Costs, benefits and management options for an invasive alien tree species: The case of mesquite in the Northern Cape, South Africa

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Abstract

Mesquite (*Prosopis* species) were introduced to South Africa to provide fodder and shade for livestock, but some have become invasive, impacting on water and grazing resources. Mesquite's net economic effects are unclear and the unequal distribution of impacts leads to conflict. We estimated the value of mesquite invasions in the Northern Cape Province for different scenarios, differentiating between productive floodplains and upland areas. The estimated net economic value of mesquite in 2009, covering 1.47 million ha, was US$3.5 - US$15.3 million. The value will become negative within 4 – 22 years, assuming annual rates of spread 0f 30 and 15%, respectively. The estimated 30-year present value (3% discount rate) of the benefits of control in the floodplains exceeded that of costs but the opposite was true in the uplands. Control efforts should therefore focus on clearing floodplains while preventing spread from uplands into cleared or uninvaded floodplains. More efficient control methods are needed as estimated control costs (>US$9.5 million yr^{-1}) exceed the financial capabilities of Public Works programmes. Control in the floodplains was not economically justifiable using an 8% discount rate, because this higher rate substantially discounted future costs. We conclude that more effective control methods, such as biological control, are needed to prevent substantial economic losses.

Keywords: Biological control; Conflicts of interest; Economic analysis; Grazing; *Prosopis* (mesquite); Water resources

1. Introduction

Most modern agriculture, plantation forestry and horticulture are based on plant species intentionally introduced for various purposes (Richardson *et al.*, 2000). Some of these species become invasive (that is, they produce reproductive offspring, often in large numbers, that establish at considerable distances from parent plants). Invasive alien plants can dominate ecosystems and are a large and growing threat to the delivery of ecosystem services (van Wilgen *et al.*, 1998; Levine *et al.*, 2003). In some cases the same invasive alien species can simultaneously provide benefits and cause negative impacts, and finding efficient and equitable solutions can be problematic due to conflicts of interest. An example of a 'conflict of interest' invasive alien plant group in South Africa is mesquite (*Prosopis* species).

Several species of mesquite were introduced to South Africa between the 1880s and the 1960s (Harding, 1987; Harding and Bate, 1991; Henderson and Harding, 1992). The introduction of mesquite was justified because of their ability to produce fodder and shade for livestock. Farmers were encouraged by government in the 1950s – through subsidies and extension programmes – to plant mesquite on their farms for shade and fodder (Poynton, 1988). Many of the mesquite species have subsequently been actively propagated for other benefits such as firewood, timber, gum, and honey. Two of the species (*Prosopis chilensis* and *P. glandulosa* var. *glandulosa*) are benign, but *P. velutina* and *P. glandulosa* var. *torreyana*, and their hybrids, have become aggressive invaders (Zimmerman and Pasiecznik, 2005) whose impacts on groundwater, grazing and biodiversity are predominantly detrimental due to their ability to form dense and unproductive stands. A range of approaches is currently being implemented to control the spread and densification of these infestations including a mix of manual, chemical and biological (limited to seed-feeding beetles) control combined with managed utilisation. All of these approaches aim to maximise the benefits and minimise the negative impacts of mesquite.

There is evidence that, despite these control efforts, mesquite infestations continue to spread and become denser, and it is uncertain whether the net effects of this are beneficial or deleterious. As a consequence, policy-makers are unsure whether to change existing approaches and/or consider additional approaches for controlling mesquite. Such decisions cannot be made with confidence until a clearer understanding of the existing situation is developed and assessed. In cases such as these where 'conflicts of interest' exist, cost-benefit analysis (CBA) is often suggested as an appropriate framework to objectively assess the relative desirability of competing alternatives in terms of their economic worth to society (Zimmerman and Pasiecznik, 2005). CBA is one of a few partial-equilibrium methods available within welfare economics for determining the monetary values of the impacts caused by (in this case) invasive alien plants on society (Feldman and Serrano, 2006) and for evaluating options for their management (Cacho *et al.,* 2008). Well designed CBAs account for externalities, uncertainties, and equity (Marsden Jacob Associates, 2004), and can evaluate the welfare effects of managing invasive plants.

This study determined the net economic impact of mesquite in arid parts of South Africa today and for a range of plausible future scenarios, and identified the pivotal factors driving these outcomes. Our assessment was based on a thorough review of the beneficial and deleterious impacts of mesquite trees combined with the application of economic-valuation tools to estimate the monetary values of the impacts. The estimated benefits and costs, together with the costs of controlling the species, were then used within a CBA framework to derive an estimate of the net present value to the study area under a range of plausible future scenarios. Because some of the impacts of mesquite could not be valued economically, and because the costs and benefits are not equally distributed across society (some people benefit while others carry the cost), these issues will need to be considered qualitatively when informing policy and management solutions.

2. Methods

2.1 The study area

Our study focussed on the Northern Cape, an arid province of South Africa that experiences an average annual rainfall of 29 – 433 mm. The area's vegetation is predominantly either savanna in the north or karroid shrub lands in the south (Mucina and Rutherford, 2006). We differentiated between the floodplains of the seasonal or ephemeral river systems and upland areas away from floodplains. We did this because floodplains typically store ground water (Hughes, 2008) which is accessed by mesquite and the additional water enables floodplains to be preferentially and more rapidly and densely invaded by mesquite. In uplands water availability is limited to rainfall infiltration and invasions proceed more slowly and typically remain sparse. To estimate the area of floodplains we buffered rivers with 100 m for each Strahler order (Strahler, 1957), as this width best matched the data on mesquite invasion patterns and riparian vegetation communities mapped by Mucina and Rutherford (2006).

2.2 Development of an economic model

Delimiting an area to undertake a partial equilibrium analysis such as a cost-benefit analysis (CBA) is challenging, and necessitates simplifying, yet realistic, assumptions. In this case, we assumed that changes in endogenous variables have negligible impacts on the neighbouring and larger systems within which they are nested. For example, we assumed that the impacts of mesquite on the provisioning of goods and services (e.g., sheep and fuelwood production) do not affect market prices for these goods and services.

Since the behaviour and impacts of mesquite differ substantially between floodplains and uplands, it was necessary to develop a model capable of mimicking the differences in interactions between mesquite and these two environments over time. This biophysical model was used to underpin the CBA, and therefore the floodplain and upland areas were accounted for separately and their economic consequences summed to estimate the total net economic value (NPV_T) of impacts of mesquite over a period of T years. The economic model is expressed algebraically as:

$$NPV_T = \sum_{t=1}^{T=25} \sum_{i=1}^{2} \left(B_{it} - C_{it} - CC_{it}\right) \cdot Ainv_{it} \cdot (1+r)^{-t}$$

(1)

where, the period of the analysis (T) was 30 years; i is an index counter for the areas within which mesquite behaviour and impacts differ (i.e., i=1 for floodplains and i=2 for uplands); $Ainv_{it}$ is the i^{th} area invaded by mesquite in year t; B_{it} and C_{it} are the benefits and costs of the beneficial and deleterious impacts of mesquite for each area i and time t, respectively; r is the discount rate; and CC_{it} are the annual control costs incurred in area i.

