THE ECONOMIC CONSEQUENCES OF ALIEN PLANT INVASIONS: EXAMPLES OF IMPACTS AND APPROACHES TO SUSTAINABLE MANAGEMENT IN SOUTH AFRICA

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Abstract. The invasion of natural ecosystems by alien plants is a serious environmental problem that threatens the sustainable use of benefits derived from such ecosytems. Most past studies in this field have focussed on the history, ecology and management of invasive alien species, and little work has been done on the economic aspects and consequences of invasions. This paper reviews what is known of the economic consequences of alien plant invasions in South Africa. These economic arguments have been used to successfully launch the largest environmental management programme in Africa.

Ten million hectares of South Africa has been invaded by 180 alien species, but their impacts are not fully understood, although they are undoubtedly significant. The indications are that the total costs of these impacts are substantial. Selected studies show that invasions have reduced the value of fynbos ecosystems by over US$ 11.75 billion; that the total cost of invasion would be about US$ 3.2 billion on the Agulhas Plain alone; that the net present cost of invasion by black wattles amounts to US$ 1.4 billion; that invasions by red water fern have cost US$ 58 million; and that the cost to clear the alien plant invasions in South Africa is around US$ 1.2 billion. These few examples indicate that the economic consequences of invasions are huge.

One of the unique aspects of invasive plant control programmes in South Africa has been the ability to leverage further benefits (mainly through employment) for the expensive control programmes from the government's poverty relief budget. This has made it possible to allocate substantial funding to a programme that would otherwise have struggled to obtain significant support. Biological control of invasive species also offers considerable benefits, but is often the subject of debate. We believe that, at least in the case of many invasive alien plant species in South Africa, biological control offers one of the best, and most cost-effective, interventions for addressing the problem.

Key words: biodiversity, biological control, cost-benefit analyses, forestry, social benefits, water resources, weeds.

1. Introduction

In South Africa, thousands of plant species from other parts of the world have been introduced for a range of purposes – as crop species, for timber and firewood, as garden ornamentals, for stabilizing sand dunes and as barrier and hedge plants.

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Many of these alien species have become naturalized, surviving in the South African landscape without needing to be tended, and some of these naturalized species have become invasive. Invasive alien species are able to survive, reproduce and spread, unaided and sometimes at alarming rates, across the landscape. The invasion of newly colonised areas by alien organisms is a global problem of significant and growing proportions (Kaiser, 1999), which can have serious implications for the environment.

In southern Africa, much of the historic concern about invasives has centred on the consequences for the conservation of biodiversity. Southern Africa is an area of remarkable biological diversity. For example, the region is home to some 21 137 species of vascular plants, about 80% of them endemic (Cowling and Hilton-Taylor, 1994). Many parts of the region have been affected by alien plant invasions. South Africa has a long colonial history dating back 350 years, and it also has a well developed infrastructure, with thriving agricultural and forestry sectors. These factors have contributed significantly to the introduction, establishment, and spread of invasive alien plants (Richardson et al., in press). About 750 tree species and around 8 000 shrubby, succulent and herbaceous species have been introduced in South Africa; of these, 161 species (38 herbaceous, 13 succulent and 110 woody) are regarded as seriously invasive (van Wilgen and van Wyk, 1999), although many more will become weeds in the future.

Biological invasions have received much attention by South African scientists and land managers in the past (see Macdonald et al., 1986; Richardson et al., 1992; Richardson et al., 1997 for recent reviews). However, most attention has been given to the history, ecology and management of invasive alien species, and little work has been done on the economic aspects and consequences of invasions. The situation is changing as people begin to realise the wide-ranging consequences of invasions. An important breakthrough was the demonstration of the current and potential impacts of invasive alien trees and shrubs on water resources in South Africa (Le Maitre et al., 1996; van Wilgen et al., 1996; van Wilgen et al., 1997). This work demonstrated the economic benefits of intervention, and led to the establishment of the 'Working for Water' programme aimed at the control of invasive alien plants to protect water resources and ensure the security of water supply (van Wilgen et al., 1998). The South African government has spent over US$ 100 million on this programme between its inception in 1995 and 1 April 2000.

In this paper, we review what is known of the economic consequences of alien plant invasions. Although studies in this field are still in their infancy, there have nonetheless been some significant advances that provide new perspectives on the problem. A review would seem timely, given that significant funds are being invested into the problem. In addition, we review the unique solutions that South Africa has pioneered with respect to dealing with the problem, and provide a short overview of the economic benefits and sustainability of such approaches.

2. Extent of the problem

Several estimates have been made of the spatial extent of alien plant invasions in South Africa. Unfortunately, each study used a different method or concentrated on particular species or areas. For these reasons, and because surveys were done at different times, these results cannot easily be merged to produce a national overview. Richardson et al. (1997) reviewed available data on the extent of alien plant invasions in different parts of South Africa. The most comprehensive set of records is the South African Plant Invaders Atlas (Henderson, 1998, 1999); these data can be summarised as frequencies by quarter degree (latitude and longitude) but cannot be easily converted to estimates of the extent of the invaded area. The same applies to the recent farmer surveys for the national desertification audit (Hoffman et al., 1999).

This gap has been partly filled, at least for woody shrub and tree species, by a rapid reconnaissance of the extent of invasions in South Africa undertaken in 1996–97 (Versfeld et al., 1998; Le Maitre et al., 2000). The emphasis of this assessment was on mapping species believed to use more water than native vegetation, so succulent (e.g. Cactaceae), herbaceous (e.g. grasses, annuals) and aquatic invaders were generally excluded. The areas of commercial plantations of the invading species, and invasions in the major urban and metropolitan areas were also excluded. The data from this survey need to be interpreted with caution. This mapping exercise was aimed at providing a 'broad brush' estimate of the extent of invasions, and various data sets from other sources were also included in the final database. The estimates derived from this survey have elicited considerable discussion, and opinions on the accuracy of the data are strongly divided, but they are the only national assessment available at present.

According to this national survey, about 10 million hectares of South Africa has been invaded by the approximately 180 species that were mapped (Table I). Of South Africa's nine provinces, the Western Cape has the most extensive invasions followed by the Northern and Mpumalanga Provinces. KwaZulu-Natal and the Eastern Cape were not adequately mapped, and the true extent in these provinces is likely to be closer to the percentage for Mpumalanga which has similar climate, vegetation, history of colonisation and land-use patterns (Le Maitre et al., 2000). Most of the invasions are concentrated in the wetter regions of the country and this is reflected in the number of species which have been recorded per quarter-degree square. The greatest number of species occur in the Western Cape and along the eastern escarpment from KwaZulu-Natal through to the Northern Province (Figure 1).

The data from the national survey were summarised by province, and not by the country's major biomes. However, it is possible to get indications from the distribution of the invasions and the representation of the biomes in the provinces. The fynbos (a mediterranean-type shrubland) biome is the best studied and the most invaded with extensive dryland invasions in both the mountains and the lowlands

TABLE I. Areas invaded by alien plants in the nine provinces of South Africa, and the mean canopy cover (Le Maitre et al., 2000). Data on biomes from Low and Rebelo (1996).

Province	Major biomes (% of province)	Area (km^2)	Total area invaded (km^2)	Total area invaded (%)	Mean canopy cover (%)
Eastern Cape	Grassland (40), Nama Karoo (25), Thicket (16)	167 398	6 720	4.01	22.51
Free State	Grassland (72), Nama Karoo (22), Savanna (6)	129 936	1 661	1.28	14.56
Gauteng	Grassland (78), Savanna (22)	16 519	223	1.35	58.56
KwaZulu-Natal	Savanna (54), Grassland (36), Thicket (8)	94 596	9 220	9.75	27.21
Mpumalanga	Grassland (64), Savanna (36)	79 571	12 778	16.06	14.49
Northern Cape	Nama Karoo (54), Savanna (30), Succulent Karoo (14)	361 981	11 784	3.26	14.10
Northern Province	Savanna (97), Grassland (3)	122 143	17 028	13.94	15.45
North West	Savanna (71), Grassland (29)	116 010	4 052	3.49	13.88
Western Cape	Fynbos (47), Nama Karoo (24), Succulent Karoo (24)	129 314	37 274	28.82	16.80
South Africa (including Lesotho)		1 217 467	100 739	8.07	17.23

as well as invasions along all the major river systems (Richardson et al., 1997; Cowling et al., 1999; Le Maitre et al., 2000; Table II). Most of the fynbos biome is located in the Western Cape, but the small portion of this biome in the Eastern Cape (10 300 km^2 or 6%) is also heavily invaded. The major invaders are *Acacia*, *Hakea* and *Pinus* species. At the scale of the whole Cape Floristic Region (comprising mainly fynbos vegetation types, but also parts of the succulent karoo, Nama karoo, thicket and forest biomes), the data from two independent assessments of the extent of dense stands are reasonably similar (Table II), but Versfeld et al. (1998) clearly underestimated the extent of the light, and overestimated the extent of the medium invasions on the Agulhas Plain. Nevertheless, these studies all highlight the extensive invasions in the fynbos biome.

