al. 2015c). Wise et al. (2012) estimated that the costs will soon exceed the benefits. Control efforts carried out to date have done little to arrest the rapid spread of invasive populations (van Wilgen et al. 2012). Three seed-feeding biological control agents (*Algarobius Prosopis, A. bottimeri* and *Neltumius arizonensis*) have been released in South Africa, but have had limited effect. *A. bottimeri* failed to establish, and the other two have not substantially slowed rates of mesquite spread (Zachariades et al. 2011). Although almost 0.5 billion Rand (US$ 50 million) was spent on mechanical and chemical control measures between 1996 and 2008 (van Wilgen et al. 2012) by the state-run Working for Water programme, invasions continue to spread rapidly and the associated negative impacts continue to rise (Wise et al. 2012). Additionally, South Africa's policy for dealing with mesquite highlights the extent to which complexities still exist relating to the use and management of mesquite within South Africa with contradictory policy in different provinces. There is clearly an urgent need for a national mesquite management strategy as there are still conflicting ideas over the use and the benefit supply of the genus and the social and ecological costs it generates within South Africa. However, before more effective management policies can be developed, further insights would be required regarding the relative use, benefits and perceptions of this invasive tree in South Africa as well as to assess if other options are available if mesquite is better managed.

This study therefore compares (1) the use of NTFPs from native trees and mesquite by different stakeholders within the invasive range of mesquite in South Africa; and (2) perceptions surrounding mesquite and native tree NTFPs. It is hypothesised that; (1) mesquite is used more than native species due to introduction history and the fact that is it highly invasive and so widespread; (2) the introduction of mesquite has led to the prevision and use of novel resources in the area; and (3) mesquite will be perceived to be more useful than native species by local communities.

5.5 Methods

5.2.1 Study site

The study took place in 10 cities, towns and villages across South Africa's Northern Cape province (Figure 5.1 and 5.2). This area covers the core of the invasive range of mesquite species in South Africa and represents a cross section of different environmental and socio-political conditions. Invasive stands of mesquite in South Africa comprise a complex mixture of several species and their hybrids (Mazibuko, 2012), and we will simply refer to as "mesquite". The study included rural and urban areas and areas with private and communal land tenure. Sampled human settlements included large towns with over 50,000 people (Kimberly and Upington), smaller towns with between 10,000 and 20,000 inhabitants (Calvinia, Carnavon and Prieska), and towns and villages with fewer than 5,000 people (Brandvlei, Loeriesfontein, Kenhardt, Mier and Madibeng).

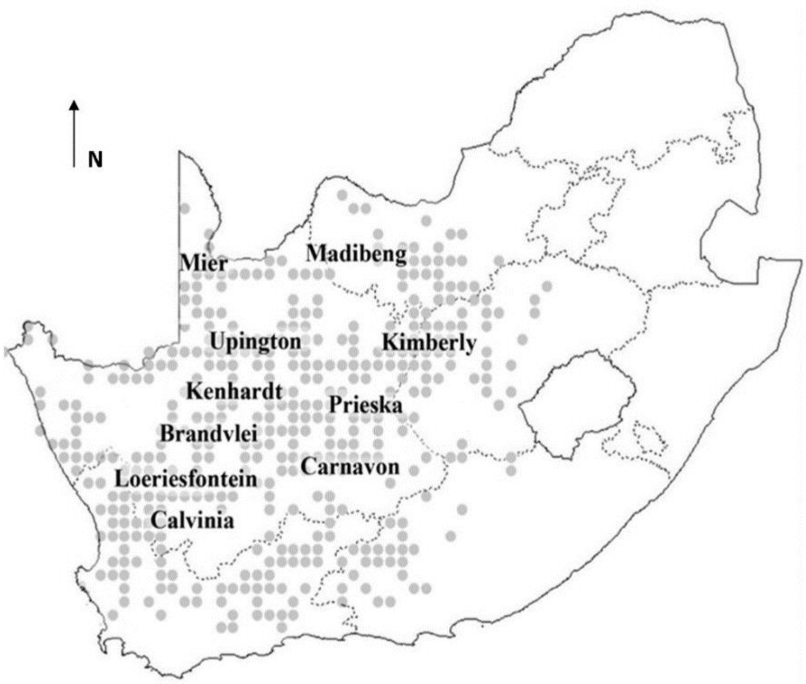

Figure 5.1: Locations of the 10 towns in South Africa where interviews were conducted on the use of non-timber forest products from *Prosopis* species (mesquite) and native trees use. Dots represent the occurrence of invasive mesquite stands (Source of Map - Henderson, SAPIA database, ARC-Plant Protection Institute, Pretoria).

The legacy of apartheid is still clearly reflected in the wealth, education, and distribution of different racial groups in the study area (Table 5.1) (Treiman, 2007). Rural land is primarily owned by Whites and is run as game or livestock farms, although there are areas of communal land populated by Black and Coloured (mix-race) communities that were demarcated as "homelands" during the apartheid era. Stark contrasts are evident in urban areas, with moderately affluent suburbs (populated mainly by Whites) and informal settlements ("townships") populated by primarily Black and Coloured residents (Table 5.1). The economy of the region is based on mining, livestock, game and irrigated crop farming and tourism. The study area is semi-arid to arid, with mean annual rainfall averaging between 150 and 450 mm at different sites and falls within three biomes: the Succulent Karoo, Nama Karoo and Savanna (Mucina and Rutherford, 2006).

Table 5.1: Demographics of the sample populations (mean ±sd) of the different stakeholder groups interviewed across the study sites. hh = household.

Stakeholder category	Mean age (yrs)	Gender (% male)	Race group (%)	Mean education of hh head (no. years)	Mean no. people in hh	Mean no. wage earners per hh	Mean no. state grants per hh	Mean no. state pensions per hh	Modal income bracket (Thousands of R/month)
Farmers	53±134	81	Coloured (12) White (88)	13±3	3±1	2±0	0±0	0±0	30-40
Communal rural	47±16	47	Black (25) Coloured (75)	7±4	5±3	1±1	2±1	1±1	0-5
Urban - Affluent	48±13	57	Black (8) Coloured (4) White (88)	14±2	3±1	2±1	0±0	0±0	<40
Urban - Informal	48±33	38	Black (28) Coloured (72)	8±4	5±3	1±1	1±1	1±1	0-5

5.2.2 Interviews

Semi-structured interviews were conducted with people from four main stakeholder groups - two in rural areas (land-owning farmers, and people living on communal lands) and two in urban areas (affluent suburbs and those living in poor informal settlements). Questionnaires were used so that quantitative data could be collected to compare use and perceptions between stakeholders. These stakeholders provided a cross section of various groups who utilise natural resources and are influenced by mesquite. The interviews sought to uncover what NTFP products households used, the quantity of used, but also to understand perceptions and trends about the use of NTFPs from mesquite and native trees. Households were selected at random by conducting interviews with all available households on randomly selected streets - although some farmers were located through snowball sampling as many lived in towns rather than on their farms. The head of the household and/or those responsible for the collection of NTFPs were interviewed in their home language (Afrikaans, English, SeTswana, or isiXhosa). A translator was used for interviews in households where interviewees were not conversant in English.

A total of 639 household interviews were conducted across 10 sites between June and September 2014. These included 130 interviews with commercial farmers, 100 in rural communal land villages and 409 in urban areas – (276 in informal settlements, 133 in affluent town suburbs). Farmers were interviewed at all 10 sites. Respondents from urban informal settlements and urban affluent areas were not interviewed at Mier and Madibeng as these areas only had rural villages on communal lands. Sample sizes varied across the stakeholder groups and were based on the demographics of different groups and the availability and ease of access for household interviews (Shackleton et al. 2015a). Farms in the area are widely separated making it costly and time-consuming to do many interviews. Unemployment is high in urban informal areas, so it was possible to conduct interviews throughout the day. In most households in urban affluent areas all the adults in the household worked so interviews could only be conducted for an hour a day in the early evenings and on weekends.

The interviews were semi-structured and comprised three main sections: (1) information regarding the demographics of the respondent household; (2) questions relating to use of mesquite and native trees; and (3) questions relating to perceptions of NTFPs supplied by mesquite and native species, and changes in patterns of use over time. This allowed us to gather information on the products and species utilised, amounts used, and local prices which allowed for the calculation of direct use values.

5.2.3 Field measurements

The key resources obtained from trees included fuelwood, pods used for various products, and fencing poles. For households that had NTFPs at their houses, daily quantities were measured using a spring scale. Many households bought resources from local traders, and indications of amounts bought per time frame were gathered. Local prices were obtained from traders. Quantities that people bought were measured at the local traders. Many households did not have NTFPs available for measurement, but respondents were able to estimate their usage in common units such as donkey carts or bakkie (small truck/ utility vehicle) loads per month or year. The contents of twelve bakkie loads and six donkey carts were weighed. This included eight bakkie loads of mesquite, two of *Acacia erioloba* and two of *A. karroo* wood and three donkey carts of mesquite, two of *A. erioloba* and one of *A. karroo* wood. There were no significant differences in the mean weights of the different species. We standardised the data for wet bakkie loads (which still had fresh bark and were on average a third heavier) to that of dry bakkie loads by subtracting the mean difference between the two. The mean weight of a bakkie load of wood was 422±119 kg. This is lower than the mean of 532 kg for three bakkie loads measured by Twine et al. (2003) - there was high variability based on the type of bakkie. The mean mass of a donkey cart load of wood was 156±66 kg, marginally higher than the average of 132 kg per donkey cart found by Shackleton et al. (2006). Market values for fuelwood, honey and pods used to produce organic medicine were gathered from local traders at each of the study sites. Because there was no market for fodder and fencing poles, a substitute for mesquite pods for fodder - Lucerne pellets - was used (R 3.10 per kg) and the value of native tree fencing poles was substituted for 3m-long *Eucalyptus* poles (R 40.00 per pole).

5.2.4 Statistics

T-tests were used to compare the total use and value (numerical data) of native tree species relative to mesquite. One-Way ANOVAs and Tukey post-hoc tests were used to compare use and value (numerical data) between different stakeholder groups. Chi-squared tests were used to compare the differences between usage by stakeholder groups and perceptions of mesquite and native species for variables with categorical data. All assumptions for each test were examined before the tests were run. Some groups of products have very small sample sizes precluding statistical analysis.

5.6 Results

5.3.1 Uses of mesquite and native trees

Fuelwood was the most common NTFP collected or bought for both mesquite and native species (Table 5.2). The proportion of fuelwood from native species and mesquite varied between stakeholder groups, and fuelwood from native species was used more amongst three stakeholder groups but marginally less by those in Urban Informal settlements who use mesquite slightly more often. Annual household use and the economic value of the use did not differ between mesquite and native trees at a household level. However, total use and value of native species was higher as more households use native species for fuelwood as compared to mesquite. The mean price of fuelwood from native species (R 1.8/kg) was also slightly higher than that of mesquite fuelwood (R 1.4/kg). The overall household direct use value of native tree fuelwood across all stakeholders was 1.2 times higher than that of mesquite. *Acacia erioloba*, *A. karroo* and *A. mellifera* made up the bulk of native species used followed by *Parkinsonia africana* and *Searsia lancea*. The use of mesquite wood also differed between stakeholder groups (Table 5.2). Farmers used more mesquite fuelwood than other groups. There was no difference in use and value of mesquite between other groups. Annual use of wood and annual value of fuelwood from native species also differed between different stakeholders (Table 5.2). Farmers used the most, followed by residents in Communal Rural villages and there were no differences between the urban stakeholder groups who used substantially less than the rural stakeholders.

Table 5.2: A comparison of fuelwood use of mesquite and native tree species (mean ± sd) for different stakeholders. Superscript letters = significant differences between different stakeholder groups - Tukey's post hoc test. hh = household.

	Mesquite fuelwood			Native species fuelwood			p-value (mesquite vs. native)		
Stake-holder group	% of hh using	Mean use (kg/hh/yr)	Mean value (R/hh/yr)	% of hh using	Mean use (kg/hh/yr)	Mean value (R/hh/yr)	% hh of using	Use (kg/hh/yr)	Value (kg/hh/yr)
Farmers	54	1648 ± 1650^a	2060 ± 2676^a	85	1784 ± 1892^a	2230 ± 2523^a	0.03	0.63	0.85
Communal rural	48	795 ± 1021^b	930 ± 1229^b	69	860 ± 1110^b	1125 ± 1253^b	0.04	0.17	0.48
Urban - affluent	19	392 ± 259^b	$586 \pm 343_b$	63	339 ± 271^c	641 ± 553^c	0.00	0.39	0.63
Urban - informal	51	539 ± 721^b	$979 \pm 1134_b$	48	528 ± 626^c	1155 ± 1214^b	0.86	0.09	0.42

Mesquite provided more direct-use services than native trees (Table 5.3). This included the collection of pods for fodder, beer and the manufacture of an organic blood sugar stabiliser marketed as "Manna". Pods were collected by farmers and milled to break the seed, so that they could feed them to livestock while eliminating the risk of spreading the seeds in dung.

The collection of pods to produce Manna was restricted to one town (Prieska). Some farmers also collected honey produced from mesquite flowers. Respondents also mentioned that children opportunistically ate the pods from mesquite, but this was not included in the study as children could not be included in the study for ethical reasons. In rural areas numerous native tree species were used to make fencing poles. The value of NTFPs other than fuelwood was approximately 9.4 times higher for mesquite than for native trees. However, fuelwood use overshadowed this and, all together, the value of direct use NTFP products of native trees averaged 1.1 times more than that of mesquite (Tables 5.2 and 5.3). Interestingly, no households in Urban Affluent areas used other NTFPs from mesquite or native tree species besides for fuelwood (Table 5.3).

Table 5.3: Usage metrics (mean ±sd) for less commonly used non-timber forest products harvested from mesquite and native trees in South Africa. hh = household.

	Farmers			**Communal rural**			**Urban – informal**		
Resource	% of hh using	Mean use (kg or l/hh/yr)	Mean value (R/hh/yr)	% of hh using	Mean use (kg or number of poles/hh/yr)	Mean value (R/hh/yr)	% of hh using	Mean use (kg/hh/yr)	Mean value (R/hh/yr)
					Mesquite				
Fodder	3.8	1976±1669	6125±5174	2	200±0	620±0	>1	960±0	2976
Beer	-	-	-	-	-	-	>1	80±28	120±82
Manna	-	-	-	-	-	-	2.2	1013±193	1215±231
Honey	>1	10	700	-	-	-	-	-	-
					Native trees				
Fencing poles	-	-	-	4	29±23	1170±912	-	-	-

Modes of obtaining NTFP products differed between stakeholder groups for both mesquite and native tree species (Figure 5.2). Most farmers and people living in rural communal areas collected products from mesquite and native species themselves, whereas in urban areas most people purchased these products. The proportion of people selling NTFPs was very similar across all stakeholder groups with 2-3 % of people selling mesquite and native tree products in Rural Communal areas and Urban-Affluent areas and up to 7 % of respondents selling mesquite products from the Urban-Informal stakeholder group and 7 % of farmers selling native tree species products. Farmers and people from Urban Affluent areas normally had larger-scale operations compared to the more informal trade within the Rural Communal areas and Urban Informal areas and employed labourers to do the work, thus creating valuable jobs.

5.3.2 Perceptions and trends over time

In general, most households viewed the products provided by mesquite as inferior to native species – particularly in the case of fuelwood (Figure 5.3).

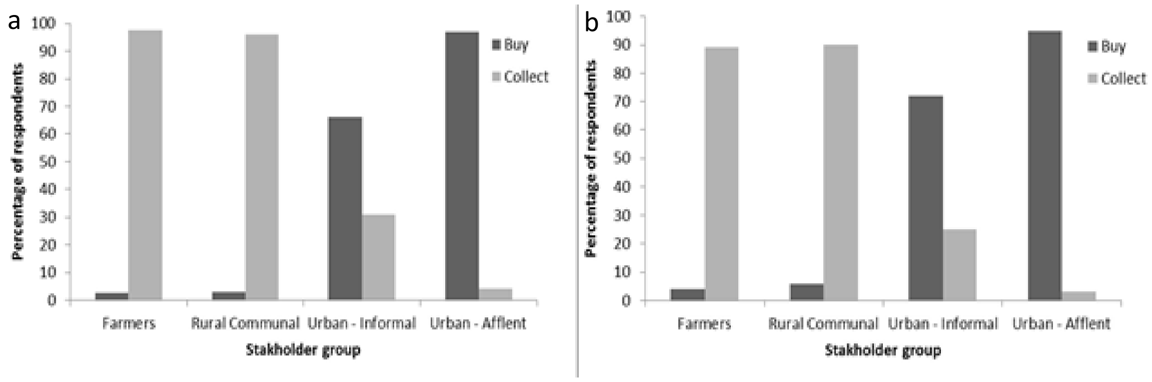

Figure 5.2: Methods of securing non-timber forest products from (a) mesquite – (χ^2 = 255.8; p < 0.0005) and (b) native species (χ^2 = 235.2; p < 0.0005) for four stakeholder groups in South Africa.

There were several reasons for this, including that mesquite wood does not generate as much heat or form coals as well as many native species; mesquite logs have smaller diameters than those from native species; mesquite has thick thorns that some people consider poisonous, making it relatively difficult to harvest and utilise; when the mesquite wood is slightly wet it produces an unpleasant smoke, and the most commonly mentioned reason was that the wood is rapidly powdered by a boring insect as it dries (which means that large quantities of wood cannot be stored for long periods) (Table 5.4).

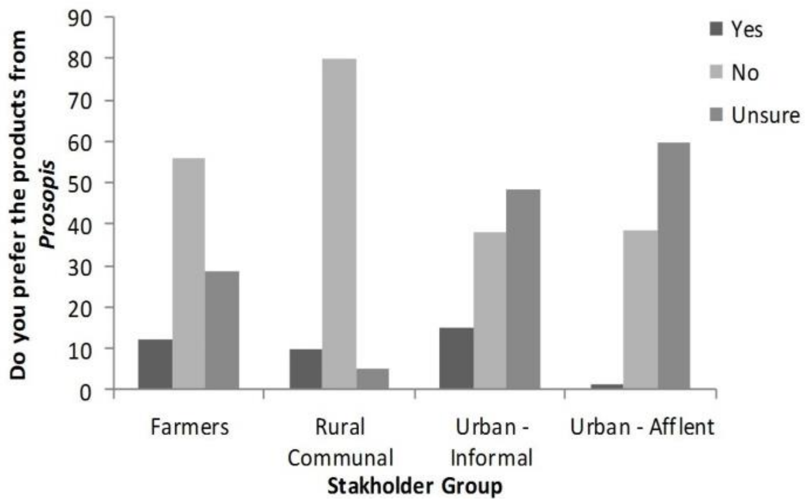

Figure 5.3: Perceptions on the usefulness of non-timber forest products supplied by mesquite compared to native tree species in South Africa (χ^2 = 189.3*;* p < 0.0005).