The economic benefits of mesquite (B_{it}) depend on: 1) the total quantity (Q_{ij}) of the j^{th} beneficial product (i.e., j =1 for pods, j =2 for wood ... j =n), which are a function of the area invaded (i.e., spread rate, s_i) and the density (i.e. densification rate, d_i); 2) the proportion of Q_{ij} that is harvested annually, which is the product of all users and the quantity consumed per user; and 3) the price (P_j) of each product *j*. The algebraic expression of the economic benefit of mesquite is:

$$B_i = \sum_{i=1}^{2} Q_{jit}(s_i, d_i) \cdot frac\_used_{ji} \cdot P_{ji} \tag{2}$$

with all variables already defined above. The beneficial goods and services from mesquite and their quantities and prices are presented in Section 2.3.2. The economic value of the deleterious impacts of mesquite, C_{it}, is estimated in a similar manner as the benefits:

$$C_i = \begin{cases} W_i(s_i, d_i) \cdot frac\_used_i \cdot P_W & \text{if} \quad d_i \leq 79\% \quad \text{(3a)} \\ W_i(s_i, d_i) \cdot frac\_used_i \cdot P_W + ssu_i(s_i, d_i) \cdot P_l & \text{if} \quad d_i \geq 79\% \quad \text{(3b)} \end{cases}$$

where, W_{it} is the quantity of water used annually by mesquite in region *i*; P_w is the economic value of the water; *frac_used* is the fraction of water losses that would have been put to productive economic use. Equations (3a) and (3b) emphasise the effect of density on costs and account for situations where infestation densities reach and exceed 80%; in which case these densely invaded areas ($Ainv_{it}$) are lost from productive use and their economic values are the forgone revenues per hectare of livestock production (P_l) (Section 2.3.3).

The present value of the total costs of clearing mesquite over 30 years was estimated as:

$$CC_{it} = (\alpha + \beta \cdot d_{it}) \cdot Aclear_{it} \tag{4}$$

where the term in brackets is the clearing cost per hectare as a linear function of infestation density (Figure 1) and $Aclear_{jt}$ is the total area cleared in each region *j* at time *t*. The costs of control are explained in detail in Section 2.3.4.

[INSERT FIGURE 1]

For simplicity, and because few data were available to verify where the mesquite invasion occurs along a typical logistic curve describing infestation and densification rates over time, we assumed the annual rates of change of both the density (*d*) and spread (*s*) to be constant. The effects of this uncertainty were subjected to scenario and sensitivity analyses. All parameters values required to parameterise the economic model are presented in Section 2.3. Our original calculations were made in South African Rands (ZAR) and then converted to US$ at a rate of ZAR7.5 = US$1.0.

2.3. Model parameterisation

2.3.1. Current and future distribution and rates of spread and densification

Current (2007) distribution

Numerous estimates of the extent and distribution of mesquite in South Africa have been reported over the past three decades (Table 1). We used the latest available estimates derived from satellite (Landsat) remote sensing (2007) for the current extent of invasion. Estimates from the Landsat data were also extensively verified in ground studies by van den Berg (2010). The latest available estimates (van den Berg 2010) indicate that 1 473 951 ha of the Northern Cape Province was invaded by mesquite in 2007.

[INSERT TABLE 1]

Potential distribution

The potential for further expansion of infestations is significant, amounting to between 5 and 32 million ha, of which only 1.47 million ha is currently invaded. The potential future distribution of the species was obtained from projections of the potential range of two mesquite taxa (*P. glandulosa* var *torreyana* and the hybrid *P. glandulosa* var *torreyana*/*velutina*) made by Rouget *et al.* (2004) using bio-climatic envelope modelling. Only areas with an invasion potential of >50% were considered reliable predictions of suitable habitat (Figure 2). Although these projections are conservative, the estimated area of South Africa that could potentially be invaded is 56 million ha, including more than 85% (32 million ha) of the Northern Cape Province. Van den Berg (2010) used a combination of vegetation indices and the occurrence of mesquite to estimate that about 8 million ha were potentially suitable for invasion but, of this, about 3 million ha were classified as having a low probability, leaving about 5 million ha as likely to be invaded.

[INSERT FIGURE 2]

Estimates of spread and densification rates

Historical estimates for the rate of spread range from 3.5 to 18% per year (Vorster, 1977; Harding and Bate, 1991; Coetsee, 1993; Versfeld *et al.*, 1998), which implies that the invaded area could double every 5 to 8 years. Van den Berg (2010) estimated that the total invaded area increased from 127 821 ha in 1974 to 1 473 953 ha in 2007, a mean annual increase of 7.4%. Her data suggest that the invaded area increased by almost a million hectares between 2002 and 2007, which is equivalent to 27.5% per year. Once established, mesquite will increase in density at a slower rate, going from open to dense stands in 10 to 24 years (Harding and Bate, 1991), and will be limited by available moisture, which is less limiting in floodplains than in the uplands. International studies report similar rates of spread. These include population density increases of 5 to 10% per year on a permanent sampling plot in the south-eastern USA (Glendenning and Paulsen, 1955) and an expansion over 23 years from 50 trees to "sparsely or moderately invaded areas covering 18 000 ha" (van Klinken *et al.*, 2007).

Mesquite does not invade steadily but rather in episodic bursts of recruitment and spread that are generally associated with years of above-average rainfall, which is a requirement for seedling recruitment (Glendenning and Paulsen, 1955; Macdonald, 1985; Poynton, 1988; Harding and Bate, 1991; López *et al.*, 2006; Squeo *et al.*, 2007). The rapid spread reported by van den Berg (2010) between 2002 and 2007 coincided with above-average rainfall which would have driven a spread and recruitment episode. In our analysis we used rates of spread of between 7.5 and 15% for uplands (where spread would have been slower), and between 15 and 30% for floodplains (where spread would have been much faster, and episodic) (see Section 2.4).

2.3.2. The benefits of mesquite

Literature surveys and interviews with affected farmers, entrepreneurs using mesquite-based products and natural-resource managers were used to estimate the benefits of mesquite. Preliminary assessments indicated that uses such as honey production, or using wood to generate steam or electricity, did not add significant value at a provincial scale, and were therefore not included in the economic model. The main benefits include the use of pods for livestock consumption and for medicinal purposes, and the use of wood for various products and as firewood. These are presented below.

Mesquite pods

Mesquite pods are highly nutritious (Felker *et al.*, 2003; Choge *et al.*, 2007) and some mesquite trees can produce between 1 000 and 20 000 kg of pods per ha per year (Felker, 1979). Farmers have thus continually been advised to take advantage of this resource. The quantity of pods produced per hectare, however, varies greatly. Scattered trees bear heavily but most trees growing nearby or even adjacent to these have few or no pods (DeLoach, 1985). For example, only 15.3 kg ha^{-1} are reported from Arizona (Parker and Martin, 1952 in DeLoach, 1985) whereas 8 000 and 12 000 kg ha^{-1} were reported from Kenya (Choge *et al.*, 2007) and California (Felker, 1979), respectively. No estimates exist for South Africa.

Many farmers in the Northern Cape currently use pods to supplement natural grazing (particularly during droughts). The value of pods when used in this way varies depending on whether the pods are hand-collected or not, the number of sheep, the quantity of pods, the time the sheep can feed, the quantity of pods eaten, and the density and area infested. Pod production is known to decline in dense stands (S.J. Milton pers. comm. 2009) but the impact of this on the typical pod production in the currently invaded areas is not known. Since the average stocking rate in the uplands and floodplains is 0.05 to 0.07 and 0.125 to 0.25 small-stock units per hectare respectively (Statistics South Africa, 2002), as many as 486 000 to 812 000 sheep could be farmed in our study area. Assuming that these sheep eat about 1.2 kg of pods per day (Harding, 1991) and the sheep only rely on pods for between 50 and 70 days each year (K. Vos pers. comm., 2008), the total number of pods eaten annually, provided mesquite densities are less than 80%, is 14 300 to 27 000 tonnes in the uplands and 14 800 to 41 500 tonnes in the floodplains. The value of the pods consumed is equivalent to 80% of the value of buying maize feedstock (i.e., US$0.25 per kg of pods, K.van Niekerk pers. comm., 2007; K.Vos pers. comm., 2008).