The forest biome has been heavily invaded but the extent cannot be quantified at present (Richardson et al., 1997). The grassland and savanna biomes have also been extensively invaded, mainly by acacias, other tree species and a variety of woody scramblers (e.g. brambles). The worst affected areas are the grasslands of the Drakensberg escarpment and the moister regions of the savanna biome along the lower escarpment and in the KwaZulu-Natal midlands and coastal belt. Most of

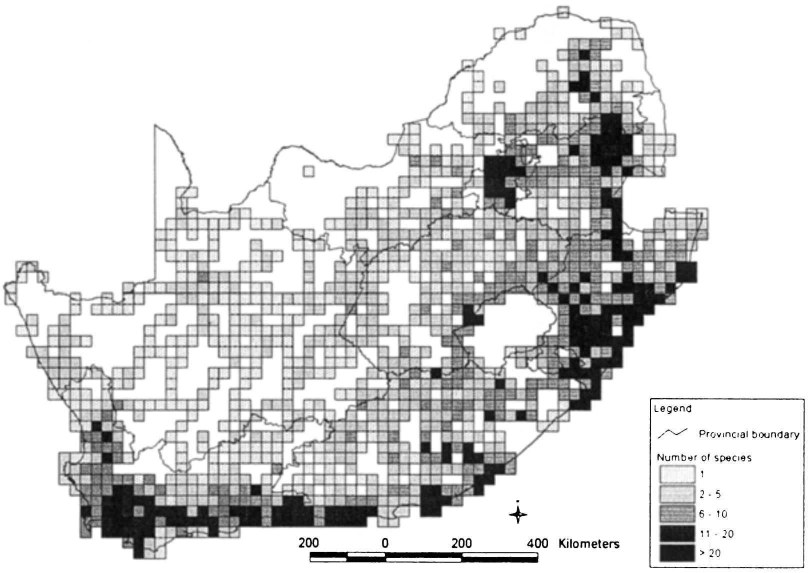

Figure 1. Map of South Africa showing number of invasive alien plant species recorded per quater-degree square; data are from Henderson (1998).

TABLE II. A comparison of the extent of invasions in the Cape Floristic Region (CFR) (Cowling et al., 1999) and Agulhas Plain (Cole et al., 2000) with data from Versfeld et al., (1998) for selected catchment areas which fell mainly within the boundaries of the CFR or the Agulhas Plain respectively. Summary statistics for the light and medium invasions for the CFR were not given by Cowling et al. (1999).

Area	Source	Total study area (km^2)	Density class (canopy cover)		
			Light (<25%)	Medium (25–75%)	Dense (>75%)
Cape Floristic Region	Versfeld et al. (1998)	94 393	29 575	6 968	1 226
	Cowling et al. (1999)	87 892	—	—	1 394
Agulhas Plain	Versfeld et al. (1998)	2 377	22	1 794	107
	Cole et al. (2000)	2 161	1 081	167	302

the invasions in these biomes are found along the banks and in the beds of the rivers; there are few, if any, river systems that have not been extensively invaded. Invading trees such as syringa (*Melia azedarach*) and jacaranda (*Jacaranda mimosifolia*) have spread into semi-arid savanna by invading along perennial rivers where the freely available water, allows them to survive the seasonal drought. The Nama Karoo (semi-desert shrubland, summer rainfall) is probably the fourth most invaded biome; woody invaders, notably mesquite trees (*Prosopis* species), have invaded at least 18 000 km^2 of the low lying alluvial plains and the seasonal and ephemeral water-courses. Several cacti (*Opuntia* species) and saltbushes (*Atriplex* spp.) have invaded large areas of the Nama karoo and succulent karoo (winter rainfall) biomes (Milton et al., 1999) and the thicket biome in the Eastern Cape (Richardson et al., 1997).

Several aquatic weeds have spread over large areas in South Africa, notably water hyacinth (*Eichhornia crassipes*), water lettuce (*Pistia stratiotes*), Kariba weed (*Salvinia molesta*), parrot's feather (*Myriophyllum aquaticum*), and red water fern (*Azolla filiculoides*). These species, in the absence of natural enemies and the presence of eutrophic waters, form large dense mats that degrade aquatic ecosystems and impact on all aspects of water utilization. Four of the five species are effectively under biological control, and the most problematic species is water hyacinth (where biological control has not been developed to its full potential). It is widespread throughout South Africa and severely impacts rivers in the Western and Eastern Cape, Kwazulu-Natal, Mpumulanga and on the Vaal River in the Gauteng and Free State provinces.

3. Environmental impacts

The development of an understanding of environmental impacts of invasive alien plants, and their consequences, would be extremely useful for the quantification of economic impacts. Unfortunately, no standard system exists for the objective quantification of the many and varied environmental impacts of invasive alien plants worldwide (Parker et al., 1999). As in other parts of the world, impacts of plant invasions in South Africa have been measured in numerous ways, making comparisons between biomes within this region, or with other regions or countries difficult. Many descriptions of impacts are anecdotal or correlative (comparing invaded sites with uninvaded sites, or comparing one site at different times), or are based on the performance of the invader in other parts of the world. Very few detailed studies and no manipulative experiments have been done to determine the magnitude, mechanisms of impacts, and implications of impacts of invasions of alien plants in South Africa. Nevertheless, we can draw some conclusions on the types and magnitude of impacts of the most important plant invaders.

Table III gives examples of the main types of impacts caused by the most widespread and damaging invaders. The types of impacts include effects on individuals (including genetics), effects on population dynamics of native species, effects on community dynamics (species richness/diversity, trophic structure), and effects on ecosystem processes and functioning.

When considering the impacts of invasive plants, it is useful to consider two categories of invaders, as proposed by Chapin et al. (1996; see also Dukes and Mooney, in press): discrete-trait invaders (DTI) and continuous-trait invaders (CTI). DTIs add a new function such as nitrogen fixation to the invaded ecosystem, whereas CTIs differ from natives only in traits, such as litter quality or growth rates, that are distributed continuously among species. Results from several parts of the world show that DTIs generally have greater ecosystem-level impacts than CTIs, although the latter can also bring about such changes, especially if they make up a large proportion of an ecosystem's biomass.

TABLE III. Examples of environmental effects of invasive alien plants in South Africa. 1: Life forms: T = tree; SW = shrub (woody); SS = shrub (succulent); V = vine; AG = annual grass; CR = creeper; PG = perennial grass; AF = annual forb; PF = perennial forb; FFM = free-floating macrophyte; FAM = floating macrophyte (attached). 2: Biomes affected: fo = forest; fy = fynbos; gr = grassland; sa = savanna; ka = karoo; aq = aquatic (Richardson et al., 1997). 3: Δ = change; ↑ = increase; ↓ = decrease. 4: Evidence: OD = observation with data; O = observation without data; OO = observation in another part of the world.

Invader (life form[1])	Biomes affected[2]	Disruption[3]	Evidence[4]	References
Acacia cyclops (T)	Fy, fo, sa	Δ in coastal sediment dynamics	O	Avis 1989
		Δ in seed dispersal dynamics	OD	Fraser 1990; Knight and Macdonald 1991
		Provides nesting habitat for rare African penguins	O	R.J.M. Crawford, unpubl. data
		Out-competes native plants	OD	Higgins et al., 1999
		↑ biomass	OD	Milton and Siegfried 1981
		↑ litterfall	OD	Milton 1981
Acacia longifolia (T)	Fy, sa	↓ diversity of ground-living invertebrates	OD	Samways et al., 1996
		↓ streamflow	OD	Prinsloo and Scott 1999
Acacia mearnsii (T)	Gr, fy, fo, sa	↓ diversity of ground-dwelling invertebrates	OD	Samways et al., 1996
		↓ streamflow	OD	Prinsloo and Scott 1999
		Destabilization of streambanks;↑ erosion	O	Richardson et al. 1997
Acacia saligna (T)	Fy, fo, sa	↑ biomass	OD	Milton and Siegfried 1981
		↑ litterfall	OD	Milton 1981
		Δ nutrient chemistry in lowland fynbos	OD	Musil and Midgley 1990; Witkowski 1991; Musil 1993; Yelenik 2000
		Δ in seed dispersal dynamics	OD	Knight and Macdonald 1991
		↑ biomass; Δ size and distribution of fuel; ↓ moisture content = Δ fire regime	OD	Van Wilgen and Richardson 1985
		Attrition of seed banks of native plants with time in dense stands	OD	Holmes and Cowling 1997a,b
Caesalpinia decapetala (CR)	Sa, gr, fo	Dense mats cause trees to collapse	O	Geldenhuys et al. 1986
Chromolaena odorata (SW)	Fo, sa	↑ flammability in forest and riverine woodland; forms "ladders" that carry fires into crowns of fire-sensitive trees	O	Macdonald 1983
		↓ biodiversity of ecotones		

TABLE III. (Continued.)