A small percentage of respondents preferred mesquite to native species, because it produces a highly nutritious fodder; invasive mesquite stands are often closer and more accessible to towns (making wood collection cheaper and faster); and some households make beer out of the pods (Table 5.4). Another reason for preferring to use mesquite was because the wood could easily be collected from debris left by government-sponsored clearing projects. Many people in the Urban Affluent stakeholder group were unsure whether mesquite products were better than native tree products and had no particular preference (Figure 5.3).

Table 5.4: Views of different stakeholders on the negative ($\chi^2 = 4.05$; $p = 0.29$) and positive ($\chi^2 = 11.5$; $p = 0.0006$) aspects of mesquite non-timber forest product provision as compared to those supplied by native trees. (% of respondents).

	Negative				Positive		
Stakeholder group	Bad smoke	Poor quality wood	Thorns	Turns to dust	Fodder	Make beer	More accessible/ it has already been cut down
Farmer	1.8	31.1	19.8	37.0	11.3	-	1.8
Rural Communal	4.6	25.8	24.2	38.5	7.0	-	3.0
Urban – Affluent	-	53	6.3	40.1	-	-	1.6
Urban – Informal	7.3	25.7	28.6	28.8	10.7	1.1	3.7

In general, most stakeholders were either using the same amount of mesquite or native tree species, or have decreased their use of fuelwood over the last 10 years (Figure 5.4). The primary reasons for reduced use – particularly in Urban-Informal settlements and in Rural Communal villages – is the recent electrification of these areas, and increased incomes through grants enabling many people to move to alternative energy sources such as electricity and gas. Only a small proportion of people in all stakeholder groups have increased their use of mesquite or native trees for NTFPs. Reasons for increased use include: bigger families driving a greater demand for wood, and the lower cost of fuelwood compared to electricity. Some people have increased their use of mesquite compared to native trees as the mesquite has spread rapidly making the wood are more accessible. Some farmers have also increased their use of mesquite as they are making more effort to control it and so use the wood of trees that have been cut down. Most people in Urban-Affluent areas used the wood primarily for barbeques, a strong tradition in the area, and are using about the same amount of wood as in the past.

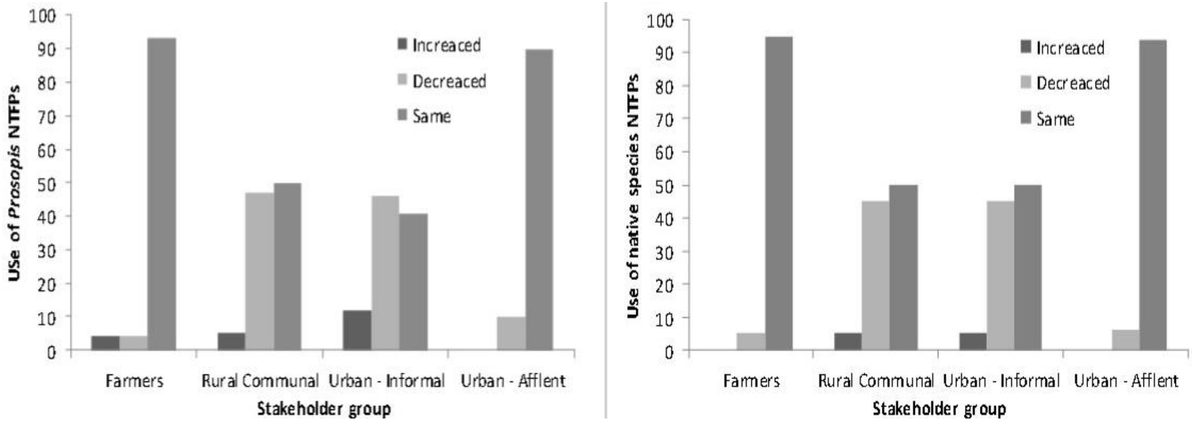

Figure 5.4: A comparison of the use of (a) mesquite ($\chi^2 = 130.0$; $p < 0.0005$) and (b) native species ($\chi^2 = 111.5$; $p < 0.0005$) since the year 2000 in South Africa.

5.7 Discussion

Many previous studies of NTFP use from invasive alien plants have focused only on the use value of a single species and provided no comparisons with usage of native species (Chikuni et al., 2004; de Neergaard et al. 2005; Shackleton et al 2007c; Shackleton et al. 2011). Such a comparison is important to illustrate the potential value invasive species can provide but also gives insight into the other alternatives and the potential opportunity costs of their use. This study has shown that the direct use and value of resources provided by an introduced "wonder plant" which has now become a major invader - mesquite - is not as high as high as that of native trees in the arid parts of South Africa. This suggests that the benefits provided by mesquite are not as high as previously assumed, and with rising costs associated with spreading invasions, management interventions to reduce the extent and density of mesquite are becoming increasingly justifiable.

5.4.1 Findings in relation to hypotheses

(1) We hypothesised that mesquite would be used more than native species. Our findings indicate, however, that native species – particularly *Acacia* species - provide higher value for direct household use to local stakeholders than mesquite provides (Table 5.2 and 5.3). The bulk of this use is for fuelwood which is the most commonly utilised NTFP in other parts of South Africa as well (Twine, 2005; Davenport et al. 2012). This suggests that mesquite is less useful than previously assumed. It also means that the pressure on native tree populations remains high as they are still being utilised and are being displaced by invasive mesquite (Schachtschneider and February, 2013; Shackleton et al. 2015b, 2015c).

(2) We hypothesised that the introduction of mesquite would lead to the provision and use of novel resources in the area, which it has, as mesquite provides a greater diversity of products than native trees in the study area. The most important novel resource is pods which are valued for fodder and to a smaller extent for the production of an organic medicine and brewing alcohol (in one town) (Table 5.3). This study did not quantify the value of consumption of pods by livestock in rangelands, although this is high (Wise et al. 2012).

However, any assessment of the value of pods as fodder would have to factor in the loss of grazing where mesquite invades (Ndhlovu et al. 2011), as well as the role of livestock in spreading mesquite seeds in their dung (Shiferaw et al. 2004).

(3) We hypothesised that the natural resources provided by mesquite would be preferred to those of native trees. However, our findings indicate that the majority of stakeholders prefer native trees over mesquite and see products of native species as superior (Figure 5.3). This is mainly because the wood quality of mesquite is perceived as poor for the reasons highlighted in Table 5.4, and fuelwood is the most widely used NTFP in the area. In Ethiopia when production of charcoal was legalised in an attempt to control mesquite through utilization, locals substituted mesquite with native *Acacia tortilis* and *A. nilotica* because these native species produced larger boles, had smaller spines and were easier to harvest, and because there were perceptions that the smoke from mesquite was poisonous (A. Witt: unpublished data). This provides another example illustrating that native species are favoured over mesquite, and highlights that planting alien species is unlikely to replace the use of native species, or to protect them. The supply of pods (a novel resource) from mesquite was the main reason why a small percentage of respondents preferred mesquite over native trees. Mesquite fuelwood was also favoured not because of its quality but because it could more easily be accessed. This has been noted elsewhere; for example, wood from *A. mearnsii* was perceived to be of lower quality than native species in the Eastern Cape of South Africa, but because it was more abundant close to villages it was used more (Shackleton et al. 2007a). Different perceptions relating to the use of natural resources of invasive species therefore often relate to their abundance, proximity, novelty, social contexts, factors surrounding introductions, cultural preferences and the opportunity costs of not using them (Shackleton et al. 2007; Kull et al. 2011).

5.4.2 Use patterns and perceptions

Most previous studies have assessed patterns of use within defined socio-economic groups, (Twine et al. 2003; Shackleton et al., 2007c; Paumgarten and Shackleton, 2009; Davenport et al. 2012; Thondhlana et al. 2012), and not between groups. Our study revealed that use patterns, methods of obtaining the resources, and use over time varied between stakeholders within different social-economic and land tenure contexts (Table 5.2 and 5.3; Figures 5.2, 5.3 and 5.4). We found that those living closer to invasions (farmers and people in rural communal land villages) mainly collected the NTFPs themselves, whereas people in urban areas relied more on purchasing these resources. People living in more rural areas also used a higher value of NTFPs compared to those in urban areas. Interestingly, the traditionally poorer stakeholders are moving away from use of fuelwood (Figure 5.4) as they adopt alternative energy sources such as electricity, gas and paraffin. The decreasing reliance on natural products has also been highlighted in other parts of South Africa, and has been linked to increased electrification and increased incomes especially through state grants and pensions (Shackleton et al. 2013). However, other sources suggest that the use of NTFPs, especially on a commercial scale, is increasing in some areas (Twine et al. 2005). Those in wealthier stakeholder groups still use similar amounts of NTFPs as there is a strong culture of using wood for barbequing.

5.4.3 Benefits vs. costs

Wise et al. (2012) estimated that mesquite invasions were providing a net benefit to local communities in South Africa, but that a net loss will result shortly as mesquite trees continue to spread. Although mesquite is providing about half of the farmers in the Northern Cape with a mean direct-use value R 2 000 per annum, the mean expenditure of farmers to control mesquite is over R 20 000 per farm per annum (Shackleton et al. 2015a). Mesquite invasions have also led to numerous other social, ecological and economic costs such as negative impacts on water, grazing potential, biodiversity and infrastructure that have not been fully valued (Mwangi and Swallow, 2005; Ndhlovu et al. 2011; Dzikiti et al. 2013; Shackleton et al. 2015a, 2015c). This suggests that mesquite invasions in South Africa generate more costs than benefits. Some argue that mesquite invasions play a positive role in that they reduce the use and pressure on native trees (FAO, 2004). However, mesquite invasions are having large-scale negative impacts on native tree population stability, abundance, density and mortality in South Africa (Schachtschneider and February, 2013; Shackleton et al. 2015b, 2015c) and natives are still being harvested in preference to mesquite. Native trees will therefore decline as mesquite stands become more widespread and dense, possibly more so than as a result of direct harvesting. In Kenya, mesquite is negatively impacting populations of native species that supply specialised NTFPs, e.g. a palm (*Hyphaene compressa*) used for weaving and thatching (Stave et al. 2007).

5.4.4 Recommendations: Policy and management options

This study, focussing on invasive mesquite species, illustrates the benefit of understanding the conflicts of interest caused by invasive species within the developing world, and how understanding natural resource use is important for informing policy and management. We suggest that similar studies in other parts of the world would help to highlight the relative values of the resources provided by invasive species and to determine whether invasive alien species provide any unique resources that may be affected by management. Our study has shown that people preferentially use native species over mesquite and are decreasing their reliance's on natural resources from trees in general. It also highlights that alternative native species are available, if mesquite was substantially reduced through more effective management. Current policy in South Africa is attempting to simultaneously maximise benefits and minimise harm, but this approach is likely to lead to growing negative impacts and continued spread. It would be better to base policy direction on overall net benefit or loss. Wise et al. (2012) predicted that a situation of net losses would arise soon, and that the magnitude of the net loss would grow rapidly as mesquite continues to spread. It would therefore appear to be better to adapt policy and treat mesquite as an undesirable invasive species everywhere (category 1), and consider using more damaging biological control agents (not only seed-attacking insects).

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Chapter 6: Identifying barriers to effective management of widespread invasive alien trees: *Prosopis* species (mesquite) in South Africa as a case study

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Abstract

Biological invasions are a major driver of ecological and social change globally. The negative effects of these invasions have led to the initiation of programs in many countries to manage these invasions. Management aims to reduce impacts and in some cases improve the benefits that some invasive species can provide. This study assesses the barriers that hinder the effective management of widespread tree invasions, drawing insights from a case study of invasions of *Prosopis* species (mesquite) in South Africa. We used questionnaire surveys and focussed workshops to identify barriers and adaption responses in four key stakeholder groups involved in various stages of management. More than 100 barriers were identified, most of them relating to social issues. Key barriers related to limited knowledge, insufficient funds, conflicts of interest, the ecology of the genus and the nature of the land it invades, as well as poor planning, co-ordination and co-operation, and a lack of prioritisation. There were marked differences between stakeholders regarding the importance of some barriers. Most Farmers (>80%) placed high importance on a lack of planning, and poor management as important barriers, while few Managers (<20%) regarded these as important, reflecting very different views about the context in which management projects operate. Workshops identified more barriers and overall shed greater insights on the dimensions of barriers. The questionnaires were, however, useful for providing quantitative data which helped to rank the importance of barriers. Although many adaptation responses were identified, not all barriers are conducive to simple solutions. Among the most intractable barriers were the lack of adequate funds and factors relating to the ecology of the genus. Problems such as adapting to new clearing methods and strategic planning need to be overcome to improve the effectiveness of control with the available funds.

6.1 Introduction

6.1.1 Global change and barriers to adaption

Invasive alien species cause major disruptions to social-ecological systems and are a major driver of global change (Vitousek et al. 1997; Pimentel et al. 2000). Many species introduced accidently and intentionally over past centuries have had severe detrimental effects on biodiversity, ecosystem services and local economies (Pyšek & Richardson 2010). The escalation of negative impacts associated with invasions has led to an increase in the number of management projects across the world that aim to reduce the negative effects of these invasions. Many such projects have limited success (Wilson et al. 2011; van Wilgen et al., 2012a; Shackleton et al., 2014), mainly because they face numerous barriers that hamper the effective management of the problem. Investigating barriers to adaptation and management is common in the fields of medicine (Flores and Vega, 1998; Gelland et al. 2011; Haung et al. 2011), psychology (Waller and Gilbody, 2009; Jansen van Vuuren and Learmonth, 2012) and climate change (Haung et al. 2011; Spires et al. 2014), but such thinking has not yet been systematically incorporated into conservation biology or invasion science (but see UNEP, 2004; Roura-Pascual et al. 2009). We suggest that improving our understanding of the barriers that potentially hamper the effective management of invasive species could improve management and help to guide adaptive responses for combatting this major driver of global change.

Barriers are factors that create obstacles or conditions that delay, hinder or divert the effectiveness of management, adaptation and transformation strategies (Moser and Ekstrom, 2010). Barriers range from those faced by individuals or households to those that operate at larger scales and that influence cities, institutions, municipalities and governments (Robinson and Gore, 2005; Lorenzoni et al., 2007; Jantrasami et al., 2010; Lehmann et al., 2014). Many different types of barriers exist, including biophysical (ecological, infrastructural), institutional (political, managerial) informational, economic and social barriers (cognitive, cultural, institutional, psychological) (Agrawal, 2008, Adger et al. 2009; Jones 2010; Gifford, 2011; Antwi-Agyei et al., 2013). Many barriers are contextual and relate to historical processes and include multiple stressors (Jansen van Vuuren and Learmonth, 2012; Shackleton et al. 2013). Identifying and recognising barriers to management is an important early step in overcoming them. Numerous methods and frameworks have been used to identify and categorise barriers to adaptation and management (Jones, 2010; Moser and Ekstrom, 2010; Nielsen and Reenberg, 2010; Antwi-Agyei et al., 2013). The concept of barriers has also been incorporated into other frameworks such as the Drivers, Pressures, States, Impacts and Responses (DPSIR) framework (Roura-Pascual et al. 2009). Many studies focus on single barriers and do not consider those that affect all stakeholders. We suggest that it is important to investigate these issues from multiple viewpoints as different stakeholders face different problems and all have unique perspectives. Overcoming such barriers requires concerted efforts by all stakeholders to make changes; there is need for adaptive management, new ways of thinking, effective legislation, prioritisation of goals and sound strategic planning (Moser and Ekstrom, 2010). Therefore, the timely identification of barriers can facilitate more efficient planning of adaptation and management strategies by considering and implementing appropriate solutions (Moser and Ekstrom, 2010). The lack of research on barriers facing managers of invasive species may be hindering effective management, especially for large-scale operations such as the ambitious Working for Water programme in South Africa (van Wilgen and Wannenburgh, 2015). The process of highlighting barriers is also useful for bringing different stakeholders together and allowing them to suggest ways of overcoming barriers.

6.1.2 Tree invasions

Until recently invasive alien trees were not widely recognised as a major threat to biodiversity and ecosystem productivity – but trees are now considered among the most widespread and damaging of invasive species in many parts of the world (Richardson and Rejmánek, 2011). The list of invasive trees and shrubs now contains more than 750 species, most of them having been introduced for horticulture, forestry and agroforestry (Rejmánek and Richardson, 2013). More than 40 species are widespread, and are invasive in six or more regions of the world (Richardson and Rejmánek, 2011). Invasive trees are now a major contributor to global change and negatively affect biodiversity, ecosystem services and human livelihoods (Shackleton et al. 2014). However, many species of invasive trees provide benefits as well as costs, leading to conflicts of interests surrounding their use management (Dickie et al. 2014; van Wilgen and Richardson, 2014). Management efforts range from *ad hoc* local-scale efforts by private land owners to large-scale national programs driven by national and international policy (Richardson and Rejmánek, 2011). There are many cases where management has reduced problems associated with tree invasions, but also many case studies where projects have failed to achieve effective management (van Wilgen et al. 2012a). Further investigation to better identify the most important barriers to the management of tree invasions is warranted, especially in developing countries. This is particularly important when developing strategic plans under international regulations such as the Convention on Biodiversity and to comply with national policies that are in place in numerous countries across the world, including Australia, South Africa and the United States. Our study focusses on invasive *Prosopis* species in South Africa as a case study species to identify barriers to management.

6.1.3 Study species and system (Prosopis in South Africa)

We used the genus *Prosopis* species (mesquite), widely recognised as one of the worst and most widespread invasive tree taxa in the world (Shackleton et al. 2015b), as a case study. *Prosopis* species have been moved around the globe during the past century to provide local communities with additional resources, notably fodder and wood. Several species and their hybrids have naturalised and/or become invasive in over 100 countries, leading to negative impacts and substantial conflicts of interest around use and management (Shackleton et al. 2014).

Prosopis species were first introduced into South Africa in the late 1800s, and then in the mid-1900s they were distributed to farmers in large numbers across the arid central parts of South Africa to provide fodder and shade for livestock, as well as extra fuelwood (Zimmermann, 1991; Poynton, 2009). *Prosopis* species have now invaded at least 1.8 million ha of South Africa, are still spreading at rates between 3.5 and 8 % per annum, and have the potential to invade a further 58 million ha of the country (Versfeld et al. 1998; Rouget et al., 2004; Van den Berg 2013). *Prosopis* was ranked as the second most widespread invasive plant taxon in South Africa after Australian *Acacia* species (Henderson, 2007) and *Prosopis* is also ranked highly for its impacts on biodiversity and ecosystem services (Le Maitre et al. 2000). *Prosopis* invasions in South Africa reduce bird, insect and tree abundance and diversity (Steenkamp and Chown, 1996; Dean et al. 2002; Shackleton et al. 2015a), destabilise tree populations and increase native tree mortality (Schachtschneider and February, 2013; Shackleton et al. 2015b), and reduce grazing potential and water reserves (Ndhlovu et al. 2011; Dzikiti et al. 2013). All of these impacts affect local livelihoods and economies negatively (Wise et al 2012; Shackleton et al. 2015c). The benefits from *Prosopis* have been found to be less important than was previously thought, and most stakeholders were in favour of more aggressive management interventions (Shackleton et al. 2015d).