Mesquite pods have medicinal properties (Choge *et al.*, 2006), but these were not seriously considered for economic exploitation until recently. In 2005 a South African company started producing organic tablets (called ‘manna’) from the pods. These tablets have the property of “retarding the absorption of glucose resulting in a flattened blood sugar curve” (www.mannaplus.com). The company currently sells 150 000 bottles per year (each containing 60 tablets) and has the potential to reach about 600 000 bottles per year if sold internationally (J. Coetzee, pers. comm., 2007). The annual profit generated from local sales is US$106 000 and, if the international market can be fully exploited, this could reach US$909 000 (J. Coetzee, pers. comm., 2007). If a conservative 500 kg of pods ha^{-1} are collected, the land required to meet local demand is only 50 ha and provides returns of up to US$302.7 ha^{-1} ($4.5 per kg of pods). If the international demand meets expectations, then 3 700 ha of mesquite will be required, creating returns ofUS$245 ha^{-1}.

Mesquite wood

Mesquite wood is generally hard, has low shrinkage values and good machining qualities (Felker, 1979) and it therefore has many uses, including timber, fencing poles, wood chunks, paper pulp, smoking chips, small furniture items and insulation batting (DeLoach, 1985). The use of mesquite for firewood also delivers substantial value, although attempts to produce charcoal in the Province have failed commercially due to excessive transport costs. Bradshaw *et al.* (2004) report that about 15% of households use wood as an energy source in the Northern Cape Province. The population of the Northern Cape Province in 2009 was 1.16 million (Statistics South Africa, 2009) of which ~ 30% live in rural areas (Elsenberg, 2005). Since each household has an average of 3.8 people (Elsenberg, 2005), the total number of households in rural areas in 2009 was ~86 800. The minimum number of these households reliant on firewood is 13 000 [based on an estimate by Bradshaw *et al.* (2004) that only 15% of rural households use firewood] and the maximum is 43 000 (assuming all firewood-using households are in rural areas). The estimated annual firewood usage per household in parts of the Northern Cape in the late 1990's was 2 100 kg (Solomon, 2000). More recent estimates of firewood usage elsewhere in South Africa are substantially higher and range between 3 836 kg and 4 987 kg per household per year (Ndengejeho, 2007). Assuming households in the Northern Cape use between 2 100 and 3 800 kg yr^{-1}, the firewood consumed annually by rural communities is between 27 000 and 163 000 tonnes. The average value of firewood is aboutUS\$0.07 kg^{-1} (Dovie *et al.*, 2002).

Other potential benefits of mesquite

While mesquite trees do provide shade, this benefit is lost when the trees form impenetrable stands, and it is not possible to estimate the economic value of this use. Mesquite trees also support honey production by providing forage for bees. However, various factors (including the distance to markets and a limited season) effectively render honey production unprofitable. Some studies (e.g., Blignaut *et al.*, 2008; Department of Minerals and Energy, 2008) suggest the use of mesquite as fuel for steam or electricity generation. Low rainfall and the need to factor transport costs into the calculations, however, will probably render this use unprofitable although conversion *in situ* to higher value products (e.g. oils, bio-char) may prove viable.

2.3.3. The negative consequences of mesquite

The literature and relevant stakeholders and government data sources were surveyed to estimate the negative consequences of mesquite. These negative consequences include mainly the loss of water resources, natural pastures for livestock, and biodiversity.

Mesquite impacts on water

Water use, and especially groundwater use, by mesquite trees is a major impact (Le Maitre, 1999). The trees can develop extensive root systems that reach water tables at depths of at least 15 m and, under certain circumstances > 50 m (Phillips, 1963; Canadell *et al.*, 1996). Mesquite forms its densest stands in floodplains where groundwater is potentially accessible. Transpiration is limited by available soil moisture, but the trees can sustain high transpiration rates despite high moisture stress levels (Le Maitre, 1999). When estimating water use by invasive mesquite trees, it is therefore necessary to distinguish between upland and floodplain landscapes. Alluvial floodplains are areas characterised with water accumulation from periodic floods and overland flow and subsurface lateral groundwater inflow from the adjacent upland areas (Kirchner *et al.*, 1991; Botha *et al.*, 1998). In these situations the mean annual evaporation, primarily transpiration, can exceed the annual rainfall (Le Maitre, 1999; Scott *et al.*, 2006; Scott *et al.*, 2008).

We used van den Berg's (2010) estimates of extent of invasion, divided into upland and floodplain landscapes, to estimate water use by mesquite. We assumed upper limits to evapotranspiration based on a review of measurements of interception and transpiration in native mesquite woodlands in the USA and elsewhere. This showed that evaporation in floodplains could range from about 350-750 mm per year (Le Maitre, 1999; Scott *et al.*, 2004; Scott *et al.*, 2008). We used an estimate of the water-use of 500 mm per year for densely invaded floodplains and the equivalent of the rainfall in densely invaded uplands. These figures were then adjusted using the estimated canopy cover in the invaded areas and the estimated water use of the native vegetation was subtracted to estimate the additional water use arising from invasion of natural vegetation by mesquite. Based on this approach estimates of mean incremental water use by mesquite were 71.3 $m^3ha^{-1}yr^{-1}$ for fully-invaded uplands and 603.2 $m^3ha^{-1}yr^{-1}$ for fully-invaded floodplains. Due to variability and uncertainty in these estimates a range of 64 to 78 $m^3 ha^{-1} yr^{-1}$ and 543 to 663 $m^3 ha^{-1} yr^{-1}$ was used for each, respectively. For the current distribution and density of invasions, the mean incremental water-use estimates were 33.2 $m^3ha^{-1}yr^{-1}$ for uplands and 212.3 $m^3 ha^{-1} yr^{-1}$ for floodplains.

A conservative economic value of the water was assumed to be US\$0.06 m^{-3}, which is the user-weighted average of the recovery costs incurred by rural and urban users (de Lange and Kleynhans, 2008). The proportion of the water lost due to mesquite that would have been used for socially beneficial economic purposes was assumed to be 17%, which is the proportion of the total recharge registered for use in the region (Department of Water Affairs and Forestry, 2005).

Mesquite impacts on grazing

The impacts of invasion by mesquite on grazing resources were estimated by assuming that livestock stocking rates would rapidly decrease to zero after the density of the invasion reaches 80% canopy cover (S.J. Milton pers. comm. 2009). In the early stages of invasion, mesquite trees do not reduce the capacity of the land to support livestock, as reductions in grass cover are compensated for by the production of edible pods. Dense stands greater than 80% canopy cover, on the other hand, eliminate grasses and livestock and do not benefit from pods as the stands become impenetrable.

The areas invaded by mesquite support sheep and goats at low stocking rates (on average about 15 ha and 5 ha per small stock unit in the uplands and floodplains, respectively). Mesquite affects the provision of grazing for livestock, but the situation is complex. The net effect on natural pastures depends on the density of infestations. At low densities (< 40% cover) the impacts are generally positive as the trees fix nitrogen and increase the moisture content of the upper soil layers. However, medium to dense stands outcompete all natural grasses and shrubs beneath them (Smit, 2005; A.S. van Rooyen pers comm., 2009). These impacts do not necessarily change stocking rates, as farmers are able to substitute the lost grazing with pods. This substitutability between pods and natural grazing is influenced by tree density. At densities of >79% both pod production and grazing are negligible, and the land is lost from productive use. The economic value of mesquite in terms of natural grazing is therefore sensitive to the density of the stands. As stands will naturally increase in density this means that at least the floodplains will inevitably become non-productive.