Invader (life form[1])	Biomes affected[2]	Disruption[3]	Evidence[4]	References
Eichhornia crassipes (FFM)	Aq	↓ degrades aquatic ecosystems Δ river flows	O	Hill and Cilliers 1999
Eucalyptus spp. (T)	Fy,gr, sa, fo	↑ water repellency and soil erosion	OD	Scott et al. 2000
Hakea sericea (SW)	Fy, fo	↑ biomass; Δ size and distribution of fuel; ↓ moisture content = changed fire regime;	OD	Van Wilgen and Richardson 1985
		↑ biomass; results in very intense fires when felled plants are burnt (water-repellent soils - erosion)	OD	Richardson and van Wilgen 1986; Breytenbach 1989
		Dense stands limit options for fire management	O	Seydack 1992
		Δ vegetation structure - ↓ abundance and diversity of native birds; Δ arthropod community structure (some taxa ↑; some ↓); ↓ leaf retention and % seed set in native Proteaceae	OD	Breytenbach 1986
Lantana camara (SW)	Fo, sa, fy, gr	↓ diversity of ground-dwelling invertebrates	OD	Samways et al. 1996
		↓ suppresses regeneration via allelopathy	OO	Baars and Neser 1999
		poisons livestock (R1.7 mill /yr)	OD	Baars and Neser 1999
Melia azederach (T)	Fo, sa	Out-competes native plants	O	Macdonald 1983
		Δ feeding dynamics of frugivorous birds	O	Macdonald 1983
Myriophyllum aqauaticum (FAM)	Aq	↓ degrades aquatic ecosystems Δ river flows ↑ mosquitoes and diseases	O	Cilliers 1999
Nasella trichotoma (AG)	Gr	↓ pasture productivity	O	Stirton 1978
Opuntia aurantiaca (SS)	Ka, sa	↓ pasture productivity	O	Stirton 1978
Opuntia ficus-indica (SS)	Sa, ka, gr, fo, fy	↓ pasture productivity	O	Stirton 1978
Pereskia aculeata (CR)	Fo	Dense mats cause trees to collapse	O	Geldenhuys et al., 1986

TABLE III. (Continued.)

Invader (life form[1])	Biomes affected[2]	Disruption[3]	Evidence[4]	References
Pinus pinaster (T)	Fy, fo, sa	Out-competes native plants	OD	Richardson et al., 1989, Higgins et al., 1999
		Dense stands limit options for fire management	O	Seydack 1992
		↓ streamflow	OD	Le Maitre et al., 1996, Le Maitre et al., in press
Pinus radiata (T)	Fy	↓ streamflow	OD	Dye 1996
Prosopis spp. (T/SW)	Sa	↑ biomass; Δ in vegetation structure; ↓ access, ↓ pasture productivity	O	Harding and Bate 1991
		Out-competes native plants	O	Brown and Gubb 1986
		↓ diversity of dung beetle assemblages	OD	Steenkamp and Chown 1996
Psidium guajava (T)	Fo, sa, gr	Out-competes native plants	O	Macdonald 1983
Rubus spp. (SW)	Sa, gr, fo	Hybridize with native Rubus sp.	O	Stirton 1981
Salix babylonica (T)	Ka, gr	Destabilizes river banks and excludes native plants	O	Henderson 1991
Salvinia molesta (FFM)	Aq	↓ degrades aquatic ecosystems Δ river flows ↑ mosquitoes and diseases	O	Bromilow 1995
Sesbania punicea (T)	Sa, fo, fy, gr	↓ access, ↑ bank erosion, ↓ streamflow	O	Hoffmann and Moran 1988
		poisoning of stock	O	Stirton 1978
Solanum mauritianum (T)	Sa, fo, gr	↓ diversity of ground-dwelling invertebrates	OD	Samways et al. 1996
		Δ feeding ecology of Rameron Pigeon (and other native birds)	OD	Oatley 1984
		Out-competes native plants	O	Macdonald 1983

The most dramatic impacts of alien plants in South African systems have clearly been from discrete-trait invaders. For example, the Australian *Acacia* species (notably *A. cyclops* and *A. saligna*) have radically altered nutrient-cycling regimes in the nutrient-poor systems of lowland fynbos due to their ability to fix atmospheric nitrogen (no widespread or abundant native species perform this role). These species and several species of *Pinus* that have invaded large areas have added a major new life form (trees) to the tree-poor fynbos. Such invasions have produced many ecosystem-level changes by altering features such as biomass distribution, plant density and vegetation height, leaf-area index, litterfall and decomposition rates. These invasions are the largest threat to endangered plant species in the Cape Floristic Region (Hall, 1987). Widespread tree and shrub invasions in vegetation types that previously had a low tree cover have radically altered habitats for animals. This is shown, for example, by the major changes in distributions of many bird species, including species that invaded the southwestern parts of South Africa from adjacent biomes in response to increased tree cover (e.g., Macdonald, 1986). Other DTIs that have caused major impacts in South African ecosystems include *Chromolaena odorata*, *Pereskia aculeata*, *Prosopis* spp. and the suite of alien trees that have invaded watercourses in formerly tree-poor systems.

The most detailed work on assessing the impact of plant invasions in South Africa has focussed on tree invasions in the fynbos biome. Several studies have documented the reduction in streamflow caused by plantations of invasive tree species (mainly*Pinus* species; Dye, 1996; Le Maitre et al., 1996; Prinsloo and Scott, 1999) and aspects of the modified nutrient regime (Musil and Midgley, 1990; Witkowski, 1991; Musil, 1993; Stock and Allsopp, 1992; Yelenik, 2000) and impacts on the seed banks of native fynbos species (Holmes and Cowling, 1997a,b) associated with *Acacia saligna* invasions. A recent countrywide study made a first attempt at assessing the effect of all woody invaders on surface water resources. Results from this investigation suggest that woody alien plants may be using as much as 6.7% of the total mean annual surface runoff or 9.95% of the utilisable surface runoff in South Africa (Versfeld et al., 1998; Le Maitre et al., 2000).

The above brief review shows that the understanding of the environmental impacts of invasive alien plants is scattered and patchy. No overall framework for the collection and synthesis of this information has been attempted, and as a result there are few overall syntheses of impacts at the scale of an ecosystem. Nonetheless, the studies that have been done could provide a useful starting point for the development of such a framework.

4. The economics of invasions

4.1. Cost benefit analyses

Invasion by alien plants in South Africa, as elsewhere in the world, results in many negative impacts, as shown above. In addition, some invasive plants also have major positive benefits, and these need to be taken into account when assessing the costs resulting from invasions. These impacts and benefits could be expressed in economic terms, although very few studies have attempted to do this until recently. Attempting an objective analysis and summary of the studies that have been done is frustrating, as every study has used a different approach, making an accurate assessment of aggregate impacts impossible. Despite this, several studies have been carried out

(Table IV), and these can be used to illustrate the known impacts, and to illustrate trends.

Most early assessments of the impacts of alien plants in South Africa concentrated on the environmental impacts, particularly the impacts on biodiversity (see above). It was not until the mid-1990s that scientists began to quantify the impacts of invasion by alien trees and shrubs on water resources in South Africa (van Wilgen et al., 1992; Le Maitre et al., 1996; van Wilgen et al., 1996). These studies were pivotal in persuading government to take the issue very seriously, while at the same time providing the impetus for further studies on the economics of plant invasions.