Due to the costs associated with *Prosopis* invasions, there has been active management to reduce impacts by the state-run Working for Water programme as well as by private land owners (Shackleton et al. 2015c). Current approaches include mechanical, chemical and biological control methods (Richardson 1998; van Wilgen et al. 2012). Biological control has been largely been ineffective; one agent (*Neltumius arizonensis*) failed to establish and the others (*Algarobius bottimeri* and *A. prosopis*) have not substantially slowed rates of spread (Zachariades et al. 2011). There have been some localised successes using chemical and mechanical control, but on a larger scale management success has been limited and the impacts and costs of *Prosopis* invasions are rising rapidly (Wise et al. 2012 van Wilgen et al.2012a). Although the Working for Water (WfW) programme spent R 435.5 million (US$ 42.7 million) between 1996 and 2008 on managing *Prosopis* invasions, mesquite continues to increase its range and density rapidly across the county (van Wilgen et al. 2012a). This suggests that there may be substantial barriers to the effective management of *Prosopis* (as is the case with other well-established invasive tree species in South Africa; e.g. Holmes et al. 2008). A previous study in the fynbos biome (Roura-Pascual et al. 2009) identified important barriers that hamper effective management of invasive trees in this region. The systematic investigation of these barriers, drawing on perspectives of key stakeholder groups involved in management, has the potential to improve the efficiency of management.

5.1.4 Working for Water programme

The legacies of South Africa's apartheid past include unemployment, inequality and poverty which need to be addressed by providing people with meaningful work and skills while ensuring sustainability. The Working for Water programme (WfW, a state public-works program), which falls under the national Department of Environmental Affairs, therefore has multiple agendas. The key ones are (1) to provide jobs and skills development to previously disadvantaged communities and (2) to manage and remove invasive alien species to reduce their negative impacts on the environment and restore the supply of ecosystem services (van Wilgen et al. 2012b). There are numerous tiers of management and implementation in the programme. WfW's activities are managed at national and provincial levels through implementing agents (government departments, municipalities and national parks and conservation authorities, and forestry and agricultural authorities). These agents tender projects out to local contractors, mainly from previously disadvantaged backgrounds (van Wilgen and Wannenburgh, 2015). These tenders (2-3 month projects) include contractors, with teams of 10 unskilled workers who are paid an agreed sum to clear demarcated areas based on norms and standards agreed on for different species, terrains and density classes (van Wilgen and Wannenburgh, 2015). These tendered projects are supervised by regional managers employed by the implementing agents (see above) on a more secure long-term basis. WfW clearing projects are conducted on both state and private land which therefore involves working with and in close proximity to additional stakeholders such as farmers. This programme is well-funded compared to other environmental programmes in Africa and receives a budget of approximately R 1.8 billion annually to control invasions across the country (van Wilgen et al. 2012b). The different agendas and the incorporation of multiple tiers of stakeholders has led to major complexity and the creation of unique barriers to each group.

This paper reports the results of a study that sought to identify barriers to *Prosopis* management as perceived by multiple stakeholders, and to highlight the key adaptation responses that would be needed to overcome these barriers.

6.6 Methods

6.2.1 Study area

Prosopis invasions are found in the semi-arid and arid interior of South Africa, with the majority of invasive populations occurring in the Northern Cape Province (Richardson et al. 2000; Shackleton et al. 2015b). Invasions occur in three major South African biomes: the Savanna, the Nama Karoo and Succulent Karoo (Shackleton et al. 2015b). Rainfall in invaded areas ranges from 150-450 mm/yr and includes winter, summer and bimodal rainfall regimes. Altitudes range from 700-1300 m above sea level. The economy of the area is driven by livestock agriculture, cropping along rivers, mining and tourism. More than twenty years after the dismantling of apartheid, the legacy of this social system is still evident in the distribution of different racial groups across the area within which *Prosopis* occurs. The most common land use is rangeland farming, which is dominated by White landowners. There are also large areas of communal land that are populated by Black and Coloured people. Stark social-economic divides exist between different communities (a legacy of apartheid), resulting in areas of high unemployment, poverty and inequality (Treiman, 2007; Shackleton et al. 2015c). This reality and the need for social transformation compounds the challenge of achieving sustainable management and conservation strategies.

6.2.2 Questionnaires and workshops

Interviews using semi-structured questionnaires were conducted and focussed workshops were held with four key stakeholder groups involved with different stages in the management of *Prosopis*. These four groups were:

1. Academics - who undertake research on many aspects relating to invasions - including their benefits, costs, ecology and management - which are used to inform managers and policy makers. (Academics that were included were people who had published peer-reviewed papers on *Prosopis* and/or management of invasive trees in South Africa)
2. Farmers - living on private land who manage invasions themselves (using their own labour and funding) but also in many cases in conjunction with the state-run WfW programme.
3. Managers employed by WfW- who are involved in planning and overseeing invasive clearing projects in the WfW programme; and
4. Workers - who are people from previously disadvantaged communities (often with low education and living in poverty) who are involved in manually clearing invasive

species in return for payment (around the minimum wage (± R 100/US$ 7 per day)) from the WfW programme.

Ninety-five questionnaires were administered to the four groups: 11 to Academics, 34 to Farmers, 17 to Managers and 33 to Workers. Most of the managers on *Prosopis*-related projects run by WfW, and the academics in South Africa were sampled, and sub-sets of farmers and workers were done at numerous points in the Northern Cape. The questionnaire included questions relating to perceptions of *Prosopis*, identification (free listing) and ranking barriers to management, possible adaptation responses and to highlight research needs (free listing). Interviews were conducted in English and Afrikaans depending on the preference of the interviewee. Qualitative methods (focus groups) were also conducted using methods and for reasons highlighted in Jones and Boyd (2011). Focussed workshops were held with each of the stakeholder groups with between 10 and 20 participants to identify barriers relating to the effective management of *Prosopis* in South Africa. Each workshop lasted 1 to 1.5 hours. Proceedings were recorded to allow us to refer back to clarify issues and to identify underlying themes. Each of the barriers listed in the questionnaire and the workshop were added separately and not pooled into pre-defined groups as done in other studies (e.g., Jantrasami et al. 2010).

The information from the questionnaires and workshops was summarised into the framework presented in Jones (2010) which categorises barriers into: (1) human and information factors (knowledge, economic and technological); (2) Natural factors (ecological and physical) and (3) social factors (cognitive, institutional and normative).

6.7 Results

6.3.1 Perceptions of Prosopis

When listing words associated with *Prosopis*, the words: “water”, “problem”, “invasive” and “alien”, and other words associated with impacts and management were commonly mentioned by all stakeholder groups (Figure 6.1). However, there were also major differences between groups. Workers commonly mentioned words relating to work and job creation and well as verbs relating to the removal of *Prosopis*. Farmers also listed many adjectives with negative connotations relating to the tree such as “plague”, “thief”, “evil” and “nightmare”. Managers and academics listed similar words which were less emotive than Farmers and Workers.

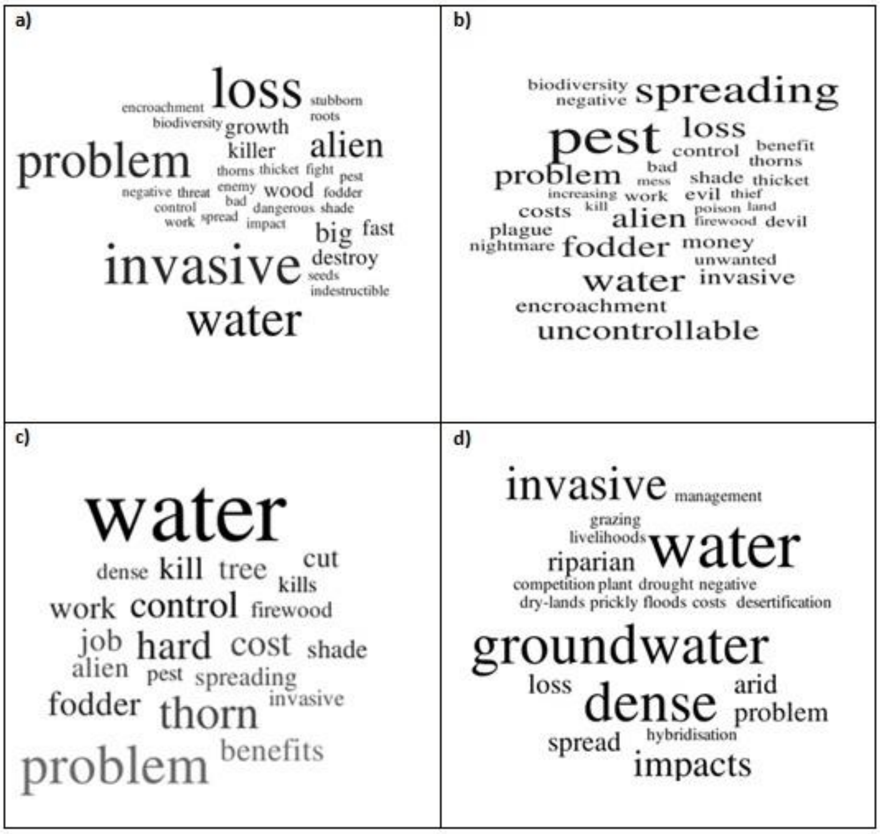

Figure 6.1: The use of words to describe *Prosopis* species by different stakeholder groups in South Africa: (a) Managers; (b) Farmers; (c) Workers; (d) Academics. Each participant was asked to list 3-5 words they associate with *Prosopis* in South Africa at the beginning of the survey (no background information was provided). The size of words in each word cloud denotes the number of times that word was used.

All stakeholders involved in the management of *Prosopis* perceived it to have negative impacts and/or costs (Table 6.1). Most stakeholders also perceived *Prosopis* to have benefits, with three stakeholders groups mentioning this more than 90 % of the time; Academics portrayed this view slightly less often (73 %). All stakeholders considered the costs to be greater than the benefits, with Workers and Farmers mentioning this 94 % and 96 % of the time respectively, and 100 % of respondents in other groups expressing this view. Ratings of different negative impacts varied between stakeholders, but costs that were rated as greatest by all stakeholder groups were reductions in water supply and reduced grazing capacity in natural rangelands (Table 6.2). The rating of benefits also differed between stakeholder groups (Table 6.2). Interestingly, Workers rated the benefits more highly than other groups. The provision of fodder, fuelwood and shade were rated as being among the most important benefits by all stakeholder groups.

Table 6.1: Perceptions of the costs, benefits and management of invasive *Prosopis* species among the four stakeholder groups. Numbers in the table indicate the percentage of affirmative answers to the questions, except for "barriers listed" where values indicate the numbers of barriers (mean ± sd).

Perceptions	**Managers**	**Farmers**	**Workers**	**Academics**
Does Prosopis have costs?	100	100	100	100
Does Prosopis have benefits?	94	100	90	73
Costs > Benefits?	100	96	94	100
Need for management?	100	100	100	100
Are there barriers to management?	100	100	100	90
Barriers listed	4.3±0.8	6.5±3.1	4.0±2.4	5.0±1.9

All respondents from all stakeholder groups considered that there was a need for *Prosopis* management, and all respondents recognized that there were barriers preventing effective management. On average, stakeholders mentioned 4.0 to 6.5 different barriers relating to the management of *Prosopis* using questionnaires, with Farmers identifying the most barriers (Table 1).

Table 6.2: Mean ranking of different costs and benefits of *Prosopis* invasions for four stakeholder groups (importance ranking: 1 = low; 5 = high).

Costs/Benefits	**Managers**	**Farmers**	**Workers**	**Academics**
Costs				
Water	4.9	4.5	4.8	4.5
Gazing	4.4	4.1	4.8	4.1
Biodiversity	3.8	4.4	4	4
Encroachment	3.9	4.5	3.9	4
Economy	4.7	4.6	4.1	4.3
Infrastructure	3.1	4.2	4	2.3
Benefits				
Fodder	2.7	3	3.7	3
Fuelwood	3.7	2.7	4.5	2.6
Medicinal	1.6	1	1	1.5
Shade	3.4	2.3	3	1.9
Edible products	1.2	1	1	1.3

6.3.2 Barriers to management

The results were categorised according to the framework used by Jones (2010) (Figures 6.2,3,4 and Table 6.3). Most barriers fell into the social node, followed by the human and information node and lastly the natural node, although the barriers found within different nodes interlink with each other. The involvement of different stakeholder groups resulted in a more comprehensive understanding of impediments to management, as different groups clearly perceived different combinations of barriers (Figure 6.2,3,4 and Table 6.3). Over 100 barriers were identified across the four stakeholder groups. Thirty-nine more or less discrete barriers affecting the management of *Prosopis* were listed by four stakeholder groups in the questionnaires (Table 6.3). Farmers mentioned the most barriers (26), followed closely by Academics (24), and Managers and Workers who mentioned 19 and 15 respectively. In the workshops the four stakeholder groups identified 100 more or less discrete barriers with Academics identifying (56), managers identifying (50), Farmers identifying 38 and Workers identifying (19) (Figure 6.2,3,4).

Table 6.3: Barriers to effective management mentioned by four different stakeholder groups involved in the management of *Prosopis*. Numbers are the percentage of respondents mentioning that barrier; importance rankings are given in brackets (1 lowest; 5 highest).

Barriers	Managers [%(rank)]	Farmers [%(rank)]	Workers [%(rank)]	Academics [%(rank)]
Human and Informational				
Knowledge				
Lack of knowledge	53 (4)	-	-	9 (4)
Lack of awareness	41 (3)	-	-	9 (4)
Technological				
Ineffective herbicide	35 (4)	35 (5)	42 (5)	9 (5)
Broken equipment	-	-	12 (4)	-
Lack of equipment	-	-	52 (5)	-
Herbicide applied poorly	29 (4)	38 (5)	-	9 (3)
Economic				
Funding constraints	82 (5)	71 (5)	-	64 (5)
Natural				
Physical				
Capacity constraints	29 (4)	-	-	9 (3)
Time constraints	-	32 (5)	-	-
Difficulty finding reliable labour	-	61 (4)	-	-
Widespread invasions	-	-	-	18 (5)
Thorns	-	12 (3)	36 (4)	-
Dangerous working conditions	-	-	10 (3)	-
Large travel distances/isolated areas	-	-	12 (3)	9 (5)
Ecological				
Fast growth and spread rates	41 (5)	15 (4)	16 (4)	45 (5)
Ineffective biological control	6 (5)	-	-	45 (5)
Hybridisation	-	-	-	18 (4)
Animals spread it (wild and domestic)	17 (3)	36 (4)	-	9 (4)
Social				
Cognitive				
Farmers rely on government/ want subsidies	-	55 (5)	-	-
Not perceived as a problem and still used	17 (5)	58 (5)	-	45 (5)
Normative				
Conflicts of interest	-	14 (4)	-	45 (4)
Institutional				
No strategic planning and prioritisation	18 (5)	76 (5)	3 (4)	64 (5)
Red tape	6 (4)	3 (3)	6 (4)	
Poor management, supervision and efficiency	18 (5)	98 (5)	12 (3)	36 (5)
No partnerships and communication btw stakeholders	35 (5)	18 (5)	-	18 (4)
Projects to short term and irregular	6 (4)	14 (4)	51(5)	18 (5)
WfW focus on job creation(mandates)	-	23 (4)	-	9 (5)
Poor follow up form WfW and farmers	27 (4)	88 (5)	9 (5)	9 (4)
Compliance, enforcement of law/ incorrect law	13 (4)	9 (3)	-	18 (4)
Poor monitoring	-	18 (4)	-	45 (5)
Corruption	-	32 (3)	-	-
Neighbours do not manage it	-	50 (5)	-	-
Unwilling to invest in rented land	-	15 (3)	-	-
Control in the wrong season	-	6 (3)	-	-
Interference from farmers	-	-	16 (3)	-
Paid late	-	-	60 (5)	-
Lack of training	-	-	6 (3)	9 (5)
Lack of restoration	6 (3)	3 (4)	-	9 (4)

6.3.3 Human and informational Barriers

Numerous factors in the human and informational node were mentioned. This included lack of knowledge in many areas and the fact that the awareness of what we do know is poor; a research-implementation gap also exists (Table 6.3; Figure 6.2). The lack of knowledge mainly covers factors relating to the effectiveness of different control techniques as well as distributions, taxonomy and negative impacts of *Prosopis* invasions (Figure 6.2). Interestingly, Managers were the main group to highlight that there was a lack of knowledge (53 %) and awareness of existing knowledge (41 %) while not many stakeholders in other groups mentioned this as a barrier.

The technological node included barriers relating to the underutilisation of potential management approaches (control through utilisation, biological control and use of heavy machinery) as well as issues with the type and quantity of equipment being used to clear trees. Other barriers also included the incorrect use of herbicide (applying it too late, and in incorrect dosages which has been linked to corruption); and selling off of allocated herbicide resulting in the use of diluted herbicide. Ineffective herbicide and ineffective application (primarily timing) of herbicide was a major barrier mentioned commonly by most of the stakeholders, as it leads to coppicing and re-invasion of cleared lands.

The economic barriers included lack of funding, inconsistent funding and factors relating to the lack of subsidies and financial incentives from the state for management by private land owners. Widespread invasions also have particularly high input costs, especially those species that can coppice and require herbicide. Interestingly no Workers listed any economic barriers. We also added an extra sub-component (Indirect economic barriers) to the human and informational node not originally found in the Jones (2010) framework (Figure 6.2). Although many of these factors are very context-specific and relate to unique landscapes and historical processes, many of these indirect economic factors will apply to other developing countries, especially arid areas with low population densities. These include: (a) South Africa’s colonial and apartheid history, where black African people were deprived of opportunities for education and employment - there is therefore great pressure to improve equality through the provision of infrastructure such as housing, schools and hospitals, which leads to less funding being available for environmental issues (Figure 6.2). (b) The effects of state social grants lead to a reduced incentive to work in jobs that pay below-minimum wages. (c) The other indirect economic factors related to the fact that the areas that *Prosopis* invade are extensive, arid and have low population densities; this results in higher costs for management (as well as less incentive to manage) because the productive value of the land (return on investment) is low compared to other parts of South Africa.