Mesquite impacts on biodiversity

While a few studies have demonstrated the negative impacts of mesquite invasions on biodiversity, the extent of these impacts has not been comprehensively documented. In sub-Saharan Africa, most mesquite invasions occupy areas formerly covered by *Acacia* and other riparian thicket species, and areas where the natural vegetation has degraded (Hoffman *et al.*, 1999). Trials in other countries have shown that mesquite species are often the only trees that survive in harsh, arid environments and are therefore the only option open to the local people for afforestation (Food and Agriculture Organisation, 2004). In these cases, biodiversity impacts are small. A few studies have empirically quantified the effects of mesquite on native biodiversity. Stands of *Acacia erioloba*, a keystone species for both wildlife and domestic livestock in the arid and semi-arid regions of South Africa (Milton and Dean, 1999), are reported to have died as a direct result of mesquite invasions lowering the water table (Woodborne *et al.*, 2000). Invasion by mesquite also radically changed bird habitats, leading to reduced species richness and diversity (Dean *et al.*, 2002). These changes include the elimination of raptors, and reductions in frugivores and insectivores. Mesquite invasions also reduce the numbers of dung beetle species, with the most marked declines being found among large species and rare species (Steenkamp and Chown, 1996).

The economic value of biodiversity is notoriously difficult to estimate as it provides indirect and non-use benefits, which cannot be traded in markets and cannot be priced. Some studies have attempted to estimate the economic value of biodiversity using surrogate-market (travel cost and hedonic pricing) and hypothetical-market (contingency and choice modelling) valuation techniques (Sukhdev, 2008). These techniques, however, provide uncertain, highly variable, and context-specific estimates. There are also ethical and moral difficulties associated with trying to put monetary values to the presence or absence of species. Because of these issues, we have only estimated the economic value of the water and pasture losses caused by mesquite.

2.3.4. The costs of control

Data on the costs of invasive alien plant control operations were obtained from the Working for Water programme, which is responsible for all control projects in the Northern Cape. Working for Water's records included the area cleared, the area subjected to post-clearing follow-up, the initial density of the invasion, and the cost. Based on these data, the unit cost of clearing mesquite varies with the density of the infestation, and ranges from ~US\$13 ha^{-1} to almost US\$534 ha^{-1} (Figure 1). These costs often outweigh the value of the land to be cleared (Harding, 1987; Vorster, 1987; Marais *et al.*, 2004). Nonetheless, effort is currently going into clearing programs in South Africa because of employment benefits (van Wilgen *et al.*, 1998).

2.3.5. Discount rate

The discount rate is a critical parameter in cost-benefit analysis whenever costs and benefits occur at different times, and especially when they occur over a long time. Harrison (2010) proposes that 8% be used as the base rate to inform investments of public funds and that testing should be done over a range of 3 to 10%. Sukhdev (2008) reports that most studies of environmental-policy areas such as biodiversity and ecosystem services – where the costs of inaction now accrue in the far distant future – used a social discount rate of 3-5%, and that none was below 3%. In this study we use a base rate of 3% in recognition of the ethical arguments proposed by Ehrlich (2008), Blignaut and Aronson (2008) and others, who state that a low or even negative discount rate is appropriate when dealing with benefits derived from ecosystems to reflect their increasing value over time and the fact that future generations will be poorer in environmental terms than those living today. The effect of this choice on the CBA solutions is tested in the sensitivity analysis.

2.4 Model scenarios and sensitivity analysis

The economic model was run for eight scenarios to account for the variability of the system, the uncertainty of future outcomes, and possible intervention strategies. These represented relatively low and relatively rapid rates of spread and densification of mesquite in the uplands and floodplains, and two control interventions: 1) stopping existing manual and chemical clearing operations and 2) increasing the control efforts to ensure the spread and densification of mesquite are contained. Each of these was also simulated using high and low estimated values for the mesquite pods and wood used and the water losses attributed to mesquite (Table 2). The spread and densification rates of mesquite in the floodplains (uplands) for the relatively slow rates are 15% and 5% (7.5% and 2.5%), respectively and for the relatively rapid rates are 30% and 10% (15% and 5%), respectively (Section 2.3.1).

We also examined the sensitivity of the economic model to a change in the discount rate. The effects of using an 8% discount rate on the present economic value of the mesquite-infested upland and floodplain areas were determined over the 30-year period for each of the eight scenarios described above.

3. Results and discussion

3.1 Economic analysis: Base-case situation

The biophysical and economic nature of the mesquite infestations today were estimated from the economic model using the parameter values summarised in Table 2. The justification and assumptions that underpin these values were presented in Section 2.3.

[INSERT TABLE 2]

The net economic contributions of mesquite in both floodplains and uplands today were estimated to be between US\$6.2 and US\$23.8 ha^{-1} and US\$0.7 and US\$4.5 ha^{-1}, respectively (Table 3). The net returns are positive because the average densities of the current infestations in the uplands and floodplains are between 20.7% and 32.8%, and so the beneficial impacts of the pods and firewood exceeded the deleterious impacts on water and pasture in the short-term. Since the economic contribution of the floodplains is about 6 to 10 times that of the uplands and the invaded area in the floodplains is less than half that of the uplands (Table 3), mesquite in the floodplain areas contributed a greater total economic value (\$2.8 million to US\$10.8 million) than the uplands (\$0.7 million to US\$4.6 million).

[INSERT TABLE 3]

The net economic value of mesquite depends on the area and density of the infestations, which are continually increasing in the uplands and floodplains irrespective of existing clearing efforts. If the existing efforts to control and utilise mesquite continue in a similar manner for the next 30 years, the annual net economic value in the floodplains will decline steadily, becoming negative after 4 to 11 years (with relatively rapid rates of spread and densification) or 8 to 22 years (with relatively low rates of spread and densification) (compare Figure 3A and 3B). As water losses increase, pod production declines and grazing from indigenous fodder species is lost. Not only do the economic returns become negative within the next couple of decades, but the net present values (NPVs) from the floodplains over the 30 years were also negative for both the relatively slow and relatively rapid spread-rate scenarios and for the high and low economic values (Table 4). In fact, negative values for the entire mesquite-infested area of US\$150 million, US\$398 million and US\$410 million (Table 4) were estimated for all scenarios except the relatively slow spread-rate with high economic values, indicating that the beneficial impacts from the uplands are generally insufficient (unless under extremely optimistic assumptions) to compensate for the substantial negative impacts in the floodplains. In fact the invaded upland areas exacerbate the declining situation in the lowlands (Section 3.4). The huge predicted losses experienced are because the density of the mesquite infestation crosses a critical threshold (in year 11 and 22 for the relatively rapid and relatively slow spread rates, respectively), where the land can no longer be used to farm livestock, and so the NPV estimate includes 19 or 7 years of forgone revenues from no sheep and wool sales (valued at between US$20.5 million and US$40.7 million per year). As this critical threshold is only crossed in the 22nd year in the relatively slow spread-rate scenario, these revenue losses do not significantly contribute to the NPV estimate, which explains the positive NPV when economic values are high.