The estimates of the impacts of invading alien trees and shrubs on the yield of water from important catchment areas was based on experiments where pines and eucalypts were planted in these areas to determine the effects of plantation forestry on water resources. The results have been extrapolated to other areas, and to estimate water use by other species (Table IV). For these reasons, the results must be viewed with caution. However, even if the estimated losses are twice the real losses, the 'costs' would still be significant. The studies listed in Table IV have shown that invasive alien plants may be using as much as 6.7% of the country's runoff (Versfeld et al., 1998); that clearing the invasive plants is a good investment simply to prevent water losses (van Wilgen et al., 1997; Hosking and du Preez, 1999); and that failure to clear stands of invading trees will result in exponential increases in the costs of clearing as catchment areas become further invaded (Le Maitre et al., in press). The economic consequences of 'lost' water would be even more important. As water is a limiting resource in South Africa, losses of water will restrict the potential for economic growth. At least one study (De Wit et al., in press) has sought to carefully quantify the impacts of lost water for urban, agricultural and industrial use, and the results showed that the cost of clearing programmes can easily be justified in terms of the economic benefits derived from preventing water losses or restoring them to pristine levels.

The significant impacts of invasive alien plants on biodiversity are difficult to evaluate in monetary terms, so this is often not attempted. For example, De Wit, Crookes and van Wilgen's (in press) study on the economic impacts of *Acacia mearnsii* invasions did not take biodiversity into account because of the lack of data or estimates on which to base such evaluations. The economic benefits of biodiversity can nonetheless be significant, both from direct use (such as grazing, or harvesting of natural products), as well as from indirect use (such as recreation and nature-based tourism). Some recent studies have included aspects of the value of biodiversity in their analyses (for example Turpie and Heydendrych, 2000; Higgins et al., 1997a; see Table IV); these show that invasions have significant economic costs as a result of the impacts on biodiversity. Turpie and Heydendrych (2000) estimated the values of harvesting of wildflowers, and for recreational use in protected areas, and showed that harvest values reduced from US$ 9.7 to $ 2.3/ha, and recreational use values in protected areas reduced from $ 8.3 to $ 1/ha, when pristine areas became densely invaded by alien plants.

TABLE IV. Studies on the economic impacts of alien invasive plants in South African ecosystems. Monetary values are in US$; where values were published in Rand, we have converted to US$ at a rate of R7 = 1 US$.

Study	Type of impacts or benefits	Value of impacts or benefits	Sources
Impact of alien plant invasions on water yield	Reduced water yield from invaded watersheds; prevention of water losses through clearing programmes	Clearing of invasive aliens would prevent losses of 30% of Cape Town's water supply at a cost of 1.3 c/m^3	Le Maitre et al., 1996
Costs and benefits of alien plant clearing programmes	Increased water yields resulting from clearing, compared to costs of operating water supply schemes	Clearing would yield water at 14% of the cost of developing new water supply schemes (1.1 vs 8.4 c/m^3 respectively)	van Wilgen et al., 1996; van Wilgen et al., 1997
Costs and benefits of alien plant clearing programmes	Increased water yields from clearing of invaded watersheds and uneconomic plantations of alien trees	Clearing yields benefit : cost ratios of between 6 : 1 and 12 : 1 for clearing invaded watersheds, and between 360 : 1 and 382 : 1 for clearing uneconomic plantations	Hosking and Du Preez 1999
Relative costs of clearing programmes compared to costs of allowing alien plants to invade unchecked	Increased water resulting from clearing (between 7 and 22% of current runoff), compared to increased losses from continued invasion (from 22 to 100% if invasions continue unchecked)	Estimated cost of clearing invaded watersheds ranged from US$ 4 to 13 million, and would increase to between US$ 11 and 278 million if invasions continue unchecked. Value of lost water was not quantified	Le Maitre et al. (in press)
Broad survey of impacts of alien plants on water resources at a national scale	Invasions estimated to be using 3 300 million m^3 per year (6.7% of the runoff of South Africa)	Value of lost water was not quantified, but estimates of cost to clear infestations range from 412 to 996 million US$	Versfeld et al., 1998; Le Maitre et al., 2000)
Ecological-economic simulation model of mountain fynbos ecosystems	Model assesses consequences of invasion for water production, wildflower harvest, hiker and ecotourist visitation, endemic species and genetic storage	Managing alien plants increases value of hypothetical 4 km^2 area from 3 to 50 million US$. This can be achieved by spending a fraction of total value on clearing programmes	Higgins et al., 1997b
Cost-benefit analysis of black wattle (*Acacia mearnsii*)	Benefits assessed from commercial crop values and other products; impacts from reduced water yield, increased fire risk, and loss of biodiversity	Continued cultivation without control programmes yields a benefit : cost ratio of 0.4. Continued cultivation with clearing, or with clearing and biological control of seeds yields benefit : cost ratios between 2.4 and 7.5	De Wit et al. (in press)

TABLE IV. (Continued.)

Study	Type of impacts or benefits	Value of impacts or benefits	Sources
Cost-benefit analysis of biological control of red water fern (*Azolla filiculoides*)	Serious economic impacts on agricultural sector through loss of water resources and livestock. Total losses estimated at US$ 58 million in South Africa	Introduction of a biological control agent has brought the problem under control at a cost of US$ 51 000, yielding a benefit : cost ratio of 1130 : 1	M.P. Hill (pers comm.)
Economic valuation of indigenous vegetation, and impacts of alien infestations, on the Agulhas Plain	Benefits from livestock, wildflower harvesting and nature-based tourism. Cost estimates for clearing invasives to prevent erosion of benefits	Benefits total US$ 3 million annually. Total cost to clear invasives amounts to US$ 5.6 million. Thus, clearing will yield positive benefits after two years	Heydenrych 1999
Analysis of the economic consequences of invasion on the use values of fynbos (shrubland) ecosystems	Values of harvesting of wildflowers, recreational use in protected areas, and of water runoff, in pristine and densely invaded areas respectively	Reductions due to invasion range from US$ 9.7 to $ 2.3/ha for harvest values and from $ 8.3 to $ 1/ ha for recreational use. The value of lost water due to invasion amounted to $ 163/ha	Turpie and Heydenrych 2000
Cost of controlling jointed cactus (*Opuntia aurantiaca*)	State introduced a subsidized scheme of supplying herbicides to farmers whose land became invaded	Costs of state-subsidized control efforts exceeded US $12 million over the past 40 years. Cost has dropped by 83.5% following the introduction of a biological control agent	H.G. Zimmermann (pers.comm.)

Invasion by alien plants increases the negative impacts of fires, by increasing fuel loads and fire intensities (van Wilgen and Richardson, 1985), making fires more difficult to control and increasing the risk of damage. The more intense fires also cause severe damage to soils (Scott et al., 2000), leading to soil loss (Euston-Brown, 2000), severe soil erosion during rainstorms and damage to infrastructure due to flooding. The economic impacts can be severe, but are difficult to demonstrate (e.g., how much worse was a fire because the area was invaded?). Examples of the costs associated with fires include a wildfire on the Cape Peninsula in March 1999 that created water-repellent conditions in an invaded area which formerly had no overland flow (Scott, 1999). Flooding followed heavy rains in April 1999, and resulted in cleanup costs of more $ 150 000. This estimate excludes the associated flood damage to 30 dwellings, which probably totalled at least another $ 150 000. These impacts did not occur to adjacent areas that were not invaded. In another example, two wildfires burnt 8 000 ha on the Cape Peninsula between 16 and 20 January 2000

(Scott et al., 2000). Insurance claims arising from this fire amounted to $ 5.7 million (Kruger et al., 2000). Most houses and structures that were damaged were in areas invaded by alien plants, where fire intensities were much higher than in adjacent uninvaded areas. The direct costs of fighting the fire were not documented, but exceeded $ 500 000 (Kruger et al., 2000). After the fires, an average of 147 tons/ha of soil was lost from alien invaded areas compared with negligible losses from areas with natural vegetation (Euston-Brown, 2000). The increases in fire intensity also have important negative effects on biodiversity, but these have been poorly studied.

The above negative impacts should not be presented in a one-sided manner, however. Almost all the important crops in South Africa are harvested from alien plants, and the point needs to be made that a relatively small percentage of these alien plants become invasive. In addition, some invasive alien species have considerable value, despite their negative impacts, and these need to be taken into account when assessing the costs resulting from invasions. Conflicts of interest arise from time to time in cases where important commercial species become invasive and spread beyond the areas where they are cultivated. These include plantation forestry (*Pinus* species; Richardson, 1998); where alien plants provide firewood (many *Acacia* species; Higgins et al., 1997a), food (*Opuntia* species; e.g. Brutsch and Zimmermann, 1993), fodder (*Prosopis* species), or nectar for bees (*Eucalyptus* species; Johannesmeier, 1985); and where they have aesthetic or utilitarian value (ornamentals, shade trees or windbreaks).