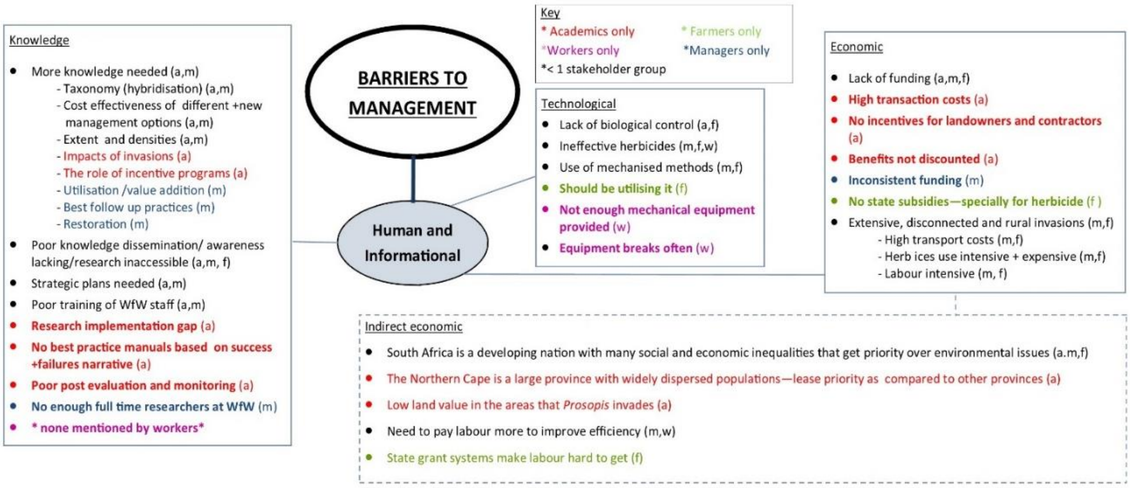

Figure 6.2: Human and informational barriers to management of *Prosopis* species (categories follow Jones, 2010) identified by different stakeholders during workshops. A new sub-component ("Indirect economic" barriers) was added.

6.3.4 Natural barriers

Natural barriers to management were mentioned least often but still have a major impact of the success of control operations (Figure 6.3 and Table 6.3). They included physical factors, such as the very extensive and dense invasions, remoteness of areas, lack of capacity and dangerous working conditions (of which the last point was only mentioned by Workers) (Figure 6.2). Numerous ecological barriers, relating to invasions processes and the ecology and traits of the tree were mentioned. The increased presence of wildlife was sometimes attributed to *Prosopis* invasions. Wild animals that feed on *Prosopis* can spread the seeds across fence lines, including kudu (*Tragelaphus strepsiceros*) and baboons (*Papio ursinus*) that jump over fences, and porcupines (*Hystrix africaeaustralis*) that burrow under fences. The dissemination of mesquite by livestock was also a key issue and is controversial in that many farmers want to use *Prosopis* to feed livestock.

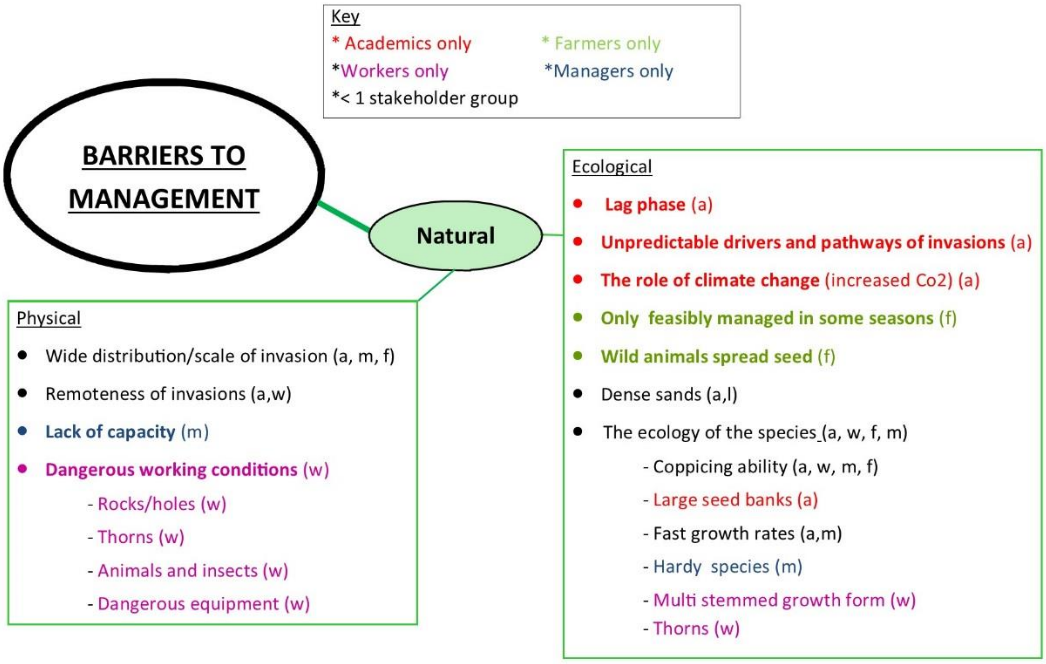

Figure 6.3: Natural barriers to management (Jones, 2010) identified by different stakeholders in workshops.

6.3.5 Social barriers

Social barriers were frequently mentioned by all the stakeholder groups, but to a lesser extent by Workers (Figure 6.4 and Table 6.4). Cognitive barriers included feelings of hopelessness and apathy, loss of interest, failure to accept and learn from other examples (Figure 6.4). Additionally, many Farmers (55 %) suggested that other farmers were wanting government support to clear and were not doing anything themselves. Many respondents from all stakeholder groups suggested that some people viewed it still be useful and not a big problem – which may be linked to the lack of awareness highlighted in the barriers to knowledge node (Figure 6.4).

The normative barriers all related to the conflicts of interest, and were not mentioned by the Workers (Figure 6.4 and Table 6.3). This is related to issues around possible management approaches (biological control and to a greater extent utilisation and the use of more mechanised approaches – which could improve clearing but potentially reduce employment), WfW's mandates (job creation vs. invasive species clearing) and the conflicts of interest around the use and benefits of widespread invasive trees.

Institutional barriers were regularly mentioned, but the specific ones mentioned differed between stakeholder groups, particularly between Managers and Farmers (Figure 6.4; Table 6.3). Major issues highlighted as institutional barriers included a lack of stakeholder cooperation and communication and partnerships was particularly highlighted by Managers (35 %). Poor strategic planning and prioritisation emphasised particularly by Farmers (76 %)

and Academics (64 %) and to a lesser extent by Managers (18 %), and issues regarding legislation. Farmers also emphasised poor management, supervision and quality control as problems (95 %), poor follow-up clearing (88 %) corruption within the state-run WfW program (32 %) and the lack of cooperation between landowners (where one clears and the other does not) as major issues affecting successful management (Table 6.3). Many narratives of corruption were discussed in the workshop – including Managers and contractors giving Farmers herbicide in return for sheep (bribes), WfW projects sites being selected using bribes and contractors claiming to have cleared land which was done by farmers and receiving money for this. Many of the institutional issues raised by Farmers were not of as much concern to Managers (Table 6.3). These discrepancies point to very different world views among the most important stakeholders involved in management. Academics raised poor monitoring (45 %), and issues relating to institutional arrangements and mandates as major barriers as well as a lack of a champion and accountability in the WfW programme (Table 6.3). The short-term and irregular nature of projects were also raised as an issue by all stakeholders, but particularly by Workers who found that this made it difficult for them to plan financially and lead to them taking up full time jobs in other sectors if and when they arose and leaving the WfW program. Workers suggested that they were not being paid on time, which linked closely to the cognitive barriers of a loss of interest in employment in the WfW programme.

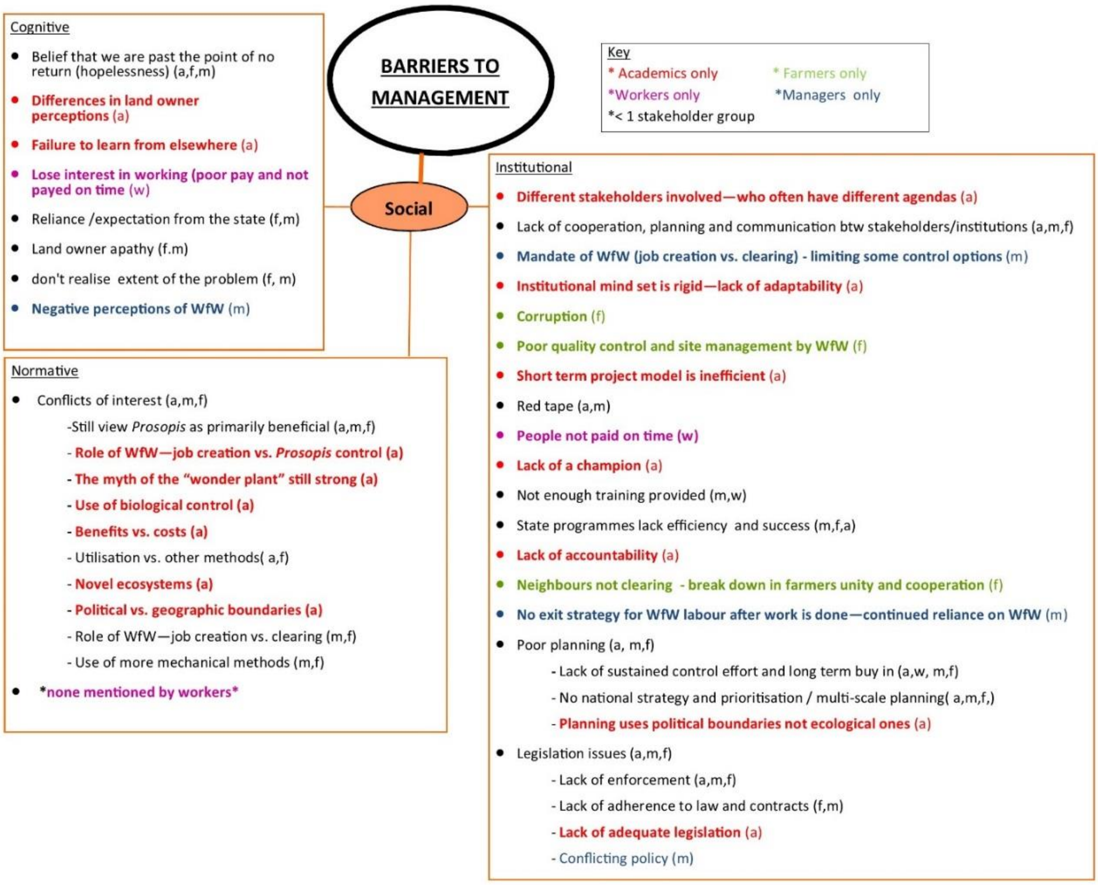

Figure 6.4: Social barriers to management of *Prosopis* species (listed under categories defined by Jones, 2010) identified by different stakeholder groups during workshops.

6.3.6 Adaptation responses

Just under 30 adaptation responses were mentioned by the four stakeholder groups; each group mentioned 11-16 different responses (Table 6.4). There was considerable overlap between the responses listed by stakeholder groups with the most common adaptation responses mentioned being: researching and using different approaches to management - this included, using biological control, utilisation approaches, different herbicides (a sub-point mentioned by all stakeholders), as well as using more mechanised approaches to improve control. Linked to this is a point mentioned by Workers: that receiving more mechanical equipment would help speed up control. Farmers mentioned that it would be important to focus more on effective clearing methods than on job creation, and to change person working days as a metric for success to another metric, such as the area of land cleared or potentially an indicator of improvement in ecosystem services. Improved awareness and research, better strategic planning and prioritisation, better stakeholder engagement and cooperation as well as changing the legislation on *Prosopis* and better enforcement of legislation and contracts were also highlighted as important among all stakeholder groups, except Workers. Improved follow-up clearing and targeting of coppicing and re-invasion were highlighted by both

Managers and Farmers. Farmers also mentioned that improving the quality of, and having more access to WfW area managers would help. They also emphasised that receiving subsidies would encourage control; this aspect is linked to the other comments regarding the provision of incentive and disincentive schemes to encourage and stimulate control. Workers mentioned that getting paid at appropriate times would be beneficial to help reduce barriers of feeling apathetic, unhappy and losing motivation about the project tenders. Academics specifically suggested that understanding and overcoming conflicts of interest would help to reduce certain barriers, as would an improved understanding of the taxonomy of the trees present in South Africa which links closely to the release of potentially more effective biological control agents and understanding the invasiveness of different species.

Table 6.4: Management and adaptation responses to improve the management of *Prosopis* suggested by four stakeholder groups. Numbers in the table indicate the percentage of each group that suggested particular responses.

Management/adaptation responses	**Managers**	**Farmers**	**Workers**	**Academics**
Awareness and research programs	35	38	-	18
Use and research diff. management approaches	58	100	9	81
More localised managers	17	3	3	-
Better stakeholder engagement	58	24	-	18
Use stronger herbicide	12	23	40	9
Increase budgets	-	-	-	18
Less focus on job creation/change indicators of success	-	24	-	9
Change and enforce legislation and contracts	47	21	-	18
More access to managers	-	21	-	-
Employ more teams	6	-	15	-
Make projects more long term/ more follow-ups	35	38	3	9
Understand and solve conflicts of interest	-	-	-	27
Provide subsidies to farmers	6	-	-	-
Restore cleared areas	12	-	-	-
Disincentivize its use	12	-	-	-
Give teams more mechanical equipment	-		55	-
Strategic planning and prioritisation	6	48	3	63
Improve monitoring	-	-	-	18
Get paid on time	-	-	21	-
Improve training	-	-	3	9
Understand taxonomy	-	-	-	27
Provide more training	-	-	3	-
Give farmers labour and herbicide subsidies	-	32	-	-
Incentive and disincentive schemes for farmers	-	58	-	-
Clamp down on corruption	-	15	-	-
Breed sterile cultivars/ id safe taxa to use	-	6	-	9
Work in the correct seasons	6	9	-	-
Change WfW operating system	-	9	-	-
Nothing or don't know	-	-	9	-

6.8 Discussion

6.4.1 The value of including both workshops and questionnaires

Widespread invasive species such as *Prosopis* that transform landscapes and ecosystems have major impacts on people and the environment (Table 6.2 and 6.4) and therefore require management to minimize impacts and potentially improve benefits. However, there are many barriers which hamper effective management of tree invasions (Table 6.2). Only eight barriers relating to the management of invasive tree species had been highlighted in previous studies in South Africa. These included: poor data on the distribution of the invasions, lack of coordination between stakeholders, budgetary limitations and unpredictable environmental drivers (Roura-Pascual et al. 2009) as well as weak policy and institutional environments, lack of critical information, inadequate implementation and lack of capacity (UNEP, 2004), all of which were identified in this study as well. Many of the barriers identified in this study are fairly fundamental and have been mentioned in similar studies of other globally important environmental changes, such as climate change (Jantarasami et al. 2010; Lehmann et al. 2014; Spires et al. 2014).

Using two approaches (each with advantages and disadvantages), over a hundred barriers to management of widespread invasions were identified (Table 6.3, Figure 6.2 and 6.3). More barriers to management were raised during workshops (100 (62 main-criteria and 38 sub-criteria)) than in the questionnaires (just under 40) (Table 6.3; Figure 6.2,3). The questionnaires were nonetheless useful for quantifying the frequency and the importance of different barriers (Table 6.3). The questionnaires had the additional benefit in that data gathering was inexpensive. The workshops clearly provide a more comprehensive understanding of the dimensions and causes of barriers and how they are linked. Three barriers were mentioned in questionnaires that were not raised in the workshops. These included the sentiments of Farmers who were unwilling to invest money to clear on land they were renting; the fact that Farmers interfered with the jobs that Workers were doing; and Farmers highlighting that time constraints were a major factor hindering the effective management of these invasive trees (Table 6.3).

There were differences in perception of barriers between different stakeholders (Figure, 6.2,3,4 and Table 6.3) which highlights the importance of including the full range of stakeholders in such assessments. A comparison of the views between Farmers and Managers regarding the listing of three particular barriers is particularly interesting (Table 6.3). First, very few Managers identified the need for strategic planning and prioritization, whereas the vast majority of Farmers think it is a big barrier. Secondly, poor management, supervision and efficiency is regarded as very important by almost all Farmers, but very few Managers mentioned this. Thirdly, almost all Farmers were concerned about poor follow-up treatments, while only a quarter of Managers considered this important. These discrepancies point to very different world views among the most important stakeholders involved in management. Clearly, Farmers are concerned about poor planning and management efficiency, and managers are not. This is probably because farmers have a genuine interest in a favourable ecological outcome, while the second goal of WfW - job creation - is given precedence by managers. Similar views have been noted by van Wilgen and Wannenburgh (2015) who discuss why more emphasis is being placed on job creation than natural resource management by the state and WfW programme, a barrier identified in this study as well. This has led to the lack of prioritisation as the ecological conservation has taken a back seat –"job creation in the short term has been traded off against natural resource protection that, in the longer that would arguably protect many more jobs – a case of the tail that has come to wag the dog" (van Wilgen and Wannenburgh, 2015).

6.4.2 Challenges presented by barriers

Many barriers that were highlighted in this study may be difficult to overcome (Figures 6.2,3,4 and Table 6.3). These include many aspects of the biology of the species: mass seeding, coppicing, and fast growth rates and the factors that mediate invasions and their persistence. However, other ecologically related factors can be addressed, there should be a focus on adaptive responses that address factors such as management of drivers and pathways of invasion, (Wilson et al. 2009) and improved methods of herbicide application (quality control) to minimise coppicing and persistence. The improved management of livestock, by putting them in holding camps before they are moved could minimise the spread of invasions and could be a potential adaption response. Also, if control measures were prioritized in space and time, such as beginning at the top of catchments, this would prevent re-invasions of cleared areas in lower parts of catchments. Others barriers that would be difficult to adapt to include: limited and inconsistent funding, and the lack of state subsidies and capacity constraints, particularly hindered by contextual issues relating to the socio-economic history of the county (Figure 6.4) (Shackleton et al. 2013). South Africa cannot provide WfW with the money and capacity to cover all invaded lands (van Wilgen et al. 2012b), making it imperative to use an adaptive management responses that would improve efficiency. Prioritisation and strategic planning through space and time could help maximise the returns on the available resources (van Wilgen et al. 2012b). This could be done using decision trees (e.g. see Grice et al. 2010) or through multi-criteria decision making analysis (e.g. Forsyth et al. 2012). Additionally, better partnerships and communication between stakeholders could improve control with available budgets. Improved site management and quality control and a clamp down on corruption may also help improve the effectiveness of management projects and prevent wastage of money – a factor that could be easily addressed. Additionally, alternative – more cost effective - methods of control could be sought such as biological control and utilisation ((which are controversial approaches (Shackleton et al. 2014)) as well as taking a more mechanised control methods (earth movers and application of herbicide using planes) and having longer term projects in one area to target re-growth (van Wilgen et al. 2012a). However, these other approaches are often hindered by conflicts of interest which need to be addressed first (Shackleton et al. 2014; van Wilgen and Richardson, 2014).