[INSERT TABLE 4 ; INSERT FIGURE 3]

These results highlight the importance of considering alternative courses of action to prevent a scenario of significant economic losses from happening, particularly because up to US$5.8 million of public funds were spent annually on clearing mesquite without changing the ultimate outcomes. In this regard two possible interventions (stopping all clearing or preventing further spread) were investigated to determine whether, and at what cost, the declining economic returns and environmental quality could be arrested.

3.2 Economic analysis of interventions

The analysis of the two interventions suggests that the optimal course of action in the uplands is to halt clearing efforts whereas in the floodplains the optimal course of action is to contain the spread of mesquite, for the relatively slow and relatively rapid spread-rate scenarios, irrespective of the economic benefits of mesquite (Table 5). In the case of floodplains it is beneficial to contain the spread to avoid the loss of substantial water and pasture benefits. The benefits of doing this, with the cost of clearing taken into account, are between US$56.4 million and US$137.3 million over 30 years for the relatively slow spread-rate scenario and between US$122 million and US$376 million over 30 years for the relatively rapid spread-rate scenario. These benefits come from: a) avoiding groundwater losses of between 520 million and 635 million m^3 yr^{-1}(Table 5) for the relatively slow spread-rate scenario and between 776 million and 948 million m^3 yr^{-1} for the relatively rapid spread-rate scenario and b) maintaining the economic benefits derived from low-density infestations. The areas that need to be cleared to achieve this are 51 455 ha and

102 911 ha per year (at an average density of 31% and 29%) and will cost US$9.5 million and US$18.5 million each year, respectively. If the demand for groundwater and its value increase over time, as is expected, these benefits of control will be larger, providing stronger justification for containing (if not reversing) the spread of mesquite in the floodplains. If the avoided deleterious impacts of mesquite on water resources are overestimated, however, then this option to control the spread may prove uneconomical. This finding emphasises the need to develop and implement cheaper and more effective control methods (such as the utilization of further biological control options) and to improve our understanding of the deleterious impacts of mesquite on water and pastures, particularly as the costs of the biodiversity losses were not accounted for.

[INSERT TABLE 5]

In the uplands, where access to groundwater is limited and pastures are not as productive, mesquite provides shade and pods that allow farmers to increase stocking densities. The economic gains from stopping clearing efforts in the uplands (except in the few densely infested areas) and allowing mesquite to cover 100% of the invadable area at densities of between 37% and 50% are aboutUS$75 million andUS$78 million over 30 years for the relatively slow and relatively rapid spread and densification rates, respectively (Table 5). There are, however, a couple of fundamental issues and concerns with allowing such upland invasions to happen unchecked, and these are discussed in Section 3.4.

3.3 Sensitivity of the economic results to a change in discount rate

The baseline results remained robust when a higher discount rate of 8% was used, except the floodplain solution under extremely optimistic assumptions (i.e., slow spread-rate and high economic benefits of mesquite). In this case the 30-year NPV switches from -$71 million (Table 4, column 3) to +$31.1 million (Table 6, column 2). This switch occurs because the delayed costs are heavily discounted.

The effects of a higher discount rate on the economic estimates of the options to maintain the status quo, halt control or contain the spread depend on assumptions about the spread rate and the economic benefits of mesquite. Interestingly, even though the baseline situation for the floodplain under optimistic assumptions was positive ($31.1 million), this increased by US$1.1 million when the spread was contained (Table 6, column 7) indicating that higher economic benefits from mesquite made it worthwhile for landholders to ensure that the density of the invasion does not increase to the critical threshold. The same solution is found for the relatively rapid spread rate. If the economic benefits from mesquite are low, however, then controlling the spread is no longer optimal because the benefits from lower-density mesquite in the first 22 years are too small to warrant the control costs and the post-threshold costs are so heavily discounted they are too small to make control worthwhile. Finally, the upland solutions are robust to the change in discount rate, and the termination of clearing efforts in uplands remains the optimal solution.

These outcomes are unsurprising because the 8% discount rate reduces the value of the delayed negative impacts of mesquite, and so biases against control which involves upfront costs to sustain longer term benefits. This explains why investments into invasive species control are lower than required and often delayed, because market discount rates in South Africa are often higher than 8%.

[INSERT TABLE 6]

3.4 *Future options for management*

This study suggests that the total economic worth of mesquite to society today is positive. It also appears that the stream of positive net economic returns will switch to negative within a decade if the economic benefits from mesquite are low and the spread rate is high (30%) or within 11 to 22 years if the economic benefits from mesquite are high and the spread rate is low (7.5%). In other words, even under optimistic assumptions for the rates of spread and densification and the economic benefits derived from mesquite, the entire floodplain (and 55% of the uplands) will be 100% invaded in 22 years, leading to the loss of pasture and livestock production potential. Exacerbating this negative trend, and not accounted for in the model, are the potential knock-on impacts of the upland invasions on the groundwater recharge in the floodplains.

The annual costs of manually containing the spread of mesquite over 30 years were between US$6.6 and US$13 million for uplands, and US$9.5 and US$18.5 million for floodplains, depending on the spread rate (Table 5), suggesting that it would be beneficial if additional, cheaper and more effective control methods, such as biological control, could be found. These findings support those of de Wit *et al.* (2003) who analysed the costs and benefits associated with another ‘conflict of interest’ species, black wattle (*Acacia mearnsii*), in South Africa at a national level.

The estimated benefits derived from control efforts in the floodplains, principally in the form of avoided pasture/grazing losses and water losses, exceeded the costs under both the relatively slow and relatively rapid spread-rate scenarios and for high and low economic benefits from mesquite. The estimated net benefits of control over the 30-year period using a 3% discount rate were betweenUS$1.9 million and US$12.5 million per year. This finding, however, was sensitive to the discount rate (Section 3.3).

An entirely different situation exists in the uplands. Our findings suggest that it would not be economically feasible to contain the spread of mesquite in the uplands due to the substantial areas involved and because benefits can be derived from mesquite in these areas. However, where densities exceed 50% in upland areas (i.e., around waterholes), or where upland infestations provide a source for the invasion of highly productive and/or high water yielding regions, these should be rapidly contained and cleared. It is also likely that the upland invasions will eventually reach densities where the water-use will balance the rainfall and there will be no lateral drainage of groundwater into the alluvial aquifers. Upland invasions in the relatively high rainfall headwaters of the rivers whose periodic flows recharge the alluvial aquifers will also reduce recharge. This could be critical for the sustainability of livestock farming which depends on groundwater as well as for the towns and settlements in the Northern Cape that depend on groundwater. In addition, if the livestock continually disperse seeds from the uplands into the lowlands this will increase the costs of clearing and containing invasions in these areas.

3.5. The use of biological control

Because mesquite plants have value, biological control of these species in South Africa has focussed on seed-feeding insects only. Three species of biological control agents (*Algarobius prosopis*, *A. bottimeri* and *Neltumius arizonensis*) were released in South Africa between 1987 and 1992 (Zimmermann, 1991; Coetzer and Hoffmann, 1997), but only *A. prosopis* has successfully established (Impson *et al.*, 1999; Klein, 2002). *A. prosopis* causes 90–98% seed destruction in certain areas where livestock are excluded (Zimmermann, 1991). Where livestock are allowed to feed on the pods, viable seeds are dispersed in the dung, but *A. prosopis* does utilise seeds in dung, thus also reducing the rate of spread (Roberts, 2006; van Klinken *et al.*, 2009). However, the recent increases in the extent of *Prosopis* – nearly 1 million ha from 2002-2007 (van den Berg 2010) – suggest that the reduced seed production has had little effect on the dispersal of the seeds by livestock or water. There is also considerable potential for the introduction of new biological control agents that attack not just seeds, but also the remaining vegetative parts of the plants (Zachariades *et al.*, 2011). However, these will only be introduced if farmers should decide that they are willing to sacrifice the pods, or even the trees themselves, to control the invasion.