A good example is provided by plantation forestry, which is an important part of the South African economy, contributing US$ 300 million, or 2%, to the GDP and employing over 100 000 people. Downstream industries, based on forestry, produce timber products worth a further US$ 1.6 billion, much of which is exported, earning valuable foreign exchange. Clearly, these activities are significant. However, a large proportion (38%) of the area invaded by woody alien plants in South Africa is occupied by species used in commercial forestry (especially *Pinus* and *Acacia* species). It is thus clear that forestry has been one of the country's major sources of alien infestation (Richardson, 1998; Richardson et al., in press).

These conflicts have to be dealt with in a sensitive manner if progress is to be made in reducing the significant negative impacts of invading alien plants. Some of the possible approaches to avoid conflict in South Africa include recognising the value of a vibrant forest industry and actively managing the spread of plantation trees; making allowance for well-managed woodlots in areas where fuelwood is scarce, using non-invasive species wherever possible, or ensuring that biological control is introduced at the start of new agroforestry projects; using biological control to reduce the invasive potential of otherwise useful species without killing them (for example, by reducing the number of seeds they produce, see section 4.2.2 below); recognizing potential invaders early and taking precautionary measures; educating people as to the dangers and costs of invasive species; and encouraging the use of alternative, non-invasive species for ornamental and utilitarian purposes.

Arriving at a comprehensive figure for the total costs of invasive plants is not possible at this stage. However, the indications are that the total costs are substantial, and a number of studies can be quoted to support this contention. Some examples are listed below.

(i) One of the few detailed studies calculated the value of a hypothetical 4 km^2 (4 000 ha) mountain fynbos ecosystem at between US$ 3 million (with no management of alien plants), and US$ 50 million (with effective management of alien plants), based on six components: water production, wildflower harvest, hiker visitation, ecotourist visitation, endemic species and genetic storage (Higgins et al., 1997b). Given that there are over 1 million ha of protected fynbos areas in South Africa, the potential reduction in value due to invasion could amount to over US$ 11.75 billion.

(ii) Turpie and Heydenrych (2000) estimated that the value of lost water amounts to $ 163/ha on the Agulhas Plain area of South Africa; thus, if 20 000 ha of this area became invaded (20 000 ha is the target area to be incorporated in the proposed Agulhas National Park), the total cost would be in the region of US$ 3.2 billion.

(iii) In a study on black wattle (*Acacia mearnsii*) invasions, De Wit, Crookes and van Wilgen (in press) calculated the economic value of streamflow lost to invasions of black wattle in South Africa using the opportunity-cost approach. First, the value added by water over the different demand sectors (irrigation, domestic and urban use, mining and industry, the environment and afforestation) was calculated. Secondly, the value added by additional water where black wattles were eradicated was estimated. These estimates were adjusted for to allow for evaporation and spillage of flood water (33% of additional water was assumed to be unusable), changes in the numbers of downstream water users over the next 20 years, and the degree to which water would contribute to the economic value added in each sector (assumed to be 10% of predicted growth in economic value added). This study revealed a 'net present cost' of US$ 1.4 billion attributed to black wattle invasions (it should be noted that this study considered only black wattles, and not the many other invasive trees in the country).

(iv) In the only detailed study to date on the economic benefits of biological control of invasive alien plants in South Africa, scientists developing biological control solutions, have shown that bringing the red water fern (*Azolla filiculoides*) under control has yielded a return on investment of 1130 : 1 (M.P. Hill, pers comm.). Red water ferns, introduced from South America, rapidly covered dams and resulted in damage to water pumps, the deaths of livestock and substantial clearing costs that totalled US$ 58 million. This was compared to $ 51 000 to carry out the research that led to the release of the biological control agent, which in turn brought the problem completely under control within 2 years of release.

(v) The cost to clear the alien plant invasions in South Africa is estimated to be around US$ 1.2 billion, or roughly US$ 60 million per year for the estimated

20 years that it will take to deal with the problem (Versfeld et al., 1998). This expense is needed to offset the considerable costs due to invasive plants, but the point needs to be made that, should the programme not be funded, the costs will grow as invasive plants spread to occupy the full extent of invasible habitats. The country is therefore forced to incur these expenses or face the even worse prospects of growing impacts.

These few examples indicate that the economic consequences of invasions are huge. The examples cited above represent only portions of the problem for which studies have been done, and a thorough analysis would undoubtedly reveal much higher costs.

4.2. Dealing with the problem

4.2.1. Using the alien plant problem to create benefits

While invasions by alien plants have significant negative environmental and economic impacts, the South African government has used the opportunities offered by the need for labour-intensive clearing programmes to generate a range of benefits. By adding these benefits to the obvious environmental and economic advantages, it has been possible to justify the spending of over US$ 100 million on the programme between 1995 and 2000. The funds have been directed through the government's 'Working for Water' programme, which engages unemployed people in labour-intensive clearing, follow-up and rehabilitation projects aimed at bringing invasions of alien plants under control. The programme also runs a parallel social development programme which seeks to maximise the opportunities for development of disadvantaged people employed by the programme. The Working for Water programme's social development activities are an integral part of the overall strategy to clear alien plants and they promote the achievement of far-reaching social development objectives. The social development programme has several main components, including: (i) a childcare programme, whereby children are looked after in crèches, allowing women time to earn much needed income to support their families; (ii) an HIV/AIDS programme, to increase HIV/AIDS awareness and condom use among workers; and (iii) partnerships, which include an ex-offender reintegration programme, and several others. Working for Water employs the poorest members of communities settled closest to the alien infested areas. The trend has been to target women, especially single mothers, and encourage them to join teams of about twenty members with supervisors to oversee their productivity.

In early 2000 the Working for Water programme employed approximately 20 000 people (largely from rural areas) in 249 projects around the country. The main social benefits from clearing activities do not only include employment, but also the improvement of poor people's livelihoods through incomes, resulting in better nutrition for children, better clothing and an ability to pay for education. Additionally, the social benefits come with a contribution towards economic empowerment through small business training and skills development for contractors, leading to better opportunities to earn a living outside the programme.

In one of the few detailed studies of the social impacts of the programme, Marais (1998) quantified benefits in the Western Cape Province during 1996/97. Wages were paid to 2 961 people employed as clearing workers, team supervisors, managers, and development, training and administration officers. The total spent on salaries for the year was $ 6.431million, a mean of $ 2 175 per person. Most of this money was invested directly into disadvantaged rural communities. Assuming an average family size of 5 people, and that only one person per family was employed in the project, the direct benefits reached as many as 14 800 people, at $ 435 per capita. This injection of funding into disadvantaged communities also had secondary effects in terms of suppliers and service providers. Protective clothing, tools and mechanical equipment constituted most of the supplies bought by the project and a number of secondary jobs were linked to the project through procurement.

To assess the effect of the above, the project was evaluated in the context of the provincial economy, using a Social Accounting Matrix Analysis (SAM, Eckert et al., 1997). Since the rich taxpayers (the source of the funding) and the workers have vastly different spending habits, the project should be redistributive in nature. Net multiplier effects should show the influence of some contraction in economic activity by taxpayers and an expansion in activity by those persons and businesses receiving project expenditures.

Marais (1998) measured direct employment as the number of person-years of employment created from $ 250 000 of additional final demand. The estimated number of secondary, indirect and induced jobs created in industries related to the programme was 8.93 for every extra $ 250 000 project budget. Based on a 1996/97 expenditure in the Western Cape of $ 10.05 million, 359 additional secondary jobs were created. Based on the above, employment benefits for South Africa were estimated using the number of direct jobs and the national expenditure during that year (Table V).

According to Eckert et al., (1997) 67.7% of government revenue from household contributions was drawn from the previously advantaged communities in the Western Cape. At the same time, the percentage of total household spending on unprocessed and processed agricultural commodities of people from previously disadvantaged communities was 73.0% and 68.1% respectively. This means that the bulk of household spending by these groups was being spent locally and benefited the local economy. On the other end of the scale, the rich were spending money on imports and other expensive items, which did not always benefit the local economy.

Eckert et al., (1997) used Gini coefficients to estimate the amount of equality or inequality in the Western Cape Province. Countries with highly unequal income distributions have coefficients between 0.5 and 0.7, while the value for countries with relatively equitable distributions was between 0.2 and 0.35.