6.4.3 The need for research

Research into the impacts of invasions and the benefits of control and the cost effectiveness of these different approaches may help to resolve some of these conflicts of interest. Research findings need to be interpreted and circulated in appropriate ways to different stakeholders to improve awareness. Recent studies have shown that *Prosopis* substantially reduces grazing potential and water supply, arguably the two most important resources in the areas (Ndhlovu et al. 2011; Dzikiti et al. 2013). The majority of people view *Prosopis* to be more harmful than beneficial and the benefits supplied to households are not as great as previously thought relative to native trees (Shackleton et al. 2015c,d). These facts need to be publicized though awareness-raising programmes; this should reduce conflicts of interest and encourage private land owners to manage invasions. Previous studies have shown that good public awareness is strongly correlated with implementation of climate-change adaptation responses and support for initiatives for managing invasive species (Semenza et al. 2008; Garcia-Llorente et al. 2011, Verbrugge et al. 2013).

6.4.4 The role of legislation

Addressing and enforcing legislation is another barrier that could be overcome and could greatly improve the control of *Prosopis.* Within the Northern Cape Province, *Prosopis* is listed as a "Category 3" invasive species. This means that the genus may remain in the province, but that further propagation or trade is prohibited (Department of Environmental Affairs, 2014). Changing legislation to make *Prosopis* a "Category 1" genus everywhere might help to improve private land owner control in an area where the spread and impacts are the worst. In addition, enforcing the legislation more systematically would improve management from a private land owner's perspective to ensure that they do not get penalised with fines.

6.4.5 Adaptive management

Adaptive management is also needed to better overcome these barriers and improve effective management of *Prosopis*. This is due to the fact that the invasions are dynamic in different areas, growing pressure from other drivers of change and changing social-economics perceptions (Wise et al. 2012; Shackleton et al. 2015a,b). However, key to underpinning this is also a need for improved monitoring to inform how management needs to be adapted (Lyone et al. 2008).

6.5 Conclusion

This case study has provided useful insights on the barriers faced when managing large-scale tree invasions. There is a need to extend these insights for other invasive plant and non-plant taxa, and to address barriers hindering the management of emerging invasive species. There will obviously be overlap, but these different taxa will have their own suite of unique barriers. A better understanding of these could help improve management effectiveness and reduce the negative impacts of biological invasions globally.

Acknowledgements

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Towards a national strategy for the management of a widespread invasive tree (*Prosopis:* mesquite) in South Africa

This chapter is intended for submission to *Environmental Management*.

Abstract

Biological invasions are a major component of human-induced global change and lead to many negative impacts for humans and the environment. Effective management is required to reduce negative impacts and, in some cases, to improve the supply of benefits. Invasive stands of *Prosopis* (several species and their hybrids; collectively termed "mesquite") now cover over 6 million ha of South Africa and could invade over 56 million ha. These stands have major impacts on biodiversity, local economies and ecosystem services such as the supply of grazing and water. We applied several methods (decision trees, workshops and questionnaires) to develop an objective basis for a national strategy to prioritise and guide the management of invasive mesquite in South Africa.

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 municipalities (lowest level of government) 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 (biological control, control through utilisation, and different combinations of chemical and mechanical control) 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 using various methods in optimal combinations would be most effective. Strategic guidelines for improving the management of *Prosopis* were produced. These included key needs and objectives, targets, time frames and indicators such as establishing coordination teams, research agendas, monitoring programs, and specific goals for categorised management areas.

7.1 Introduction

7.1.1 General introduction

A small proportion of species moved by humans to new regions become naturalised, and some of these become invasive and are increasingly leading to negative impacts on biodiversity, ecosystem services, local economies and human health in many parts of the world (Pimentel 2011; Jeschke et al. 2014). Biological invasions play an important role in 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 (Shackleton et al. 2007; van Wilgen and Richardson, 2014). This makes understanding the various social, ecological and economic aspects of invasions and the implications of these invasions for different stakeholders important for guiding best management practice. Such a holistic and integrated understanding requires a transdisciplinary approach that transcends different disciplines and knowledge systems resulting in plans and solutions that are co-developed with different 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. Some notable initiatives include the Weeds of National Significance program in Australia (WoNS) (Thorp and Lynch, 2000; Australian Weeds Committee, 2012.), the Working for Water (WfW) program in South Africa (van Wilgen and Wannenburgh, 2015), 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 signatories to take steps to manage invasive alien species. Although some countries have produced high-level management strategies for dealing with invasive species, many lack species-specific plans and strategies. The lack of clear guidelines for 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). In South Africa, requirements for managing invasive species 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 regulations stipulate 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.

Strategic planning or management strategies have been developed for various invasive species globally (Throp and Lynth, 2001; van Wilgen et al. 2011). These strategies aid to guide and improve management though developing goals and monitoring progress towards them, and to galvanise cooperation and learning between stakeholders and improve control implementation all in the context of legislation to ensure improved management outcomes with available funding (Bryson, 1988). Key to developing plans is capturing all knowledge and involvement of stakeholders (Thorp, 1999). The WoNS program in Australia has been seminal for producing and implementing strategic plans to manage various invasive plant taxa with in Australia. Australia has strategic plans for 20 species under their Weeds of National Significance program (Thorp and Lynch, 2000) program, and South Africa has species specific case-study examples for Australian *Acacia* species and *Parthenium hysterophorus* invasions (van Wilgen et al. 2011; Terblanche et al. under review). 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). For example, a strategy to guide the managed of all aquatic invasive species in the state of Arizona (Arizona Game and Fish Department, 2011).Some strategies use approaches that focus on particular pathways of introduction or area-specific interventions and include all invaders together (Lee and Chown, 2009).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 the risks and impacts of invasive species 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 this recognition, such approaches have rarely been used (Roura-Pascual et al. 2009, 2010; Grice et al. 2011; Forsyth et al 2012; Le Maitre et al. 2015). Objective spatial prioritisation (ranking the importance of land areas by importance) must be done to guide management and to optimize the allocation of limited funds (Raw et al. 2010; 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; Nielsen and Fei, 2015). Decision trees have been used to assign management approaches to different areas (e.g., prevention of spread to unoccupied areas, local eradication, containment, asset protection) would be most appropriate (see Grice et al. 2010; Le Maitre et al. 2015). A range of options usually exists 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 engagement to assess wants and needs important (van Wilgen et al. 2011; Shackleton et al. 2014). Multi-criteria decision analysis (MCDA) provides tools 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 and facilitates transdisciplinarity (Angelstam et al. 2013) - this is crucial in cases where invasive species generate conflicts of interest (Saaty, 1990; Forsyth et al. 2012).

7.1.2 Prosopis in South Africa

7.1.21. 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 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 a hybrid swarm of numerous species (Mazibuko, 2012) is now the second most widespread invasive plant genus in South Africa after *Acacia* (Henderson, 2007). It occurs through the interior at varying levels of abundance (Figure 1a). *Prosopis* occurs within the boundaries of 61 of the 234 municipalities in South Africa and occurs across almost half the country (Figure 7.1a). Past research 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 6.5 million ha of South Africa (43% in the Northern Cape). Additionally, *Prosopis* could potentially invade up to 56 million ha

(63% in the Northern Cape) in the future, indicated by climatic suitability models (Mgidi, 2004; Rouget et al. 2004) (Figure 7.1b).

There is growing evidence of negative impacts due to *Prosopis* invasions in the country. These include negative impacts on ecosystem services (notably water and grazing; Ndhlovu et al. 2011; Dzikiti et al. 2013), biodiversity (Shackleton et al. 2015a,b 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 invasions become more widespread and increase in density, and as the reliance on natural resources from *Prosopis* declines simultaneously (Wise et al 2012; Shackleton et al. 2015d).The key challenge for managing *Prosopis* is therefore to reduce the negative impacts, while maintaining certain benefits where feasible.

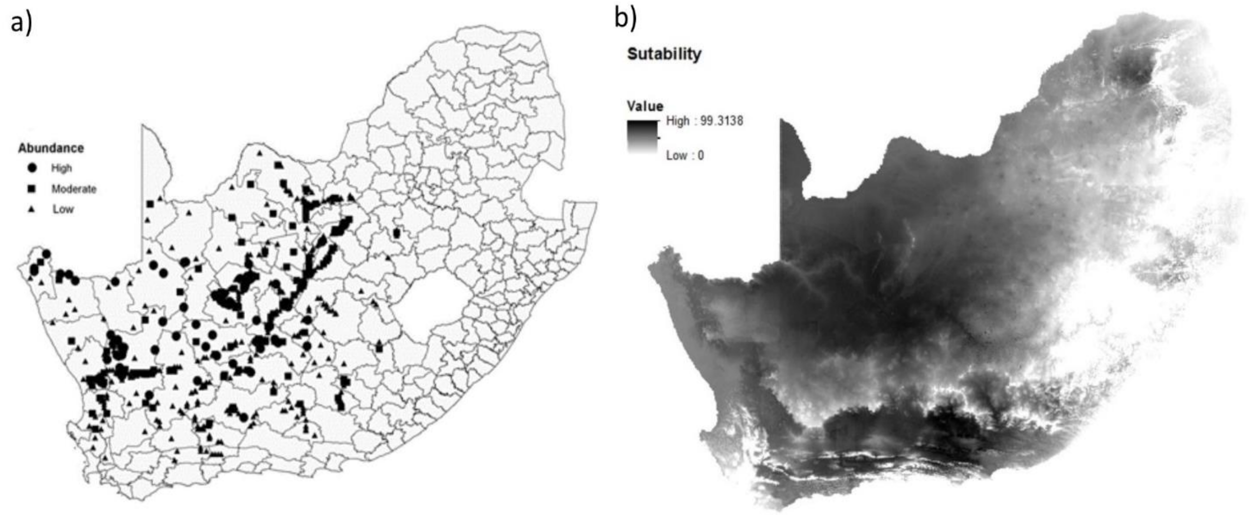

Figure 7.1: (a) Distribution of *Prosopis* spp. in South Africa (Sources: SAPIA database – L. Henderson; Van den Berg, 2010; Shackleton 2015a and 2015b); (b) Climatically suitable areas for *Prosopis* spp. in South Africa based on Mgidi (2004).

7.2.3 Legislation and management

As required by the regulations under the (NEM:BA, 2004; Act No. 10 of 2004: Alien and Invasive Lists, 2014), South African legislation divides invasive species into three categories based on their use and impact – similar to categories used in Australia (Australian Weeds Committee, 2012; Department of Environmental Affairs, 2014;). 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. However, 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. In other South African provinces mesquite is a Category-1 invader which means that invasive populations must be controlled wherever they occur. The NEM:BA regulations stipulate 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 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 of 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 in this paper accommodate key aspects of the existing legislation and provide additional considerations that will hopefully guide the revision of the legislation in the future.

The management of *Prosopis* invasions in South Africa has been primarily funded and co-ordinated by the WfW programme over the past two decades, although many private land owners 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. 2012). 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 and under review; van Wilgen and Wannenburgh, 2015). 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 biological control is widely considered a crucial facet of improved management for *Prosopis* in South Africa (Zachariades et al. 2011; Wise et al. 2012; Shackleton et al. 2015c).

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, 2015). These dual goals exist because of the high levels of inequality in South Africa as a society arising from colonialist and apartheid policies that marginalised a large proportion of the population. Providing employment and developing skills in historically marginalised communities is an overriding political imperative. 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, 2015). Contracts typically consist of projects lasting 2-3 months. Field teams include a contractor with teams, usually comprising about 10 unskilled workers, who are paid to clear demarcated areas based on norms and standards set for different species, terrain categories and density classes (van Wilgen and Wannenburgh, 2015). WfW receives an annual budget of about R 1.8 billion to manage invasions nationally, and is extremely well funded compared to other natural resource management projects in South Africa (van Wilgen et al. 2012b).

The extent of *Prosopis* invasions, their rapid spread, and the major negative impacts they have on human livelihoods and the environment make it important to manage them effectively to reduce costs and improve benefits. This paper describes the development of a national strategy to prioritize 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.

7.2 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 framework shown in Figure 7.2. 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 and specific case studies we conducted (many of which include different stakeholders) which have now been published. 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 (Figure 7.2). Step three reviewed current and past management of *Prosopis* (Figure 7.2). This included the literature and the use of workshops and surveys to identify key barriers that impede effective management and identified strategic and adaptive approaches that need to be applied to improve control of *Prosopis* (Shackleton et al. under review). Step four used various approaches to define components of a national strategy for *Prosopis* (Figure 7.2). This included drawing on published literature, in particular, examples from the WONS programme in Australia and strategies developed for other invasive plant taxa in South Africa (van Wilgen et al. 2011; Australian Weeds Committee, 2012; Terblanche et al. under review), to assess different control options and to identify needs for developing strategies and associated implementation plans. Multi-stakeholder workshops that included farmers, academics and private and public managers were used to develop and overarching goal for the strategy. These workshops were also used to identify crucial needs and outcomes for the strategy as well as for scenario planning as seen in Table 7.1, and Figure 7.3. The effectiveness and role of different control options and approaches were discussed in these workshops and through interviews with key informants (Table 7.2). Decision-tree models (Grice et al. 2010) were used to assign appropriate control objectives to different parts of South Africa (Figure 7.4). Using the current and potential distribution (Figure 7.1), the Grice et al. (2010) decision-tree framework was used to allocate management priorities to each of the 234 municipalities in South Africa (Figure 7.4). The decision tree allocated each municipality to one of five zones: Prevention which included: (1)

passive surveillance for areas 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 eradication is feasible; (4) containment for populations that cannot be eradicated and that fall on the border of heavily and uninvaded areas; and (5) asset protection for areas with widespread dense invasion, 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 et al. 1990) was used to achieve an objective, spatially-explicit, prioritisation of assets for protection in areas with widespread *Prosopis* invasions (Forsyth et al. 2012) (Figure 7.5; Table 7.3) and 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 through input 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.*

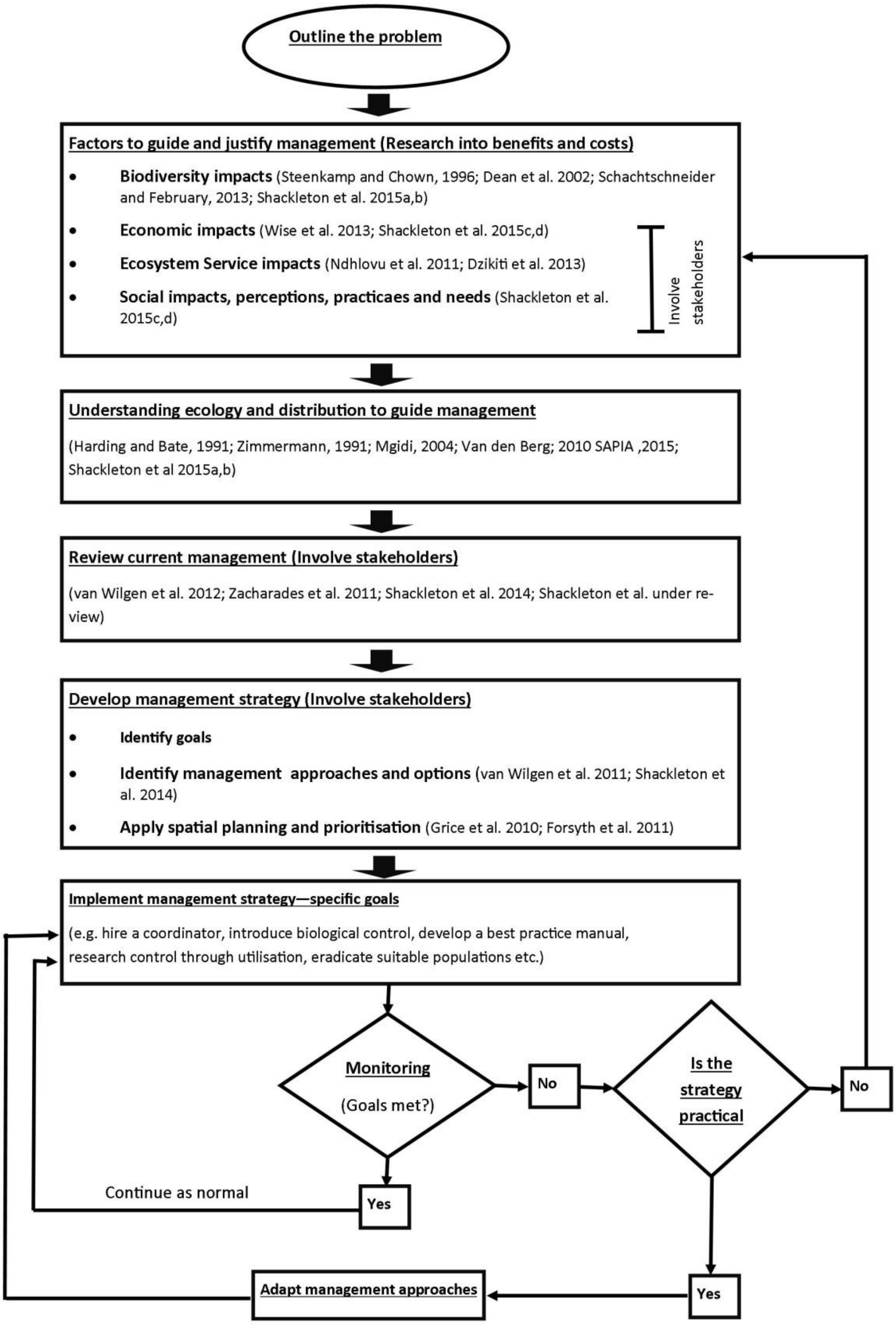

Figure 7.2: Framework and sources used to develop a national strategy for *Prosopis* in South Africa

7.3 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 control of *Prosopis* in South Africa.

7.3.1 Goal

The goal (agreed to by multiple stakeholders) to guide the management of *Prosopis* in South Africa was: "To effectively control, contain, reduce 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 7.1).

Table 7.1: Strategic planning needs to achieve the goal of improving the effectiveness of managing invasive *Prosopis* in South Africa as determined through workshops and consultation with multiple stakeholders.