4. Conclusions

Our findings strongly suggest that maintenance of the status quo will lead to substantial economic losses to the region (negative NPV for all scenarios except the extremely optimistic situation where a slow spread rate occurs with high economic benefits from mesquite), and that a new approach needs to be developed and implemented. Our findings suggest, based on a 3% discount rate, that control efforts should be focused on clearing existing infestations in the floodplains, while at the same time preventing the spread into currently un-invaded highly productive areas and investigating the possibility of significantly more effective biological control agents. The control costs would be justified by the additional water made available for meeting the social and economic activities that depend on water and the ecological reserve to sustain the integrity of ecosystems. Because many of the benefits are public goods and therefore cannot be easily privatised, innovative mechanisms will need to be developed to generate funding to help cover the costs of these clearing operations. Also, because the benefits of control are delayed relative to the annual costs, a higher discount rate of 8% that reflects the time preferences of the landholders in the region, means these costs are given an extremely low value today, and so the ‘status quo’ and the ‘halt clearing’ options are the preferred options for private landholders. The plurality of perspectives and values of the various stakeholders involved means ecological-economic assessments such as this – that account for the dynamics and uncertainties of the system – need to be used within participatory decision-making processes to inform the co-development of solutions that are sensitive to intra- and inter-temporal distributional issues and to tradeoffs between public and private values.

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Figure 1. Potential distribution of (A) *Prosopis glandulosa* var *torreyana* and (B) the hybrid *Prosopis glandulosa* var *torreyana/velutina* based on climatic data (Rouget *et al*. (2004). The 1/4º latitude x longitude squares (QDS) where it had been recorded up to 2003 are also shown

Figure 2: Costs (excluding herbicides) associated with clearing mesquite infestations, as a function of density of infestation, estimated from 5 years of data from the Western Cape, Northern Cape and Free State Provinces (Department of Water Affairs and Forestry, 2008). The regression line is $y = 5.15x$, where *y* is the cost in US$, and *x* is the density expressed as % cover; R^2 = 92.3)

Figure 3: Flow of the net value of mesquite infestations from upland and floodplain areas in the Northern Cape Province over 30 years, for relatively slow and relatively rapid spread and densification rates and for high and low estimated benefits from mesquite

Table 1. Estimates of the extent of invasive mesquite species in South Africa

Date	Estimated area (ha)	Notes
1977	186 000	Limited to the Karoo region (arid shrublands) of South Africa (Vorster, 1977)
1987	200 000	Limited to the (then) north-western Cape Province (Harding, 1987)
1998	1 800 000	Estimate covers all density classes; about half of this was in the Northern Cape province (Versfeld *et al.*, 1998)
2007	1 473 951	Estimate covers all density classes in the Northern Cape Province (van den Berg, 2010). This includes a substantial recent (post 2002) increase of nearly 1 million ha in the total invaded area

Table 2: Base-case values and assumptions for biophysical and economic parameters used in an economic simulation model of mesquite in the Northern Cape, South Africa

Parameter	Symbol	Units	Value		Source
			Upland	Floodplain	
Economic variables					
Pod Price	P_i	US$ Mg^{-1}	253.3		Vos (pers. comm.,2008)
Firewood Price	P_i	US$ Mg^{-1}	66.7		Dovie *et al.*, (2002)
Water Price	P_w	US$ m^3	0.061		de Lange and Kleynhans (2008)
Livestock Price		US$ SSU^{-1}	80.0		Statistics South Africa (2002)
Clearing cost, y intercept	α		0.0		Department of Water Affairs and Forestry (2008)
Clearing cost, slope parameter	β		5.15		
Rural households using firewood			15 000		Bradshaw *et al.* (2004); Elsenberg (2005)
Pods eaten per sheep per year		kg yr^{-1}	60 to 84		Harding (1991); Vos (pers. comm.,2008)
Firewood use per household		Mg yr^{-1}	2.1 to 3.8		Solomon (2000); Ndengejeho (2007)
Fraction of lost water with direct economic value	*frac_ used*	%	17		Department of Water Affairs and Forestry (2005)
Discount rate (High)	*dr*	%	3 & 8		Sukhdev (2008); Harrison (2010)

Biophysical variables					
Max infestation density		%	50	100	van den Berg (2010)
Current average infestation density		%	20.7	32.8	van den Berg (2010)
Maximum invadable area		ha	-	2 016 168	Rouget *et al.*'s (2004) suitability >0.5
			4 976 964	-	van den Berg (2010), see Section 2.3.1
Current invaded area		ha	1 022 214	452 838	van den Berg (2010), see Section 2.3.1
Mesquite water use	W_j	m^3 ha^{-1} yr^{-1}	64 to 78	543 to 663	Incremental water-use estimate for dense invasions (100% cover) (Section 2.3.3)
Sheep stocking rate		ha SSU^{-1}	15 to 20	4 to 8	Statistics South Africa (2002); Vos (pers. comm.,2008)
Spread rate	s	% yr^{-1}	7.5 to 15	15 to 30	van den Berg (2010)
Densification rate	d	% yr^{-1}	2.5 to 5	5 to 10	Milton (pers. comm., 2009)
Biomass production		Mg ha^{-1}	4 to 9	5 to 20	Versfeld *et al.*, (1998); Blignaut *et al.*, (2008)

Table 3. Values of economic and biophysical variables that describe the current (2009) situation regarding mesquite invasions in the Northern Cape Province, South Africa

	Uplands	**Floodplains**
% of invadable area invaded	21	22
Average density of invasion (%)	21	33
Area cleared (ha yr^{-1})	33,733	7,698
Water loss (million $m^3 yr^{-1}$)	16.5	98.5
Clearing costs (US$ $ha^{-1} yr^{-1}$)	106.7	169.1
	Low economic benefits	
Total net economic returns (US$)	697 081	2 815 844
Net economic returns (US$ ha^{-1})	0.68	6.22
	High economic benefits	
Total net economic returns (US$)	4 555 920	10 782 840
Net economic returns (US$ ha^{-1})	4.46	23.81

Table 4: Summary values for the key variables describing the economic and biophysical impacts of mesquite over the next 30 years in the Northern Cape Province, South Africa, for two spread and densification scenarios, assuming the existing management regimes remain unchanged

	'relatively low rate of spread and densification'			**'relatively rapid rate of spread and densification'**		
	Uplands	**Floodplains**	**Total**	**Uplands**	**Floodplains**	**Total**
Proportion of area invaded (%)	55	100	-	55	100	-
Average density of invasion (%)	25	87	-	25	87	-
Area cleared (ha yr^{-1})	34 471	5 117	39 588	34 471	5 117	39 588
Water loss (Mm^{3} yr^{-1})	37	730	767	30	597	628
Clearing costs per year ($ yr^{-1})	4 205 491	1 588 525	5 794 016	4 205 491	1 588 525	5 794 016
Clearing costs per hectare per year ($ ha^{-1}yr^{-1})	122.00	310.42	432.42	170.11	402.26	572.38
	Low economic benefits					
NPV (US$)	712 770	-151 099 115	-150 386 345	-12 381 365	-385 250 509	-397 631 874
Net economic return per ha (US$ ha^{-1})	0.36	-94.20	-93.84	-3.32	-214.33	-217.65
	High economic benefits					
NPV (US$)	79 269 983	-71 298 127	**7 971 856**	68 556 600	-478 550 764	-409 994 165
Net economic return per ha (US$ ha^{-1})	40.11	-44.45	**4.97**	18.39	-266.23	-247.84

Table 5: Key variables describing the economic and biophysical status of mesquite over the next 30 years in the Northern Cape Province, for two intervention scenarios (stop clearing and contain spread) using ‘relatively low rates’ and ‘relatively rapid rates’ of spread and densification. The values in brackets indicate the change in the value of that variable relative to the baseline in Table 4.