TABLE V. Annual economic benefits in the 1996/97 financial year associated with the employment of people in alien plant clearing programmes. Data for the Western Cape are from Marais (1998). Data for South Africa are extrapolations based on Marais (1998) and employment data for the Working for Water programme at a national level (Department of Water Affairs and Forestry 1997).

Measure of benefit	Western Cape (after Marais 1998)	South Africa (extrapolated)
Direct employment (number of people employed)	2 961	8 386
Approximate number of people supported by direct employment (assuming five – seven per family)	14 800–20 700	41 900–58 700
Indirect employment (number of secondary jobs created)	359	714
Approximate number of people supported by secondary jobs (assuming five – seven per family)	1 800–2 500	3 600–5 000
Approximate total number of people supported	16 600–23 200	45 500–63 700
Annual expenditure (Millions of US $)	10.05	20

(Whiteford and McGrath, 1994). The Gini coefficient for all Western Cape households was 0.509 (Eckert et al., 1997). The total income of the highest income group including the corporations, upper- and middle-income groups in the province declined over the study period by approximately 0.09%. On the other hand the poorest of the poor showed an increase of 3.08% in their household income, and the Gini coefficient was reduced to 0.507 (Eckert et al., 1997). If the size of the project in relation to the provincial GDP is taken into account, this was significant. The total household income before the project started was $ 10 476 225. After the project it was $ 10 476 903. The net income change of participants in the programme in the Western Cape was $ 677 750, or 6.74% of the total project expenses for 1996/97. It can be seen as significant that a project of such limited size should have an effect of this magnitude.

4.2.2. The economic advantages of biological control programmes

The labour-intensive control programmes aimed at clearing and rehabilitating the extensive invaded areas are unlikely to be sustained in the long term. The clearing programmes should therefore aim to develop components that will ensure that cleared areas do not simply become re-invaded. One of the most cost-effective ways of doing this would be to use biological control, where species-specific organisms are introduced to bring the invasive species under control, or to reduce it’s invasive potential.

Biological control of invasive alien species is one of the most cost-effective ways of reducing the impacts of such invasions. South Africa has been very successful in finding effective biological control solutions to many invasive weed problems (Richardson et al., 1997; Olckers and Hill, 1999), but the true value of these initiatives has not been quantified in any rigorous way. Historically, 103 biological control agents have been released in South Africa against 46 weed species; of these, 22 weed species are now under complete or substantial biological control (Olckers and Hill, 1999). It is hoped to build on these successes, and the country's biological control research programme has been expanded to include some species (e.g. *Acacia* and *Pinus* spp.) that were previously excluded from research because of their commercial value (Stubbings, 1977; Pieterse and Boucher, 1997). In such cases, the approach would be to introduce control agents that reduce seed output (and therefore invasive potential) without impacting on the growth potential of the plant. This has been done for several species already, notably Australian *Acacia* species. The total cost of the biological control research initiative between 1997 and 2000 was US$ 3 million. Indications are that these activities represent unprecedented returns on investment.

The example of the economic benefits bringing the red water fern (*Azolla filiculoides*) under control (section 4.1 above) has yielded a return on investment of 1130 : 1. Not all research projects will yield such dramatic results. Nonetheless, there are several examples where biological control has led to significant reductions in costs. For example, the South African government has, for the past 40 years, provided subsidized herbicides to farmers whose land has become infested with jointed cactus (*Opuntia aurantiaca*). The costs of this programme have exceeded US$ 12 million over the past 40 years. The recent introduction of a successful biological control agent has seen the annual expenses incurred by government fall by 83.5%. Another preliminary estimate has been made for the control of the Port Jackson willow (*Acacia saligna*), which has invaded over 1.8 million ha in South Africa. The introduction of a biological control agent has effectively eliminated the need to proceed with expensive mechanical control programmes, yielding a return on investment of $ 800 for every $ 1 invested in the research (van Wilgen et al., 2000).

The cost of bringing invasive alien trees and shrubs under control in South Africa is estimated to be around US$ 1.2 billion, or roughly US$ 60 million per year for the estimated 20 years that it will take to deal with the problem (Versfeld et al., 1998). By introducing biological control as a factor, it was estimated that clearing costs over 20 years could be reduced to US$ 400 million (or US$ 20 million per year), a far more manageable target for a developing country like South Africa. Given that the clearing programme is seen as essential for ensuring water and environmental security, such potential savings are substantial.

5. Conclusions

The above review has highlighted the need for a thorough economic assessment of the invasive alien plant problem in South Africa. Almost all of the studies carried out to date have indicated that the impacts of invasive alien plants are severe, and that intervention in the form of control programmes is justified. The studies done to date are preliminary, however, and the conclusions of economic analyses are often subject to criticism because of the assumptions on which they are based. Given the indications of the severity of the problem, more studies will be needed in order to understand where the most important economic impacts will lie. These in turn will assist in designing optimal means for funding the control interventions.

One of the unique aspects of invasive plant control programmes that has emerged in South Africa to date has been the ability to leverage further benefits for the expensive control programmes. Most of the funds for the 'Working for Water' programme have been sourced from the government's poverty relief budget (and not only from budgets aimed at protecting water resources, agricultural land and biodiversity). This leverage has made it possible to allocate substantial funding to a programme that would otherwise have struggled to obtain significant support. The links are fragile, however, and convincing economic assessments of the consequences of diverting funds from the clearing programme into other necessary interventions (such as education and health care) will go a long way to maintaining the support and the benefits that it brings.

Biological control of invasive species is one solution that appears to offer considerable benefits. Biological control cannot solve the invasive species problem in all cases, but there have been a number of remarkable successes. In each of these cases, the benefits have far outweighed the costs. Biological control is nonetheless often the subject of some debate (as it involves the introduction of yet more alien species into new environments, with some degree of risk, see van Wilgen et al., 2000). We believe, at least in the case of many invasive alien plant species in South Africa, that biological control offers one of the best, and most cost-effective, interventions for addressing the problem.

Finally, in arguing a case for the control of invasive plants in South Africa, there are bound to be conflicts (see 4.1 above). Many invasive species also bring benefits, and with benefits come vested interests. In such cases, the argument for or against control often becomes polarised, with the case being argued from one side or the other, with little balance (see, for example, Johns, 1993; Cellier, 1994). The education of the broader public in understanding the complexities of the problem, and thus enabling them to judge the merits of control programmes, is an enormous, and critical, challenge if broad support is to be obtained.

References

Avis, A.M.: 1989, 'A review of coastal dune stabilization in the Cape Province of South Africa', *Landscape and Urban Planning* **18**, 55–68.

Baars, J-R. and Neser, S.: 1999, 'Past and present initiatives on the biological control of Lantana camara (Verbenaceae) in South Africa', *African Entomology Memoir* **1**, 21–33.

Breytenbach, G.J.: 1986, 'Impacts of alien organisms on terrestrial communities with emphasis on communities of the south-western Cape' in I.A.W. Macdonald, F.J. Kruger and A.A.Ferrar (eds.), *The ecology and management of biological invasions in southern Africa*, Cape Town, Oxford University Press, pp. 229–238.

Breytenbach, G.J.: 1989, 'Alien control: Can we afford to slash and burn hakea in fynbos ecosystems?', *South African Forestry Journal* **151**, 6–16.

Bromilow, C.: 1995, *Problem plants of South Africa*. Pretoria, Briza Publications.

Brown, C.J. and Gubb, A.A.: 1986, 'Invasive alien organisms in the Namib Desert, Upper Karoo and the arid and semi-arid savannas of western southern Africa' in I.A.W. Macdonald, F.J. Kruger and A.A.Ferrar (eds.), *The ecology and management of biological invasions in southern Africa*, Cape Town, Oxford University Press, pp. 93–108.

Brutsch, M.O. and Zimmermann, H.G.: 1993, 'The prickly pear (*Opuntia ficus-indica* [Cactaceae]) in South Africa: Utilization of the naturalized weed, and of the cultivated plants', *Economic Botany* **47**, 154–162.

Cellier, S.: 1994, 'Are all trees green? The forest industry replies', *Africa Environment and Wildlife* **2**(1), 79–85.

Chapin, F.S. III, Reynolds, H.L., D'Antonio, C.M. and Eckhart, V.M.: 1996, 'The functional role of species in terrestrial ecosystems', in B. Walker and W. Steffen (eds.), *Global change and terrestrial ecosystems*, Cambridge University Press, pp. 403–428.