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 programme and a multiple stakeholder working group	• Develop a programme 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 programme 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
Mandates and legislation		
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 – possibly take a non-compliant farmer to court in the next year to act as a warning for others – alternatively develop an incentive scheme for compliant farmers in the next year e.g. herbicide subsidies • Indicator – number of land owners provided or provides incentive subsidies

Develop a research agenda	• Identify priority research areas to be addressed – particularly biological control, control through utilisation, and monitoring	• Produce a 5-year research plan (driven by working group and coordinators) in the next 2 years
Develop a best practice manual for private land owners	• 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 iSpot Indicator – 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 • 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)	• Report back annually • Map changes in asset protection zones annually

	• Use multiple control approaches to maximise control and be adaptable • Engage with stakeholders (farmers union meetings other departments)	• 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 and management costs

7.3.2 Co-ordination of programs and stakeholders involved

Better coordination, as identified in the workshops, was seen as important for the strategy (Shackleton et al. under review). Participants also highlighted that coordination and cooperation at different levels (international to local) is crucial for alignment with South African legislation and for overall control success (Table 7.1). It was also identified that cross-border coordination and cooperation will help to ensure successful management (Table 7.1).

We therefore propose that national and regional coordinators and a 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) needs to be appointed in the next year to guide management (Table 7.1). 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 land owners and oversee stakeholder engagement, monitoring and performance evaluations (Table 7.1).

Report-backs should be conducted at least annually and plans need to be reviewed and revised if necessary at least every 5 years - a process driven by the coordinators Annual feedback to interested and affected stakeholders, primarily farmers unions (Table 7.1) will help to build cohesion, cooperation, awareness and accountability. The state is unable to manage *Prosopis* alone; this makes bringing private landowners on board an important part of the strategy. We highlighted the need to set up and promote the use of citizen spotter networks, and the need for regional managers to engage and report to farmers at union meetings (Table 7.1). The production of a best-practice manual that can be widely distributed to promote awareness among private land owners and management by non-governmental stakeholders is needed. Incentive/disincentive schemes for non-compliance with legislation and contracts by private land owners need to be implemented as soon as possible to improve buy-in and overall management participation by different stakeholders (see section 3.3).

7.3.3 Mandates of programs and legislation

Mandates for the strategic programme must be adopted by WfW operations and apply to the latest NEM:BA regulations which should be reviewed based on the outcomes of the strategy (Table 7.1).). We also suggest that a case should be made to move *Prosopis* from a category

3 species in the Northern Cape to a category 1 species which would ensure improved management. This is based on the growing body of evidence that shows that at current and future invasion rates the costs are higher than the benefits (Wise et al. 2012; Shackleton et al., 2015a,b,c). Compliance with contracts between WFW and farmers as well as NEM:BA regulations is currently low; this is a major barrier hindering effective management of *Prosopis* (Shackleton et al. under review). Therefore, efforts to raise awareness of legislation among stakeholders are required. Getting mass buy-in and cooperation of private land owners is important if control is to be successful. Enforcement of legislation to improve compliance, in particular contracts between farmers and WfW, will improved efficiency and reduce wattage of resources. (Table 7.1). Incentive and disincentive schemes could help improve compliance (Shackleton et al. under review) 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 improve options for management in the long run (Table 7.1).

7.3.4 Control options and approaches

Various control options exist for *Prosopis,* each with their own benefits and costs, as identified in the literature and through stakeholder workshops and interviews (Shackleton et al. 2014; Table 7.2). At the current rates of control using the cut-stump method applied by WfW, *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 (van Wilgen and Wannenburgh, 2015; Shackleton et al. under review). This is largely because WfW focusses primarily on job creation and gives less attention to optimizing clearing methods to reduce the extent of invasions (van Wilgen and Wannenburgh, 2015; Shackleton et al, under review).

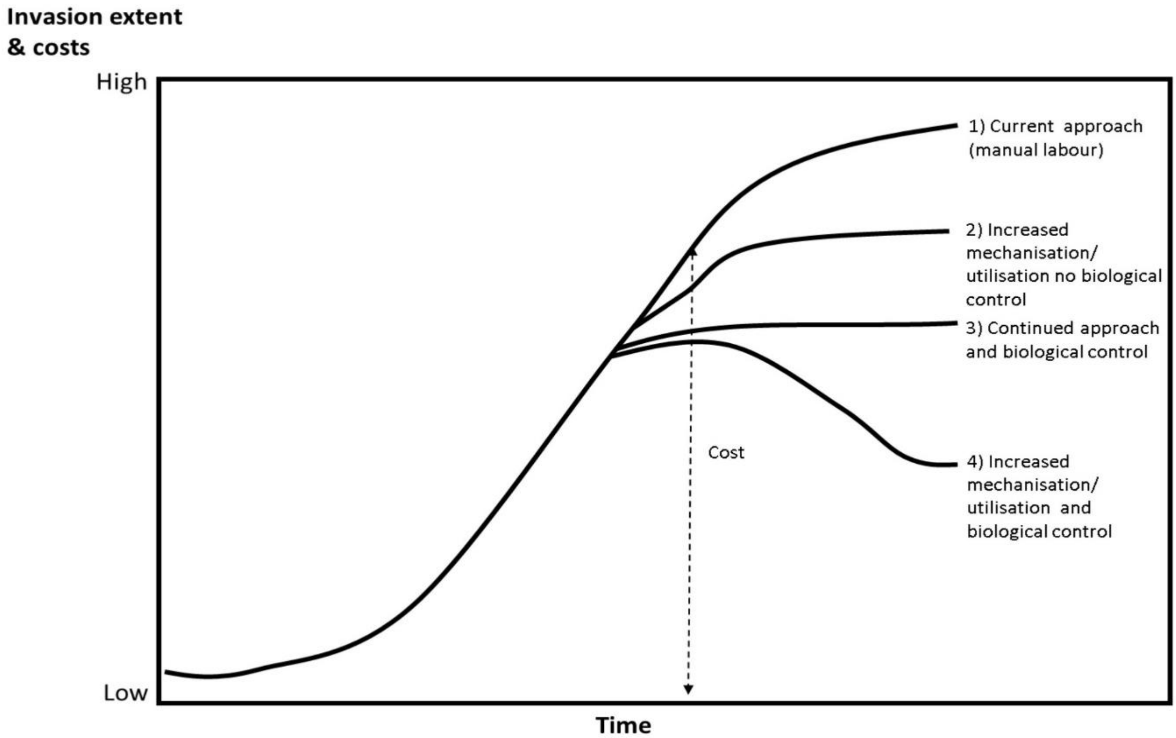

Figure 7.3: Scenarios of the extent of *Prosopis* invasion and associated costs over time based on different control options, combinations of options, and their potential effects on invasion extent.

This strategy outlines that an integrated management approach needs to be applied if *Prosopis* is to be controlled effectively (Figure 7.3). Integrated management includes the combination of two or more different control approaches (Figure 7.3; Table 7.2) (van Wilgen et al. 2001). We suggest that in particular three important control options need to be researched and implemented. This includes; (1) the release of more lethal biological control agents as the most important factor (Figure 7.3; Table7. 4). If the correct agents are found biological control will be the most cost effective approach to controlling invasions (Appendix 2). We also suggest that; (2) less labour-intensive methods such as aerial spraying or use of heavy machinery methods, which can clear areas at greater rates, will be needed if *Prosopis* is to be managed effectively in areas where important assets needs to be protected (Table 7.2). This will ensure rapid control in important areas, cut stump can be used for eradication and containment programs and maintain high employment in the WfW program (Figure 7.4). We also identified that, (3) the role of large scale control through utilisation as a potential control approach needs further research (Figure 7.3; Table 7.1 and 7.2). This approach could allow for faster control and rural economic development, however, there are still controversial issues around this approach such as creating a dependency on a resource that is expected to decrease and issues around potentially promoting spread of invasive species (Table7.2). 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." Additionally, the strategy suggests that 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 7.1). The use of spatial planning and prioritisation (Figure 7.4 and 7.5) to direct and prioritise control approaches is needed to improve control effectiveness in the long run especially in light limited funding and capacity (see Figure 7.4; Figure7.5; Table 7.3) (Shackleton et al. under review). In addition, improving coordination, and enforcement of legislation will also improve the effectiveness of mechanical control. See Appendix 2 for more details on the different control options highlighted above and in Table 7.2.

Table 7.2: 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 *A. prosopis, A. bottimeri and N. 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] Low – a few researchers and lab assistants	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] Low – a few researchers	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.
Mechanical & chemical control	Cut stump (standard WfW approach)	[a]± R 5 000- 7 000 for (wages and herbicide) [b]± 3 days/ha [c] High -11 people	It is the slowest *Prosopis* clearing method, but it best meets the duel 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 with more mechanical 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	Is 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 in highlighted in Table 7.3 and Figure 7.4
	Mechanised approach – herbicide spraying with aircraft	[a] ± R 1000 [b] < 1 000 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 tons 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 of the state. Investigation into the feasibility of approach is required urgently. Other utilisation possibilities include charcoal, paper and mulching etc.
Other approaches	Livestock management	[a] No clearing – prevents spread *Fencing could be expensive if needed [b] Prevents spread [c] Low	Has other rangeland benefits as well. If fencing needed costs will rise, but will also aid employment
	Transport managed	[a] No clearing – prevents spread [c] Prevents spread [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. That said as invasions move into the high rainfall grassland areas of South Africa this approach may be appropriate. Small concentrated fires at the base of large trees have been used effectively for killing single isolated trees.

7.3.5 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. 2010). Numerous stakeholders considered this as important for improving management success of *Prosopis* (Shackleton et al. under review). Using current and potential distribution (Figure 7.1), municipalities were divided into five different management areas (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) (Figure 7.3). 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 7.1). 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 7.1). 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 prioritisation, focusing on the assets that need to be protected, is required. 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 (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 (Figure 7.3). It is also 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 7.1 (changes in population density, cost, etc.). 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 7.1).

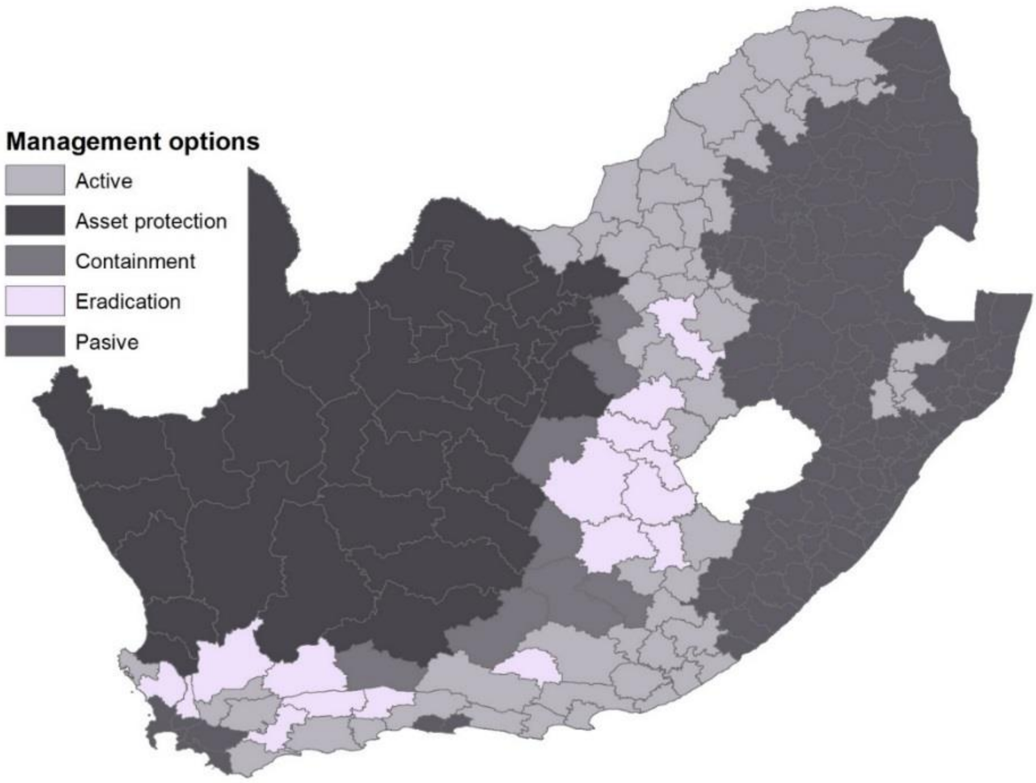

Figure 7.4: Spatial differentiation of approaches for managing invasive *Prosopis* species in South Africa to be applied to each municipality in the country using the decision-tree framework of Grice et al. (2010). This spatial differentiation is based on current and potential population sizes. The management approaches include: Prevention (active and passive surveillance in areas with no *Prosopis*); Eradication (in areas with small, isolated populations): Containment (along the boundaries of areas with numerous populations); and Asset protection (in areas with widespread and dense populations).

7.3.6 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 (Figure 7.4 and 7.5; Table 7.3). 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 7.3). Water was raised as a primary issue, as *Prosopis* invades arid areas where water scarcity is a major problem. The deep roots of *Prosopis* can exploit and reduce the limited ground water resources (Dzikiti et al. 2013). This corresponded closely to the assets that farmers and WfW managers highlighted as being important and that require protection in individual questionnaires (Appendix 4). Interestingly, 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 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 (Figure 7.3).

Table 7.3: Criteria and sub-criteria and their relative weightings used in prioritisation of assets to be protected in areas with dense *Prosopis* invasions. These criteria and weightings were identified and weighted by multiple stakeholders in facilitated workshops.

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, vineyards and orchards)	**9.4**	
Maintain and improve rangeland potential (grazing)	**5.4**	

Most of the high-priority municipalities within the asset protection zone (Figure 7.4) were in the western part of South Africa (Figure 7.5a). The western part of South Africa is found in upper catchment areas due to being on the border of three of major South Africa mountain ranges (Cederberg, Roggeveldberg and Nuweveldberg), but it also receives higher rainfall which gives it greater rangeland and cropping potential. This area is also located in a global biodiversity hotspot, namely the Succulent Karoo. 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 7.1). Farm or catchment boundaries should be used to spatially prioritise areas requiring protection at finer scales based on the criteria in Table 7.3. An example of this is provided for the Hantam municipality (Figure 7.5b) which was ranked as a “highest priority” municipality within the asset protection zone of South Africa (Figure 7.4, Figure 7.5a). Similar to the example for the whole of South Africa (Figure 7.5a), the highest priority catchments lie to the west (Figure 7.5b) for the reasons identified above. 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.

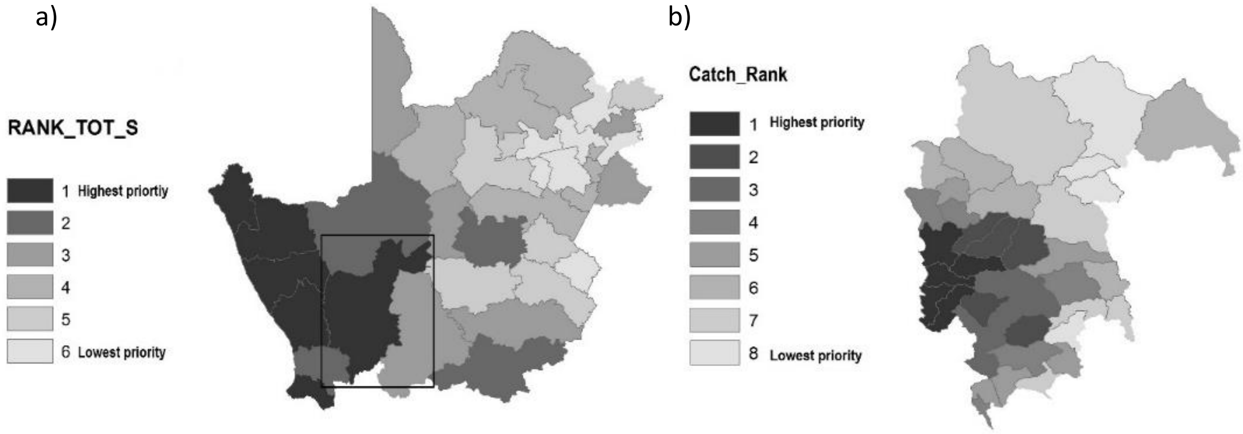

Figure 7.5: Spatial prioritisation of management for invasive *Prosopis* species in South Africa using criteria identified and ranked by means of analytic hierarchy process (AHP) illustrated in in Table 7.3 (a) shows spatial prioritization of municipalities within the asset protection category in South Africa highlighted in Figure 7.3. (b) gives an example of fine-scale prioritization of quaternary catchments in the Hantam municipality (the rectangle in (a); this municipality was ranked as highest priority in Figure 7.5a).

7.3.7 Monitoring, evaluation and indicators

Monitoring and evaluation are crucial in any environmental management program or strategy (Figure 7.2). 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. under review). Important factors that require monitoring include changes in *Prosopis* populations (mapping), costs, levels of awareness, compliance with legislation and the effectiveness of different control techniques and management successes and failures (Table 7.1). Monitoring needs to be standardised at various levels and in different areas to allow for cross comparisons through the use of common indicators (Tables 7.1 and 7.5). These could include the number of populations eradicated in the "eradication zone" and metrics relating to the cost and land area treated (Table 7.1). 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 revised where necessary (every 5 years) to optimise control over time (Table 7.1). Feedback must also be given to interested and affected stakeholders at least annually (Table 7.1) to promote mass buy-in and involvement.

7.4 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. under review). 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).

Current approaches are not effectively controlling populations, and are expensive (van Wilgen et al. 2012b; Shackleton et al. under review). 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 7.1; Figure 7.2). 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. 2010), involving the splitting South Africa into smaller management units, is crucial for planning and implementing management and needs to be done at finer scales. Additionally, 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 land owners is vital for effective management. Employing coordinators and setting up a research and monitoring program are also key to improve, review and adapt the management of *Prosopis.* 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.

7.5 Acknowledgements

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8.2 Introduction

Humans have moved species to areas outside their native ranges for millennia, and alien species are now common components of most ecosystems. The agriculture, forestry, pet and horticulture trade enterprises in most parts of the world are largely based on alien species. Some examples of valuable alien species that have been introduced globally are tomatoes, native to the South American Andes, chickens from Asia, and roses which are native to Asia, Europe, North America and northwest Africa.

Only a very small proportion of alien species become invasive. These invasive species have major ecological and socioeconomic impacts in their new areas. For example, the famine weed (*Parthenium hysterophorus*), native to southern United States, has been accidentally introduced to South Africa and it soon became an environmental and agricultural pest. It grows on any type of soil and in a wide range of habitats. Famine weed suppresses native vegetation, crop yields and contaminates crop seed, meat from livestock that has eaten the weed is not fit for consumption and regular contact with the plant produces allergenic dermatitis and asthma in humans. Another example is the Asian fruit fly. The Asian fruit fly was accidentally introduced to Africa around 2003, and soon after the first introductions, it spread rapidly throughout the continent, carried through infested fruits. Currently, it is the world's worst destructive pest of fruit and vegetables affecting the livelihoods of many farmers.