	Stop clearing		**Contain the spread**	
	Uplands	**Floodplains**	**Uplands**	**Floodplains**
	‘relatively low rates of spread & densification’			
NPV ($ million)	155.6	-170.8	35.8	**66.0**
(**High economic benefits**)	**[76.3]**	[-99.5]	[-43.5]	**[137.3]**
NPV ($ million)	75.7	-193.2	-42.1	-94.7
(**Low economic benefits**)	**[75.0]**	[-42.2]	[-42.8]	**[56.4]**
Clearing costs ($ million yr^{-1})	0.0	0.0	6.6	9.5
	[-4.2]	[-1.6]	[2.4]	[7.9]
Proportion of invadable area	100	100	21	22
invaded (%)	[45]	[0]	[-35]	[-78]
Average density of invasion	37	100	20	31
	[12]	[13]	[-5]	[-56]
Area cleared (ha yr^{-1})	0	0	58 077	51 455
	[-34 471]	[-5 117]	[23 606]	[46 338]
Water loss (million m^{3} yr^{-1})	66	671	13	78
(**High economic benefits**)	[36]	[74]	[-17]	[-520]
Water loss (million m^{3} yr^{-1})	81	820	16	95
(**Low economic benefits**)	[43]	[90]	[-21]	[-635]
	‘relatively rapid rates of spread & densification’			
NPV ($ million)	147.1	-490.8	-89.6	-102.6
(**High economic benefits**)	**[78.5]**	[-12.3]	[-158.1]	**[375.9]**
NPV ($ million)	65.3	-378.4	-167.5	-263.2
(**Low economic benefits**)	**[77.7]**	[6.8]	[-155.1]	**[122.0]**
Clearing costs ($ million yr^{-1})	0.0	0.0	13.0	18.5
	[-4.2]	[-1.6]	[8.8]	[16.9]
Proportion of invadable area	100	100	21	22
invaded (%)	[0]	[0]	[-79]	[-78]
Average density of invasion	50	100	19	29
	[4]	[0]	[-26]	[-71]
Area cleared (ha yr^{-1})	0	0	116 153	102 911
	[-24 722]	[-3 949]	[91 431]	[98 962]
Water loss (million m^{3} yr^{-1})	109	867	13	75
(**High economic benefits**)	[19]	[16]	[-77]	[-776]
Water loss (million m^{3} yr^{-1})	133	1,060	16	92
(**Low economic benefits**)	[23]	[20]	[-94]	[-948]

Table 6: The sensitivity of the economic results to a higher discount rate of 8%. The values in brackets indicate the change in the value of that variable relative to the baseline in columns 2 and 3.

	Baseline		**Stop clearing**		**Contain the spread**	
	Uplands	**Floodplain**	**Uplands**	**Floodplain**	**Uplands**	**Floodplain**
	‘relatively low rate of spread and densification’					
NPV ($ million) (**High economic benefits**)	49.8	**31.1**	95.5	-4.2	16.5	32.2
	-	-	[45.7]	[-35.3]	[-33.4]	**[1.1]**
NPV ($ million) (**Low economic benefits**)	2.6	-43.9	47.8	-56.7	-30.5	-64.6
	-	-	[45.1]	[-12.7]	[-33.1]	[-20.7]
Average annual clearing costs ($ million yr^{-1})	4.3	1.3	0.0	0.0	7.3	10.4
	-	-	[-4.3]	[-1.6]	[3.1]	[8.8]
	‘relatively rapid rate of spread and densification					
NPV ($ million) (**High economic benefits**)	45.2	-169.7	91.3	-178.7	-64.6	-78.0
	-	-	[46.1]	[-9.1]	[-109.8]	**[91.6**
NPV ($ million) (**Low economic benefits**)	-3.0	-162.7	42.6	-159.9	-111.5	-174.8
	-	-	[45.6]	[2.8]	[-108.5]	[-12.1]
Average annual clearing costs ($ million yr^{-1})	4.3	1.3	0.0	0.0	14.5	20.4
	-	-	[-4.3]	[-1.6]	[10.3]	[18.8]

Figure 1. Potential distribution of (A) *Prosopis glandulosa* var *torreyana* and (B) the hybrid *Prosopis glandulosa* var *torreyana/velutina* based on climatic data (Rouget *et al*. (2004). The 1/4º latitude x longitude squares (QDS) where it had been recorded up to 2003 are also shown

Figure 2: Costs (excluding herbicides) associated with clearing mesquite infestations, as a function of density of infestation, estimated from 5 years of data from the Western Cape, Northern Cape and Free State Provinces (Department of Water Affairs and Forestry, 2008). The regression line is $y = 5.15x$, where *y* is the cost in US$, and *x* is the density expressed as % cover; R^2 = 92.3)

Figure 3: Flow of the net value of mesquite infestations from upland and floodplain areas in the Northern Cape Province over 30 years, for relatively slow and relatively rapid spread and densification rates and for high and low estimated benefits from mesquite

Figure 1

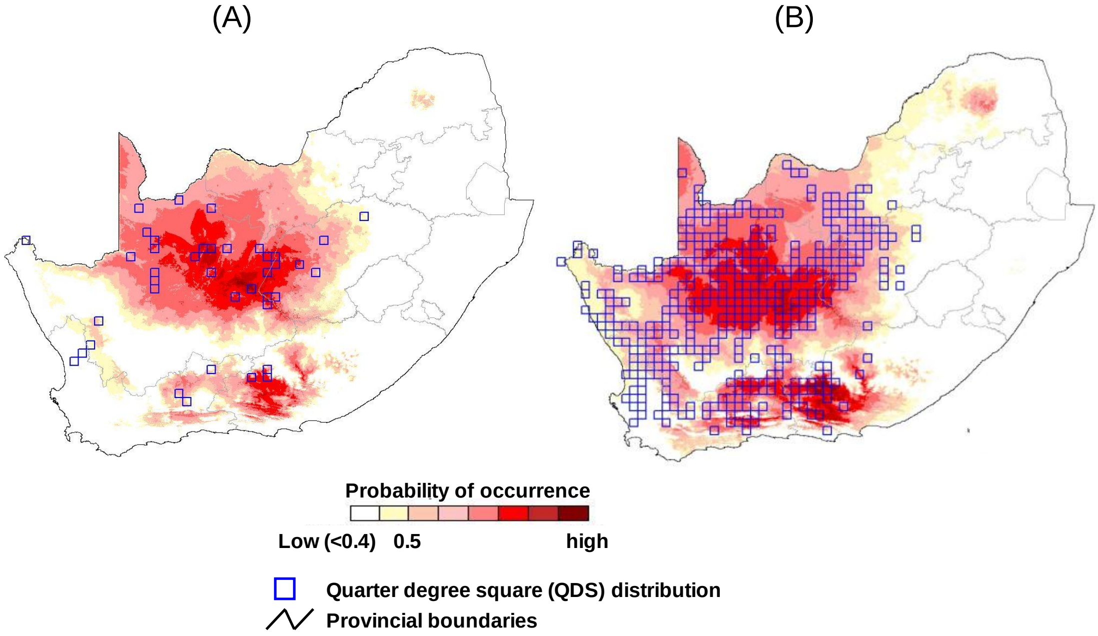

(A)
(B)
Probability of occurrence
Low (<0.4)
0.5
high
Quarter degree square (QDS) distribution
Provincial boundaries