Cilliers, C.J.: 1999, 'Biological control of parrot's feather, *Myriophyllum aquaticum* (Vell.) Verd. (Haloragaceae), in South Africa', *African Entomology Memoir* **1**, 113–118.

Cole, N.S., Lombard, A.T., Cowling, R.M., Euston-Brown, D., Richardson, D.M. and Heijnis, C.E.: 2000, *Framework for a conservation plan for the Agulhas Plain, Cape Floristic Region, South Africa*, Institute for Plant Conservation, University of Cape Town.

Cowling, R.M., Pressey, R.L., Lombard, A.T., Heijnis, C.E., Richardson, D.M. and Cole, N.: 1999, *Framework for a conservation plan for the Cape Floristic Region*, Institute for Plant Conservation, University of Cape Town.

Cowling, R.M. and Hilton-Taylor, C.: 1994, 'Patterns of plant diversity and endemism in southern Africa: an overview', in B.J. Huntley (ed.), *Botanical diversity in southern Africa*, Pretoria, National Botanical Institute, pp 31–52.

Department of Water Affairs and Forestry: 1997, *The Working for Water Programme 1996/97 Annual Report*, Department of Water Affairs and Forestry, Pretoria.

De Wit, M., Crookes, D. and van Wilgen, B.W.: 'Conflicts of interest in environmental management: Estimating the costs and benefits of black wattle (*Acacia mearnsii*) in South Africa', *Biological Invasions*, (in press).

Dukes, J.S. and Mooney, H.A: 'Biological invaders disrupt ecosystem processes in western North America.', in G.A. Bradshaw, H.A. Mooney and P. Alaback, P. (eds.), *Disruptions and variability in ecosystem processes and patterns*, New York, Springer-Verlag, (in press).

Dye, P.: 1996, 'Climate, forest and streamflow relationships in South African afforested catchments', *Commonwealth Forestry Review* **75**, 31–38.

Eckert, J.B., Liebenberg, G.F. and Troskie, D.P.: 1997, *The Macroeconomics of Western Cape Agriculture: Analysis With A Social Accounting Matrix*, Department of Agriculture of the Western Cape, Cape Town.

Euston-Brown, D.: 2000, '*The influence of vegetation type and fire severity on catchment stability after fire: a case study from the Cape Peninsula, South Africa*', Working for Water Programme, Department of Water Affairs and Forestry, Cape Town.

Fraser, M.W.: 1990, 'Foods of Redwinged Starlings and the potential for avian dispersal of *Acacia cyclops* at the Cape of Good Hope Nature Reserve', *South African Journal of Ecology* **1**, 73–76.

Geldenhuys, C.J., le Roux, P.J. and Cooper, K.H.: 1986, 'Alien invasions in indigenous evergreen forest'. in I.A.W. Macdonald, F.J. Kruger and A.A.Ferrar (eds.), *The ecology and management of biological invasions in southern Africa*, Cape Town, Oxford University Press, pp. 119–131.

Hall, A.V.: 1987, 'Threatened plants in the fynbos and karoo biomes', *Biological Conservation* **40**, 29–52.

Harding, G.B. and Bate, G.C.: 1991, 'The occurrence of invasive *Prosopis* species in the north-western Cape, South Africa', *South African Journal of Science* **87**, 188–192.

Henderson L.: 1991, 'Alien invasive *Salix* spp. (willows) in the Grassland Biome of South Africa', *South African Forestry Journal* **157**, 91–95.

Henderson, L.: 1998, 'South African plant invaders atlas (SAPIA)', *Applied Plant Sciences* **12**, 31.

Henderson, L.: 1999, 'The southern African Plant Invaders Atlas (SAPIA) and its contribution to biological weed control', *African Entomology Memoir* **1**, 159–163.

Heydenrych, B.: 1999, '*An investigation of land-use practices on the Agulhas Plain (South Africa), with emphasis on socio-economic and conservation issues*', M.Sc. dissertation, University of Cape Town.

Higgins, S.I., Azorin, E.J., Cowling, R.M. and Morris, M.J.: 1997a, 'A dynamic ecological-economic model as a tool for conflict resolution in an invasive alien, biological control and native-plant scenario', *Ecological Economics* **22**, 141–154.

Higgins, S.I., Turpie, J.K., Costanza, R., Cowling, R.M., Le Maitre, D.C., Marais, C. and Midgley, G.F.: 1997b, 'An ecological economic simulation model of mountain fynbos ecosystems: Dynamics, valuation and management', *Ecological Economics* **22**, 155–169.

Higgins, S.I., Richardson, D.M., Cowling, R.M. and Trinder-Smith, T.H.: 1999, 'Predicting the landscape-scale distribution of alien plants and their threat to plant diversity', *Conservation Biology* **13**, 303–313.

Hill, M.P. and Cilliers, C.J.: 1999, 'A review of the arthropod natural enemies, and factors that influence their efficacy, in the biological control of water hyacinth, *Eichhornia crassipes* (Mart.) Solms-Laubach (Ponterderiaceae), in South Africa', *African Entomology Memoir* **1**, 103–112.

Hoffmann, J.H. and Moran, C.M.: 1988, 'The invasive weed, *Sesbania punicea* in South Africa and prospects for its biological control', *South African Journal of Science* **84**, 740–742.

Hoffman, M.T., Todd, S., Ntshona, Z. and Turner, S.: 1999, *Land degradation in South Africa*, National Botanical Institute, Kirstenbosch, South Africa.

Holmes, P.M. and Cowling, R.M.: 1997a, 'The effects of invasion by *Acacia saligna* on the guild structure and regeneration capabilities of South African fynbos shrublands', *Journal of Applied Ecology* **34**, 317–332.

Holmes, P.M. and Cowling, R.M.: 1997b, 'Diversity, composition and guild structure relationships between soil-stored seed banks and mature vegetation in alien plant-invaded South African fynbos shrublands', *Plant Ecology* **133**, 107–122.

Hosking, S.G. and Du Preez, M.: 1999, 'A cost-benefit analysis of removing alien trees in the Tsitsikamma mountain catchment', *South African Journal of Science* **95**, 442–448.

Johannesmeier, M.F.: 1985, *Beeplants of the South-Western Cape*. Department of Agriculture, Pretoria, 59 pp.

Johns, M.: 1993, 'Are all trees green? The spotlight on forestry', *Africa Environment and Wildlife* **1**(3), 77–85.

Kaiser, J.: 1999, 'Stemming the tide of invasive species', *Science* **285**, 1836–1841.

Knight, R.S. and Macdonald, I.A.W.: 1991, 'Acacias and korhaans: an artificially assembled seed dispersal system', *South African Journal of Botany* **57**, 220–225.

Kruger, F.J., Reid, P., Mayet, M., Alberts, W., Goldammer, G.J. and Tolhurst, K.: 2000, *A review of the veld fires in the Western Cape during 15 to 25 January 2000,* Department of Water Affairs and Forestry, Pretoria.

Le Maitre, D.C., Versfeld, D.B. and Chapman, R.A.: 2000, 'The impact of invading alien plants on surface water resources in South Africa: A preliminary assessment', *Water SA* **26**, 397–408.

Le Maitre, D.C., van Wilgen, B.W., Chapman, R.A. and McKelly, D.H.: 1996, 'Invasive plants and water resources in the western Cape Province, South Africa: modelling the consequences of a lack of management', *Journal of Applied Ecology* **33**, 161–172.

Le Maitre, D.C., van Wilgen, B.W., Gelderblom, C.M., Bailey, C., Chapman, R.A. and Nel, J.: 'Invasive alien trees and water resources in South Africa: Case studies of the costs and benefits of management', *Forest Ecology and Management*, (in press).

Low, A.B. and Rebelo, A.G.: 1996, *Vegetation of South Africa, Lesotho and Swaziland*. Department of Environmental Affairs and Tourism, Pretoria.

Macdonald, I.A.W.: 1983, 'Alien trees, shrubs and creepers invading indigenous vegetation in the Hluhluwe-Umfolozi Game Reserve Complex in Natal', *Bothalia* **14**, 949–959.

Macdonald, I.A.W.: 1986, 'Range expansion in the Pied Barbet and the spread of alien tree species in southern Africa', *Ostrich* **57**, 75–94.

Macdonald, I.A.W., Kruger, F.J. and Ferrar, A.A.: 1986, *The ecology and management of biological invasions in southern Africa*, Cape Town, Oxford University Press.