8.1.2 Costs, benefits and conflicts of interest

Despite the previously mentioned examples of "desirable" and "undesirable" alien species there are many that provide both benefits and costs. These can raise substantial conflicts of interests around their use and management. For example, alien conifers were introduced from Europe and North America over 300 years ago and have been widely planted in South Africa. These trees bring many benefits to the South African economy by providing timber and jobs. People also like them for aesthetic reasons. However, these trees cause several unintended problems: dense stands of invasive trees reduce water supply, grazing potential and lead to the loss of South Africa's natural habitats and species. These wide ranges of positive and negative impacts have created a conflict of interests between foresters (who make money from plantations), the public (who like the trees for aesthetic reasons, or whose land is negatively impacted by them) and conservationists (who want to conserve biodiversity).

As a consequence of these kinds of conflicts, there has been increasing interest in assessing the perceptions of different stakeholders involved with alien species. However, in most cases there is still a lack of collaboration between different parties, such as scientific researchers, the commercial sector (e.g. nurseries, pet shops, landscapers, and farmers), invasive species managers, policy makers and the public. This can result in the failure to develop and implement sustainable management strategies for invasive species.

Figure 8.1: American Giant one of the spineless cultivars of *Opuntia ficus-indica* (cactus pear). Image A. Novoa

In this article we explore approaches for facilitating interactions between stakeholders involved with alien species. We use the family Cactaceae (“cacti”) and the genus *Prosopis* (“mesquite”) in South Africa as cases to find solutions for this problem.

Figure 8.2: Open discussion between stakeholders who benefit from cactus species in South Africa and stakeholders who want to reduce their negative impacts. Image A. Novoa

8.2 Cacti

8.2.1 The problem

Cactaceae is a family of 1919 plant species that are almost all native to the Americas. The first alien cactus species arrived in South Africa early in the 18th century. Over the following two centuries many species were introduced to produce fruit for human consumption and fodder for livestock and are still being used for this today. Over the last 60 years, hundreds of new species were introduced to South Africa, almost exclusively for ornamental purposes. Food-science researchers (specializing in a wide range of crops) are also looking to develop the agro-industry around cactus in South Africa: fruit can be processed into jams, marmalades, juices, syrups and cladodes (the fleshy leaf-like structures) can be consumed as vegetables, pickles and flour.

However, many of the introduced species have become naturalized and 35 cactus species are currently listed by the government as invasive in South Africa. The negative impacts of invasive cacti on South African biodiversity, ecosystem functioning, resource availability, national economy and human health have been recognized for well over a century. These benefits and costs have resulted in numerous conflicts.

8.2.2 The solution

To address the conflicts of interests surrounding cacti in South Africa, we identified relevant stakeholders (nursery owners, farmers, land managers, scientists) and assessed their perceptions through questionnaires. We found that those stakeholders who were positively affected by cactus species were not aware of some of the negative environmental and socio-economic impacts of cactus invasions, while those stakeholders who wanted to reduce the negative impacts of cactus species in South Africa were not fully aware of their positive impacts.

We then tried to enhance the interaction between stakeholder's groups through open dialogues and discussions in a one-day workshop organized by the Centre for Invasion Biology. Surprisingly, one session of interaction and dialogue between stakeholders was enough to increase their "cactus knowledge" and improve the willingness of all stakeholders to collaborate on cactus management actions.

After this first interaction, we arranged open discussions to help in identifying key barriers for cactus management in South Africa. Some of the identified barriers (e.g. "Lack of funding "or "Lack of prioritization of control efforts") are common to all invasive species management. However, other barriers came from particular parties' interest, such as "some invaded areas are not easy to access" identified by managers from South African National Park (SANParks). It was only by involving all parties in the workshop that we could identify all the barriers to successful management. These discussions also allowed us to openly discuss potential solutions for each barrier and develop regulations to guide the management of harmful invasive cacti. As a result, management objectives were broadly supported by all stakeholders.

Cactus pear vs. prickly pear

Figure 8.3: The fruit of the prickly pear. Image Wikimedia Commons

The Prickly pear (*Opuntia ficus-indica*) was introduced from Mexico to South Africa early in the 18th century. Since then, many stakeholders benefited from the species: households sell prickly pear jam in local markets, traditional medicines are used both domestically and sold, fruits are a source of income and nutrition for many local communities, and it is used as an important agro-forestry species for fruit consumption and animal fodder. However in the 1980s Prickly pear become invasive, displacing native vegetation and crops, negatively affecting livestock and humans (injured by its spines), and creating a conflict of interests between positively affected stakeholders and those stakeholders who wanted to reduce its negative impacts. This conflict of interests was soon addressed, thanks to the existence of a non-invasive alternative: the Cactus pear. In the 20th century, an American nursery owner (Luther Burbank) developed spineless cultivars of *Opuntia ficus-indica*. Due to their lack of spines, these cultivars (known as Cactus pear) are not invasive. Therefore, stakeholders positively affected by the prickly pear, could use a non-invasive alternative, the cactus pear. Nowadays, cactus pear is being widely used in South Africa and all over the world as an important agro-industrial crop. However, more awareness and transfer of knowledge is needed to stop the use of spiny *Opuntia* species in South Africa.

8.3 Mesquite

8.3.1 The problem

Prosopis species (mesquite) were introduced to South Africa from the Americas to provide fire wood, fodder and shade to farmers and communities in arid parts of the country. These trees still provides these benefits, but with time and increased invasion in the mid-1900s, numerous negative impacts on humans and the environment were observed. These include: reduced water supply and impacts to natural grazing lands, loss of biodiversity, decreased property values, and breakage of infrastructure due to strong roots. The wide range of positive and negative effects of mesquite stands had led to conflicts of interest between those who want to use and promote the usefulness of mesquite trees (e.g. some farmers and NGOs) and those who want to reduce the negative impacts of mesquite (some farmers and conservation managers). But before alternative management approaches can be adopted (biological control) it was important to get a better understanding of stakeholder perceptions, wants and needs.

Figure 8.4: Dense stands of *Prosopis* species (mesquite) fringe water courses in many parts of the arid interior of South Africa. Image R. Shackleton

8.3.2 The solution

As explained in the previous example, we assessed the perceptions of stakeholders to get a better understanding of the issues regarding mesquite in South Africa. We found that some stakeholder groups use and benefit from mesquite (farmers use the trees to provide fodder while poor communities harvest trees for fuel wood). However, other groups are predominantly negatively impacted by it (e.g. urban dwellers). People from urban areas (suffering impacts on their infrastructure and aesthetics) face different impacts as a result of mesquite invasions to people in rural areas (who experience loss of land). We also found that for all stakeholders the costs of mesquite were greater than the benefits, warranting the need for improved management.

Through workshops with different stakeholders, we are getting a better understanding of the factors that prevent effective management of mesquite. This work has highlighted that different groups are facing different problems and have different perspectives on what is needed relating to manage mesquite. For example, Working for Water Programme managers highlighted high expenses and the fact that government departments are not working together as the biggest barriers to effective management, whereas researchers suggested that contrasting interests, lack of knowledge and poor prioritisation are the major issues.

Figure 8.5: A survey was done across the invasive range of mesquite in South Africa to determine the perceptions of stakeholders regarding the benefits and costs associated with the species. Image R. Shackleton

8.4 What did we learn from *Prosopis* and *Cactaceae*?

Invasive species are a major driver of global change, affecting numerous groups of people in positive and negative ways. This situation can make understanding the roles of invasions difficult for society. Moreover, it can complicate the choice and/or application different policy decisions and management options.

The case studies described above (and others) have shown that we need to consult all interested parties to understand all dimensions of the problem, to identify misconceptions and gaps in knowledge, to understand how this knowledge can be transferred to the population, to solve conflicts of interests around alien species, and to build consensus and integrate different perspectives to arrive at sustainable strategies for managing invasive species.

Thesis conclusion

This thesis had multiple aims, with its end-goal being to provide, through the application of a novel combination of ecological and sociological studies, key information required for the formulation of an objective strategy to guide the management of *Prosopis* in South Africa. The thesis was conducted in transdisciplinary manner, and the chapters apply a range of economic, ecological and sociological approaches involving multiple stakeholders, to gain a holistic understanding of the role of *Prosopis* in social-ecological systems and to identify fundamental requirements for the effective management of this major invasive species that has negative impacts but also provides clear benefits.

The chapters of the thesis contribute much new information on many aspects of the emerging problem of tree invasions, and in particular the role of *Prosopis* invasions in South Africa. Most of the chapters build on existing literature, but the thesis charts a new course for understanding the role of tree invasions and how they affect people and the environment. Despite the advances made through this work, much remains to be done to improve our knowledge and control of invasive species, especially regarding the management of those that are beneficial in some ways, and harmful in others.

Prosopis has become extremely widespread globally, and several species and their hybrids have naturalised or become invasive in more than 100 countries, where they lead to substantial negative impacts on people and the environment. Insights from the global review in Chapter 1 helped to conceptualize the complex interplay of factors that determine responses to invasions by "conflict" invaders such as *Prosopis* species. They provides insights into what drives interventions (or the lack of interventions) in different socio-political contexts. One of the main messages is that the level of available knowledge about the distributions, ecology and impacts of the invader influences the level of management intervention. This suggests that understanding the role of invasions is crucial to justify, promote and guide management initiatives. It was also found that national GDP was a good indicator of the management approach that would be adopted. Countries with low GDP were more likely to use "utilisation" approaches to manage *Prosopis* whereas countries with high GDP primarily applied chemical and mechanical control, with intermediate-GDP countries most often applying a variety of control techniques. This knowledge also helps to guide the strategic management planning of for countries based on their situations.

The next chapters (Chapters 2 and 3) delved into the large-scale ecological processes and the impacts of *Prosopis* across South Africa. This information helped to inform the management of *Prosopis* in South Africa from an ecological standpoint, and knowledge of widespread impacts (particularly the impacts of *Prosopis* on native plant biodiversity) was needed to improve the management. First of all, it identified that *Prosopis* is having impacts, therefore justifying the need for management on an ecological bases, and also identified some key species that are at threat that need to be protected (e.g. *Acacia erioloba*). This work was novel in that it applied techniques commonly used to assess population trends in rare and threatened plants (Botha et al., 2004; Venter and Witkowski, 2010; Cousins et al., 2014) but which have not yet been used in invasion science (analysis of size-class distributions using Quotients and the Permutation Index to assess *Prosopis* and native tree population trends and stability). These methods were applied to gain better understanding of the ecology of *Prosopis* and the mechanisms that drive its negative impacts on native populations (including decreased native tree recruitment, and increased juvenile and adult native tree mortality through competition for limited resources).The impact that *Prosopis* has on native tree recruitment and mortality is serious and threatens to cause marked declines in populations of *Acacia erioloba*, a protected indigenous tree that also provides important natural resources. *Prosopis* also reduces native grass and herbaceous species that are important for grazing. This, therefore, helps to highlight the need to manage *Prosopis* to protect our native biodiversity and the important ecosystem services and natural resources provided by plant native species.

Chapters 4 and 5 applied sociological approaches to further elucidate the perceived and real impacts of *Prosopis* invasions on humans and the environment within South Africa. The use of social approaches and stakeholder engagement when investigating invasive species is still in its infancy, but recognition of the importance of understanding the "human dimensions of invasions" is growing rapidly - in particular for species that generate conflict (Shackleton et al. 2007; García-Llorente et al. 2008 and 2011; Kull et al. 2011). These studies helped to elucidate the perceptions and practices of different stakeholders living or working in areas with *Prosopis* invasions. Results showed that the net value of costs and benefits of *Prosopis* were negative for all stakeholder groups. This provides much-needed justification for management of *Prosopis* – until now the view that mesquite has substantial benefits has prevented the adoption of a clear policy on its management (Wise et al. 2013). Findings of this work also revealed that many private land owners are actively trying to control the spread of invasive *Prosopis*. Also, engaging different stakeholders helped to identify underlying factors that influence the awareness and perceptions of invasive species, the primary one being people's orientation towards the land (e.g. living in rural versus urban settings). In addition, unique negative impacts, such as the damage caused by the roots of *Prosopis* to infrastructure such as house foundations, walls and water pipes were also raised through including urban stakeholders groups in the study, where previously the focus has only been on rural communities. Chapter 5 applied the non-timber forest product (NFTP) valuation method, but added to the theory, by including a comparative study on the use of invasive *Prosopis* and native tree substitutes. This facilitated the calculation of the relative value of *Prosopis* compared to native trees (substitutes for *Prosopis*) for households in South Africa. This case study provided further evidence for the need to improve management, as the relative use of *Prosopis* was lower than that of native trees which are utilised more and preferred by local communities. This suggests that despite *Prosopis* being readily available, people still prefer natives, so retaining *Prosopis* will not take much pressure of the use of native species. This is important especially in light of the findings in Chapter 2 and 3 which demonstrated that *Prosopis* invasions are displacing native trees which provide more valuable resources for local communities. It was also found that reliance on *Prosopis* is declining rapidly, which provides objective justification for allocating resources to improved management of *Prosopis* to safeguard the supply of ecosystem services.

The above case studies provided ecological and social evidence of the need to control *Prosopis* due to negative impacts for people and the environment along with other publications highlighted in the review chapter (e.g. Ndhlovu et al. 2011; Dzikiti et al. 2013). A key contribution of this work was to involve the full spectrum of stakeholders in systematically identifying the dimensions of barriers that are hindering current control and potential adaptation responses. The systematic elucidation barriers to adaption and management is common in medical and psychological research, and has been applied recently in the climate-change literature (Spires et al. 2014), but remains to be widely used in the biological conservation and natural resource management domains. This work resulted in the identification of more than 100 unique barriers and important adaption responses that are needed to improve the management of *Prosopis*. This study was also interesting in that it showed that different groups perceived different factors to be hindering management, with stark contrasts existing between the views of farmers and Working for Water managers. Farmers identified the lack of strategic planning, prioritisation and quality control, but not as a major barrier, and managers raised, in particular, that lack of partnerships and cooperation between different stakeholders – notably farmers - to be a major barrier. One of the key messages of this study is that stakeholder interaction in matters relating to *Prosopis* as an environmental issue is inadequate and that urgent attention needs to be given to facilitating improved interactions to pave the way for more effective and transparent management of *Prosopis*. In addition, the need for better strategic planning and spatial prioritisation was identified as important to improve management effectiveness and efficiency, which is addressed in the final chapter of this thesis.

All of the above case studies (which provide, for the first time, a holistic picture of *Prosopis* invasions in South Africa) which, together with other publications on *Prosopis* in South Africa (in particular, Van den Burg 2010; Ndhlovu et al. 2010; Wise et al. 2012; Dzikiti et al. 2013), were used to develop a strategy to guide the management of *Prosopis* in South Africa. Chapter 7 partly fulfils a key requirement of the regulations published under NEM:BA, Act of 2004 (DEA, 2014) which stipulates that species with substantial negative impacts need national management strategies and management programmes). The strategy for *Prosopis* is one of the first to be produced.

Using a social-ecological study process this thesis has provided a case study example of what is needed to understand and develop national strategies for the management of biological invasions (Figure 7.2). This process can be used as a model system for understanding and managing other widespread, conflict-of-interest invasive trees, for example species in the genera *Acacia*, *Eucalyptus* and *Pinus* (van Wilgen and Richardson, 2014). The approach used in this thesis was useful to get a holistic understanding of the issues pertaining to widespread tree invasions; key to the success of the approach was the engagement of different stakeholder groups. This helped to understand the trade-offs between the costs and benefits that must be achieved to reach practical management solutions. It is recommended that this process could be profitably applied for other invasive trees in South Africa. However, many invasive species, particularly those introduced accidently, have mainly costs and very few benefits (e.g. *Parthenium hysterophorus*). Applying the rigorous process followed in this thesis would be unnecessary for such species, and some steps of the process (Figure 7.2) could be left out.

There are still large gaps in our knowledge of *Prosopis* and invasive species management in general in South Africa and internationally, and better understanding of these gaps could improve the management of *Prosopis*. Some key issues that require further research are listed below**.**

- Globally and within South Africa there are still major issues relating to the taxonomy of the genus. This relates to misidentification and incorrect labelling of initial introductions as well as widespread hybridisation between numerous introduced species (Pasiecznik et al. 2004; Mazibuko, 2013). Improving identification will be important for finding effective biological control agents, and this requires further research. Linked to this, the role of hybridisation of *Prosopis* in mediating invasiveness needs to be further examined.

- Research and testing of further biological control agents is needed. There is evidence that the costs of *Prosopis* outweigh the benefits, and that the costs will continue to increase as invasions spread (Chapter 4 and 5; Wise et al. 2013). The costs of mechanical and chemical of control within South Africa are high, and *Prosopis* is spreading faster than the capacity available to contain it (van Wilgen et al. 2012). If more effective biological control agents can be found, the benefits of *Prosopis* could rise and the cost will be reduced through decreased densities of invasion (Zachariades et al. 2011). There is growing support for the positive role of biological control in Australia, and South Africa needs to learn from this experience (van Klinken, 2012).

- The role of control through utilisation needs to be researched further. There are case studies of small-scale utilisation projects (making *Prosopis* flour in Kenya) which are touted as successful, but these have probably had very little, if any, effect on reducing *Prosopis* densities and rates of spread (Choge et al. 2006). The knowledge of role of intensive national or international-scale utilisation projects as a control method is lacking, and this approach may be successful, although it is still highly controversial (van Wilgen et al. 2012). Large scale and intensive utilisation could be a useful management approach in that it reduces rates of spread and densities and thus impacts, at the same time providing employment and local economic development. However, utilisation could create dependency on problematic species and benefit some stakeholders at the cost of others. It could potentially encourage the spread of invasive species to new areas once people perceive it to have economic potential thus spreading negative impacts to new areas as well (van Wilgen et al. 2012). However, provided that invasions could be contained and all their impacts were confined to their immediate environment, then consideration could be given to sustainable utilisation.

- Identifying ways of reducing conflicts of interest and building cohesion between stakeholders with regards to the management of invasive species that induce both benefits and costs is an urgent priority. Addressing this could aid in developing more efficient management strategies in the future. This problem deserves a thorough, participative, scientific assessment - as done when the South African government decided to develop a widely accepted policy for managing elephants (Scholes and Mennel, 2008). Such assessments are the product of processes that translate existing scientific information into a form usable by policy makers. Assessments of conflicts of interest have three critical success factors: (1) legitimacy (the stakeholders have to accept that the process is well founded), (2) saliency (it must be relevant to an expressed need), and (3) credibility (it must be conducted in a transdisciplinary and transparent manner, to the highest standards) (Cash et al. 2002; Scholes and Mennel, 2008). Assessments are characterised by an extensive, transparent review process by both experts and stakeholders. An assessment requires the authors to provide their own expert judgements when the data are sparse or equivocal (as long as these judgements are clearly identified as opinions), but puts checks and balances in place to ensure that all reasonable viewpoints are fairly reflected. Assessments include an explicit evaluation of the uncertainties on key issues, either quantitatively in terms of probability ranges (e.g. ‘near certain’ is >95% confidence of being true), or qualitatively (such as ‘established’, ‘established but incomplete’, ‘competing explanations’ or ‘speculative’).