Figure 2

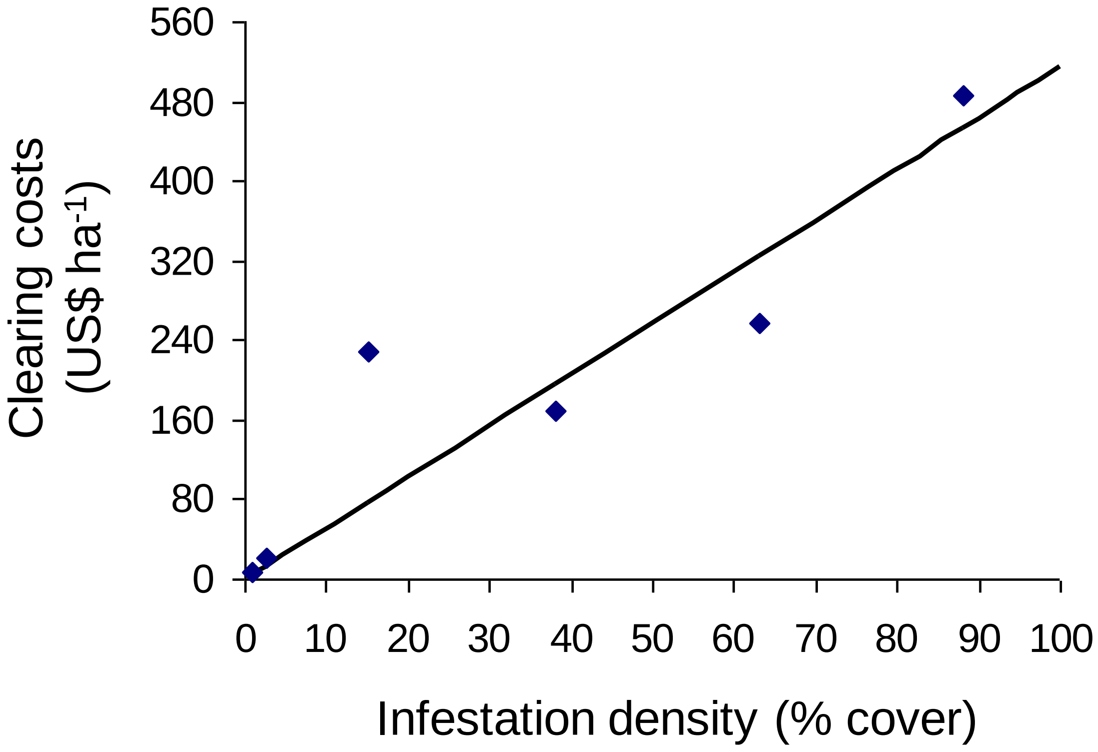
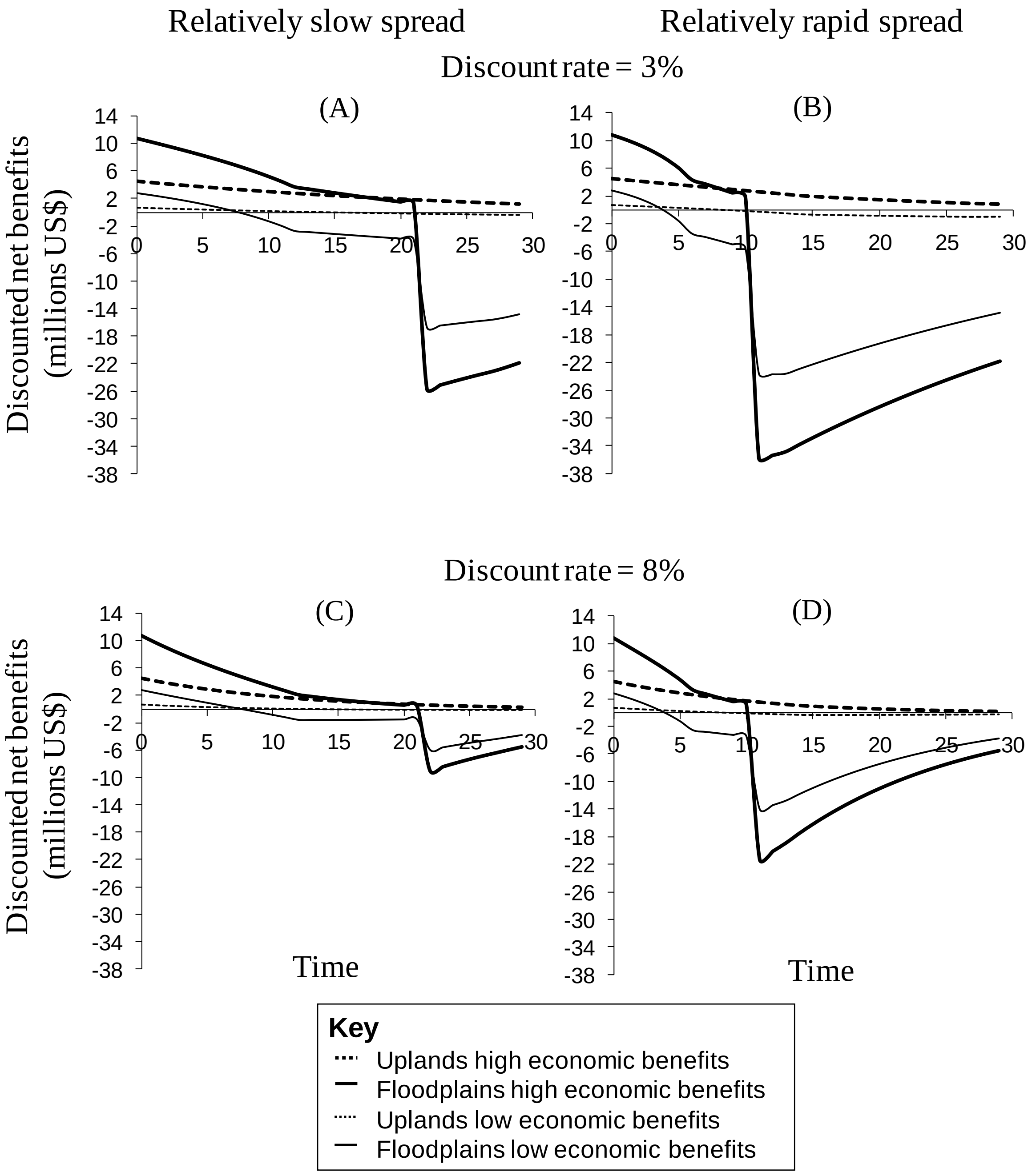

Clearing costs (US$ ha^{-1})
560
480
400
320
240
160
80
0
0
10
20
30
40
50
60
70
80
90
100
Infestation density (% cover)

Figure 3


Relatively slow spread
Relatively rapid spread
Discount rate = 3%
(A)
(B)
Discount rate = 8%
(C)
(D)
Discounted net benefits (millions US$)
14
10
6
2
-2
-6
-10
-14
-18
-22
-26
-30
-34
-38
0
5
10
15
20
25
30
Time
Key
Uplands high economic benefits
Floodplains high economic benefits
Uplands low economic benefits
Floodplains low economic benefits