Marais, C.: 1998, *An economic evaluation of invasive alien plant control programmes in the mountain catchment areas of the Western Cape Province, South Africa,* Ph.D. dissertation, University of Stellenbosch.

Milton, S.J.: 1981, 'Litterfall of the exotic Acacias in the South Western Cape', *Journal of South African Botany* **47**, 147–155.

Milton, S.J., and Siefried, W.R.: 1981, 'Above-ground biomass of Australian Acacias in the Southern Cape, South Africa', *Journal of South African Botany* **47**, 701–716.

Milton, S.J., Zimmermann, H.G. and Hoffmann, J.H.: 1999, 'Alien plant invaders of the karoo: attributes, impacts and control, in W.R.J. Dean and S.J. Milton (eds.), *The karoo – Ecological patterns and process*, Cambridge, Cambridge University Press, pp. 274–287.

Musil, C.F.: 1993, 'Effect of invasive Australian acacias on the regeneration, growth and nutrient chemistry of South African lowland fynbos', *Journal of Applied Ecology* **30**, 361–372.

Musil, C.F. and Midgley, G.F.: 1990, 'The relative impact of invasive Australian acacias, fire and season on the soil chemical status of a sand plain lowland fynbos community', *South African Journal of Botany* **56**, 419–427.

Oatley, T.B.: 1984, 'Exploitation of a new niche by the Rameron Pigeon *Columba arquatrix* in Natal', *Proceedings of the Fifth Pan-African Ornithological Congress*, Johannesburg, Southern African Ornithological Society, pp. 323–330.

Olckers, T. and Hill, M.P.: 1999, 'Biological control of weeds in South Africa (1990–1998)', *African Entomology, Memoir No. 1.*

Parker, I.M., Simberloff, D., Lonsdale, W.M., Goodell, K., Wonham, M., Kareiva, P.M., Williamson, M.H., Von Holle, B., Moyle, P.B., Byers, J.E. and Goldwasser, L.: 1999, 'Impact: toward a framework for understanding the ecological effect of invaders', *Biological Invasions* **1**, 3–19.

Pieterse, P.J. and Boucher, C.: 1997, 'A.C.A.C.I.A. (A Case Against Controlling Introduced Acacias) – 19 years later', *South African Forestry Journal* **180**, 37–44.

Prinsloo, F.W. and Scott, D.F.: 1999, 'Streamflow responses to the clearing of alien trees from riparian zones at three sites in the Western Cape', *South African Forestry Journal* **185**, 1–7.

Richardson, D.M.: 1998, 'Forestry trees as invasive aliens', *Conservation Biology* **12**, 18–26.

Richardson, D.M. and Van Wilgen, B.W.: 1986, 'The effects of fire in felled *Hakea sericea* and natural fynbos and implications for weed control in mountain catchments', *South African Forestry Journal* **139**, 4–14.

Richardson, D.M., Macdonald, I.A.W., Holmes, P.M. and Cowling, R.M.: 1992, 'Plant and animal invasions', in R.M. Cowling (ed.), *The ecology of fynbos*, Cape Town, Oxford University Press, pp. 271–308.

Richardson, D.M., Macdonald, I.A.W., Hoffmann, J.H. and Henderson, L.: 1997, 'Alien plant invasions', in R.M Cowling, D.M. Richardson, and S.M. Pierce (eds.), *Vegetation of Southern Africa*, Cambridge, Cambridge University Press, pp. 534–570.

Richardson, D.M., Cambray, J.A., Chapman, R.A., Dean, W.R.J., Griffiths, C.L., Le Maitre, D.C., Newton, D.J. and Winstanley, T.: 'Vectors and pathways of biological invasions in South Africa – Past, future and present', in G. Ruiz and J. Carlton (eds.), *Pathways of invasions: strategies for management across space and time*, Washington, D.C., Island Press, (in press).

Samways, M.J., Caldwell, P.M. and Osborn, R.: 1996, 'Ground-living invertebrate assemblages in native, planted and invasive vegetation in South Africa', *Agriculture, Ecosystems and Environment* **59**, 19–32.

Scott, D.F.: 1999, *Report on an inspection of the burn site between Fish Hoek and Glencairn, Monday 10 May, 1999*, Ad hoc report prepared for Gibb Africa, Cape Town.

Scott, D.F., Prinsloo, F.W., and Le Maitre, D.C.: 2000, *The role of invasive alien vegetation in the Cape Peninsula fires of January 2000*, Report ENV-S-C 2000-039, Division of Water, Environment and Forestry Technology, CSIR, Stellenbosch.

Seydack A.H.W.: 1992, 'Fire management options in fynbos mountain catchment areas', *South African Forestry Journal* **161**, 53–58.

Steenkamp, H.E. and Chown, S.L.: 1996, 'Influence of dense stands of an exotic tree, *Prosopis glandulosa*, Benson, on a savanna dung beetle (Coleoptera: Scarabaeinae) assemblage in southern Africa', *Biological Conservation* **78**, 305–311.

Stirton, C.M.: 1978, 'Plant invaders, beautiful but dangerous', Cape Provincial Administration, Cape Town.

Stirton, C.H.: 1981, 'Notes on the taxonomy of Rubus in southern Africa'. *Bothalia* **13**, 331–332.

Stock, W.D. and Allsopp, N.: 1992, 'Functional perspectives of ecosystems', in R.M. Cowling (ed.), *The ecology of fynbos; Nutrients, Fire and Diversity*. Cape Town, Oxford University Press, pp. 241–259.

Stubbings, J.A.: 1977, 'A case against controlling introduced Acacias (A.C.A.C.I.A.)', *South African Forestry Journal* **102**, 8–14.

Turpie, J. and Heydenrych, B.: 2000, 'Economic consequences of alien infestation of the Cape Floral Kingdom's Fynbos vegetation', in C. Perrins, M. Williamson and S. Dalmazzone (eds.), *The economics of biological invasions*, Cheltenham, Edward Elgar, pp. 152–182.

Van Wilgen, B.W. and Richardson, D.M.: 1985, 'The effects of alien shrub invasions on vegetation structure and fire behaviour in South African fynbos shrublands: A simulation study', *Journal of Applied Ecology* **22**, 955–966.

Van Wilgen, B.W., Bond, W.J. and Richardson, D.M.: 1992, 'Ecosystem Management' in R.M. Cowling, (ed.), *The Ecology of Fynbos; Nutrients, Fire and Diversity*. Cape Town, Oxford University Press, pp. 345–371.

Van Wilgen, B.W., Cowling, R.M. and Burgers, C.J.: 1996, 'Valuation of ecosystem services – A case study from South African fynbos ecosystems', *Bioscience* **46**, 184–189.

Van Wilgen, B.W., Little, P.R., Chapman, R.A., Gorgens, A.H.M., Willems, T. and Marais, C.: 1997, 'The sustainable development of water resources: History, financial costs, and benefits of alien plant control programmes', *South African Journal of Science* **93**, 404–411.

Van Wilgen, B.W., Le Maitre, D.C. and Cowling, R.M.: 1998, 'Ecosystem services, efficiency, sustainability and equity: South Africa's Working for Water Programme', *Trends in Ecology and Evolution* **13**, 378.

Van Wilgen, B.W. and van Wyk, E.: 1999, 'Invading alien plants in South Africa: Impacts and solutions', in D. Eldridge and D. Freudenberger (eds.), *People and rangelands: Building the future*, Proceedings of the VI International Rangeland Congress, Townsville, Australia, pp. 566–571.

Van Wilgen, B.W., van der Heyden, F., Zimmermann, H.G., Magadlela, D. and Willems, T.: 2000, 'Big returns from small organisms: developing a strategy for the biological control of invasive alien plants in South Africa', *South African Journal of Science* **96**, 148–152.

Versfeld, D.B., Le Maitre, D.C. and Chapman, R.A.: 1998, *Alien Invading Plants and Water Resources in South Africa: A preliminary assessment*, Report TT99/98, Water Research Commission, Pretoria.

Yelenik, S.: 2000, *Ecosystem-level feedbacks of N-fixing invasive aliens in lowland fynbos*, M.Sc. dissertation, University of Cape Town.

Whiteford, A. and Mcgrath, M.: 1994, *Distribution Of Income In South Africa*, Human Sciences Research Council, Pretoria.

Witkowski, E.T.F.: 1991, 'Effects of invasive alien Acacias on nutrient cycling in the coastal lowlands of the Cape Fynbos', *Journal of Applied Ecology* **28**, 1–15.