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Thesis supplementary material

(To access the appendices for Chapter 1 please use the following link http://aobpla.oxfordjournals.org/content/6/plu027.full - the appendices for Chapter 7 are included below (not published))

Chapter	Appendix number	Caption
Chapter 1	Appendix 1	Methods for literature review, climate matching, regression analysis, classification and regression tree.
	Appendix 2	Global distribution of *Prosopis* species. Status codes (*sensu* Pyšek *et al*. 2004 with additional category weedy to describe native species that are invasive in their native rages) are given in brackets: N = naturalised; I = invasive; NA = native; W = weedy; U = unknown. Countries partaking in management of *Prosopis* species are marked with an asterisk.
	Appendix 3	Bioclimatic modelling output – list of climatically suitable countries and the associated species (excluding known native species)
	Appendix 4	Underlying information of *Prosopis* invasions woldwide
Chapter 7	Appendix 1	Detailed methods for the development of a strategic and prioritisation plans for the management of *Prosopis* in South Africa.
	Appendix 2	Detailed discussion of different control options available for the management of *Prosopis* within South Africa
	Appendix 3	Mean rank (scale of 1-5; 1 being low and 5 being high) of importance of different option for controlling invasive *Prosopis* in South Africa and the mean number of people supporting the introduction of biological control as a form of management.
	Appendix 4	Criteria for prioritisation identified through online surveys with farmers and Working for Water managers involved with the management of invasive *Prosopis* in South Africa [mean and (modal rank of importance from 1-5; 1 = low, 5 = high)].

Appendix 1: Detailed methods for the development of a strategic and prioritisation plans for the management of *Prosopis* in South Africa.

Methods

Various methods were integrated to develop the strategic and prioritisation plans for *Prosopis*. This included building on past work, drawing on published case studies, and the use of decision trees, workshops, surveys and spatial planning. This appendix gives more detail about the steps followed.

Decision-tree models for spatial differentiation of control actions

Grice et al. (2010) proposed a decision tree model for the differentiation of spatially-explicit management objectives for invasive plants using *Hymenachne amplexicaulis* invasions in Australia as a case study. This approach has been proposed as being well suited to guiding management of invasive species with major impacts in South Africa (Le Maitre et al. 2015) and has been applied to *P. hysterophorus* invasions in South Africa (Terblanche et al. under review). Under NEM:BA species with major impacts (like *Prosopis*) need holistic management strategies of which spatially differentiated planning is important (Le Maitre et al. 2015).

Current and potential distributions of Prosopis

The decision tree model allows for spatial units to be placed into five management categories, based on current and potential invasion extent illustrated in Figure 7.1 (Grice et al. 2010). Various sources of information were used to gather information on the distribution and abundance of *Prosopis* in South Africa (South African Plant Invaders Atlas (SAPIA) database; van den Berg 2010; Shackleton et al. 2015a,b). A potential distribution map was produced for *Prosopis* in South Africa using climatic variables (Mgidi, 2004; Roget et al. 2004). Only areas with a climatic suitability probability of 50 % and greater were considered as areas fully suitable for *Prosopis* invasion. Based on current distribution and extent and potential distribution, each municipality was assigned to one of the above mentioned management action categories using the Grice et al. (2010) decision tree.

Application of decision-tree model

Management areas were zoned within municipal boundaries across South Africa to guide the management practices needed in each municipality (Le Maitre et al 2015; Terblanche et al. under review). This was to fall in line with NEM:BA regulations requiring each organ of state to produce plans. Potential management actions included: Prevention ((1) passive surveillance or (2) active surveillance) for areas with no *Prosopis*; (3) Local eradication where possible; (4) Containment for areas at the edges of large invasions; (5) Asset protection for areas with large and widespread invasions (Grice et al. 2012; Le Maitre et al. 2015). In the prevention category, passive surveillance was allocated for municipalities where there are no records of *Prosopis* and where it is incompatible climatically, while those municipalities with no occurrence records that fell into climatically suitable areas were assigned to active surveillance management approach (Figure 7.1). Areas with low populations (< 1 ha or 100 individuals and at least 50 km from a large population), isolated to a small number of properties or one catchment were assigned to the local eradication category. Municipalities with moderate populations on the borders of those with major invasions were assigned to the containment category, and municipalities with widespread and high density invasions were assigned to the asset protection category. Within the containment and asset protection management approaches there are various control methods available including biological control, various forms of chemical and mechanical control and control through utilisation - each with their benefits and costs (van Wilgen et al. 2011; Shackleton et al. 2014). Online (using Surveymonkey) and telephone surveys were also conducted with 19 farmers and 11 WfW managers to rank the importance of the different management options highlighted in the Grice model. Questions were also asked about preferences and views on different control techniques, and specifically whether respondents would support the introduction of additional biological control agents as containment and asset-protection strategy. Since *Prosopis* is so widespread, the asset protection management category is extremely large, making it important to identify assets needing protection and to spatially prioritise them using AHP (see below).

Multi-criteria decision making (Analytic Hierarchy Process) for asset protection prioritisation

Multi-criteria decision making, using AHP, was applied to identify, rank and spatially prioritise assets for management within asset protection management categories (Figure 7.2 and 3). This step was important, as unlike other species the Grice model has been applied to *Prosopis* is extremely widespread, therefore has a large asset protection zone (Grice et al. 2011; Le Maitre et al 2015; Terblanche et al. under review). This approach has been used to spatially prioritise invasive species management in other areas of South Africa (Forsyth et al. 2012).

AHP is a decision-making tool that facilitates inputs from multiple stakeholders, where parties negotiate to ensure that each is adequately represented, allowing for a single comparison that accommodates all viewpoints (Saaty, 1990; Ramanthan, 2001; Regan et al. 2006). A survey was used to arrive at a preliminary goal for the management of *Prosopis* and to identify criteria for asset prioritisation. Online and telephonic surveys with 19 farmers and 11 managers in the Northern Cape were conducted. The survey included sections on defining a goal, identifying criteria and sub-criteria (free listing) to prioritise areas for control and ranking these criteria on a scale of 1-5 (1 = low priority; 5 = high priority). Data from the survey were presented at the workshop (see below) to guide participants and speed up the workshop process as well as to allow for broader participation in the AHP process.

A one-day multiple-stakeholder workshop was run with 18 participants (six academics, seven government managers and policy makers, three farmers and two from companies involved in invasive plant utilization and management). During the workshop a goal for management was determined and assets requiring protection were identified and ranked. The identified assets were used as criteria and sub-criteria for spatial prioritisation within the asset-protection management area. AHP was run using the Super Decision software which allowed for pairwise comparisons to be made between the identified criteria to rank them in order of importance. The final criteria were sent out to all stakeholders who gave initial input for approval. Once the model was approved (consensus from all stakeholders) we collected relevant spatial data sets to allow for the objective comparison and prioritisation of each catchment within the asset protection zone in South Africa (Forsyth et al. 2012). Spatial data sets used for the analysis included; utilisable groundwater exploitation potential (Water Resources of South Africa, 2005), sum of the length NFEPA river classes (CSIR, 2011), water quality (Total dissolved solids) (Water Resources of South Africa, 2005), NBA ecosystem threat status (SANBI, 2012), NFEPA river FEPAs (CSIR, 2011), protected areas of South Africa (SANBI, 2005), land capability (ARC-LNR, 2004), and grazing potential (CSIR, 1998). Analysis was conducted using Arc Map 10.3 and spread sheets in Excel.

Strategic planning guidelines and options

Within the MCDA workshops, time was allocated to discuss options for strategic management planning and participants in the telephonic and online surveys (see above) provided important feedback on control options and management needs. In a previous study workshops were also held with four stakeholder groups (Academics, Farmers and Working for Water Managers and Workers) to identify barriers to management and adaption responses which were important to feed into the strategic management plan (Shackleton et al. under review). Key informants were also approached for information on costs and aspects relating to the efficiency of different management options and for input to the plan - these included WfW managers, consultants working on invasive species control and utilisation, academics and farmers. The draft plan was sent to all stakeholder groups involved in the workshops for comment. Examples from the literature, particularly from the Australian WONS programme, were also used to guide the development of the *Prosopis* national strategy for South Africa.

Appendix 2: Detailed discussion of different control options available for the management of *Prosopis* within South Africa

The different control options identified in table 7.2 are discussed further in this appendix

Biological control

To date the benefits of biological control have been limited. Only seed feeding beetles were introduced to reduce rates of spread but allow for continued used of *Prosopis*. However, one failed to establish and the other two have had limited affects and populations crash in the winter as in South Africa they are colder than in the agents native range (Zachariades, et al. 2011; Shackleton et al. 2014). There is growing evidence that conflicts of interest regarding *Prosopis* in South Africa are not as severe as has been previously suggested, that the costs far outweigh the benefits (Zachariades et al., 2011; Wise et al. 2012; Shackleton et al 2015c,d). Use is lower than previously perceived and there is large scale demand for improve management in south Africa (Shackleton et al. 2015c,d) suggesting more damaging agents should be sought out. If a suitable biological control agent can be found, this approach will be the most cost effective and efficient. We suggest in the strategy that additional biological control agents which are showing success in Australia (*Evippe* spp.) (van Klinken, 2012; van Klinken and Pichancourt, 2015) should be researched and released in South Africa as soon as possible to improve the efficiency of integrated management (Figure 7.3). More successful biological control could considerably improve benefits by decreasing densities, thereby allowing for the production of larger stemmed trees (more suitable for harvesting) and improved fodder production and access for livestock (Zachariades et al., 2011). A review of all biological control programs (successes and failures) in Australia yielded a benefit to cost ratio of 23.1:1 (Page and Lacey, 2006). The benefit ratio for *Prosopis* was low (+ 0.5) but it has likely grown considerably in light of more recent findings (van Klinken, 2012; van Klinken and Pichancourt, 2015). A review of success achieved between 1996 and 2008 in managing woody invasive plant species by WfW in South Africa showed that only species under successful biological control (e.g. *Acacia cyclops*, *A. saligna*, *Hakea* spp. and *Opuntia ficus-indica*) have decreased in extent, whereas species with relatively ineffective biological control (e.g. *Lantana camara* and *Prosopis* spp.) continue to increase in extent and density despite large expenditure on various other control options (van Wilgen et al. 2012b).

This suggests that further work on biological control is warranted. Successful biological control could considerably improve benefits, by decreasing densities thereby allowing for the production of larger stem (more suitable for harvesting) and improving fodder production and access for livestock (Zachariades et al., 2011). All managers believed it to be a good approach and 90 % of farmers supported biological control (Appendix 3). Those that did not support biological control were not against it because of a potential loss of benefits from *Prosopis*, but rather were unaware of the rigorous pre-release testing, and were worried about host switching.

Chemical and mechanical control

Numerous options exist for chemical and mechanical control (Table 7.2). Current approaches used by Working for Water teams (cut stump) are beneficial in that they provide extensive employment. However, the rate of clearing is too slow to have substantial impacts on the density and rates of spread of *Prosopis* in South Africa (Figure 7.3). Concerns have also been raised regarding quality control, corruption around clearing and the misuse of herbicides, leading to coppicing and reinvasion (van Wilgen and Wannenburgh, 2015; Shackleton et al. under review). Approximately 150 000 ha of *Prosopis* invasions were cleared between 1996 and 2008, but over that same period, increases in extent of between 200 000 and 500 000 ha per year were recorded (van Wilgen et al. 2012b). Therefore this method is simply not resulting in the treatment of enough of the current invasions to result in the containment, let alone the reduction of *Prosopis* invasions. It must be noted that for eradication programs, the current cut-stump methods are appropriate and will create large scale employment and aid in significantly reducing the potential costs of *Prosopis* before they arise in new areas, but the method is too slow to achieve effective management of widespread and dense invasions.

Other mechanical approaches that carry out clearing at a greater rate, using bulldozers and backactors, are useful for clearing areas that will be used for cropping as roots are removed (Table 2). This approach is, however, very destructive in rangelands (Table 4). Machinery used to harvest forestry trees would be less destructive than bulldozers and backactors and exponentially faster than the cut stump approach. This would involve large capital investment, and lead to much faster rates of clearing, and would not substantially reduce opportunities for employment, as cut trees could still be utilised for biomass and labour would be needed to apply herbicide to stumps. By far the most cost effective and rapid approach is to apply herbicide using aerial spraying (Table 2). Labour teams can then be employed a year later to do manual follow-ups which would be easier and faster as invasions would be much less dense. Aerial spraying should be considered for managing *Prosopis* in priority areas defined on the basis of environmental and economic assets (Figure 7.4).However, it will be important to assess the potential negative effects of herbicide on the environment.

Control through utilisation

As highlighted above, the current labour intensive cut stump approach is unfeasible for controlling *Prosopis* spread although it is attractive because it requires a large labour force (Table 2). This suggests that other options, such as control through utilisation, which could provide substantial job creation and possibly an increase rate of treatment, needs to be researched further, although scepticism has been expressed about the effectiveness of this method in reducing the extent of the problem (van Wilgen et al. 2011; Shackleton et al. 2014). Encouraging utilization potentially exacerbates conflicts of interests in that it promotes dependencies on the invasive species (van Wilgen et al. 2011; Shackleton et al. 2014).This could be ok, as long as the populations are contained and the other environmental and social impacts costs are minimal, and some areas could potentially be managed for suitable agroforestry. Although this is a problem, control through utilisation has many potential benefits. For example, it could lead to the establishment of private companies, thereby reducing the burden on the government to fund and manage control. If undertaken within a program such as WfW, profits realized through utilisation could be re-invested to fund other options for *Prosopis* management. Also, this approach is potentially faster than the cut stump approach and could employ more labour (Table 4). Various utilisation options exist. For example, in Kenya the making of flour from *Prosopis* (which is touted as an utilisation success story) is unlikely to have a major impact in reducing invasion. Similarly, the utilisation of pods to produce organic medicine "Manna" in South Africa is unlikely to have any effect of reducing impacts and rates of spread (Wise et al. 2012). However, the power stations that are being built in Kenya to utilise *Prosopis* biomass on a large scale could have a major impact on reducing the extent of *Prosopis* (Shackleton et al. 2014). Other utilisation approaches in South Africa, such as the use of fuelwood at localised scales (Kull et al. 2011; van Wilgen et al. 2012b; Shackleton et al. 2015c), and the production of biopellets which are exported to Europe for energy production using Australian acacias and offcuts from the pine and *Eucalyptus* industry (J. Cloete (SA Wood Pellets), pers. comm.) could aid in reducing impacts and rates of invasion. Many other options also need to be investigated urgently, such as the production of bioenergy for local use, potentially making some of the small towns in the arid interior of South Africa self-sufficient. Other options exist as well and require research such as charcoal production, making of mulch for restoration, paper and many others (Shackleton et al. 2014). These projects however need to be done on a large scale to be cost effective and successful in reducing *Prosopis* populations. The main issue with this approach is the high transport costs – as *Prosopis* invasions are restricted to arid areas which have human low population's densities and very widely dispersed commercial centres (Shackleton et al. under review). An example for bio pellet production for export to Europe for energy production is shown in Table 4. If a manual approach is taken, control time could be similar to the cut-stump approach used by WfW. The use of machinery will yield much faster clearing with the same amount of labour and similar costs (Table 2). The benefit of this approach is that for the production of 20 000 tonnes of bio pellets, approximately R 3 million profit could be made and would result in substantial clearing. To get round high transport costs it would be more feasible to set up numerous moderate sized plants (e.g. 4 X 20 000 tonnes per years) than one 80 000 ton plant (J. Cloete; SA Wood Pellets, pers. comm.). Having numerous moderate sized plants will also increase labour requirements, clear invasions at different localities, and reduce transport costs. Not enough is known about this approach and the guidelines suggest that in-depth research on this approach needs to be conducted within the next 5 years (Table 1).

Other approaches

The use of fire as a tool for controlling *Prosopis* previously lacked widespread applicability in the invaded range in South Africa where low fuel loads in the arid conditions mean that fires are rare. Also, hybrid-swarms of *Prosopis* have shown substantial resistance to fire in other parts of the world (Shackleton et al. 2014). However, *Prosopis* is moving rapidly into wetter grassland areas of the country where fires are common, and this approach needs to be considered in this areas. Although the use of fire on a large scale is not feasible in most areas (low biomass in arid areas and fire-resistant hybrids) – some farmers have effectively used concentrated burning using old tyres at the base of large, widely dispersed trees to successfully kill them. These factors need to be highlighted and incorporated into the best-practice manual and given to private land owners as they are not widely known (Table 1).

Other approaches that also need to be considered are livestock camp management and transport practices which will act on one of the major pathways and vectors of spread (Lee and Chown, 2009; (van Klinken and Pichancourt, 2015). Fencing off major invasions and establishing holding camps to allow for seeds to be passed before livestock are moved from invaded to non-invaded camps. Another approach could be to not allow livestock into invaded areas to eat pods, but rather employ people to collect pods. These pods could then be milled down – breaking the seed – and fed to livestock – which would allow for the benefits of the utilisation of pods for fodder but reduce dispersal and spread. Preventing overgrazing and overuse of land could also reduce rates of invasion (van Klinken and Pichancourt, 2015).

Appendix 3: Mean rank (scale of 1-5; 1 being low and 5 being high) of importance of different option for controlling invasive *Prosopis* in South Africa and the mean number of people supporting the introduction of biological control as a form of management.

Ranking of the importance of different management approaches	**Farmers mean rank and %**	**Managers mean rank and %**
Prevention: Active surveys for new invasions combined with rapid application of control measures for any plants that are found	3.1	3.4
Eradication of small and isolated populations	4.1	4.5
Containment by clearing along the edges of major invasions to prevent them from spreading outwards	4.1	4.9
Asset protection: Allocating resources to clear well established invasions in areas where they are having a negative impact (e.g. aquifers used for town or farm water supplies) (Asset protection)	3.9	3.1
Additional question: Would you be happy with the introduction of further biological control agents to act as a method to contain and protect assets from *Prosopis* invasions, knowing it will never kill all trees in South Africa?	89.5	100

Appendix 4: Criteria for prioritisation identified through online surveys with farmers and Working for Water managers involved with the management of invasive *Prosopis* in South Africa [mean and (modal rank of importance from 1-5; 1 = low, 5 = high)].

Criteria	**Farmers % and (weighting)**	**Managers % and(weighting)**
Water	68 (5)	88 (5)
Biodiversity	21 (3)	50 (4)
Agricultural/irrigation lands	42 (5)	25 (4)
Grazing land	16 (5)	13 (5)
Tourism	-	13 (3)
Maintain gains	37 (5)	-
Poverty alleviation	5 (2)	25 (3)
Top of catchment	63 (5)	63 (5)