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An ecological economic simulation model of mountain fynbos ecosystems
Dynamics, valuation and management

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Abstract

Mountain fynbos ecosystems in South Africa are threatened by alien plant invasions and by a lack of funding for effective management of these invasions. This paper develops an ecological-economic argument for the effective management of plant invasions in mountain fynbos ecosystems. We do this by building a dynamic ecological economic model which values the ecosystem services that fynbos ecosystems provide under different management regimes. We propose that the services that mountain fynbos ecosystems provide fall into six components: water production, wildflower harvest, hiker visitation, ecotourist visitation, endemic species and genetic storage. A scenario analysis based on a hypothetical 4 km^2 mountain fynbos ecosystem in the western part of the fynbos biome estimated that the ecosystem's value varies from R19 million (under low valuation and poor management scenario) to R300 million (under high valuation and good management scenario) [R4.50 = US$1]. Water production and genetic storage were the most valuable ecosystem services. The model showed that the cost of clearing alien plants (under the proactive management scenario) was a tiny (0.6–5%) proportion of the value of mountain fynbos ecosystems. This result motivates an injection of funds for clearing alien plants from mountain fynbos ecosystems. © 1997 Elsevier Science B.V.

Keywords: Valuation; Ecosystem services; Mountain catchments; Fynbos; Alien plant invasion

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1. Introduction

Westman (1977) recognized the need for the economic valuation of the services that natural ecosystems provide as a means of articulating the value of ecosystems to both decision makers and the public. Despite Westman's call and a growing need for the articulation of the value of ecosystem services, few studies have attempted ecosystem valuation. This may, in part, be due to some ecologists' philosophical objections to ecosystem valuation (Pearce and Turner, 1990), the lack of appropriate theoretical and technical tools for the task (Costanza et al., 1993; Suter, 1995), and the lack of effective trans-disciplinary collaboration (Russel, 1995). Those who have attempted ecosystem valuation have typically adopted a static approach (e.g. Costanza et al., 1989; but see Krysanova and Kaganovich, 1994). However, there is a growing recognition that the effective articulation of ecosystem value will require a dynamic approach that combines, in integrative models, both ecological and economic processes (e.g. Costanza et al., 1991; Bockstael et al., 1995).

The fynbos ecosystems of southwestern South Africa are recognized as a global center of floral diversity (Cowling, 1992). At present these systems are inadequately managed for conserving biodiversity and sustaining ecosystem services. The reason for this poor management is not a lack of ecological or management knowledge, but a lack of funding in the face of increasing management challenges. The allocation of insufficient funds for management stems from the perception by policy makers that fynbos ecosystems provide few economic benefits to society.

The primary management challenge in fynbos is the control of invasive alien plants. This situation has motivated fynbos scientists to begin to articulate the ecological (Le Maitre et al., 1996) and economic (van Wilgen et al., 1996) consequences of poor alien plant management in mountain fynbos ecosystems. However these studies have not integrated ecological and economic processes into a dynamic model and have taken a narrow view of the ecosystem services provided by mountain fynbos ecosystems. The broad objective of this paper is to develop a dynamic, integrated, ecological-economic model of mountain fynbos. We will use this model to explore the value of ecosystem services that mountain fynbos ecosystems produce under different management regimes. In particular we ask:

1. What type and quantity of ecosystem services do mountain fynbos ecosystems provide?
2. What are the values of these ecosystem services?
3. How does the invasion of alien plants and management strategies influence the flow of ecosystem services from mountain fynbos ecosystems and consequently the value of mountain fynbos ecosystems?

2. Ecology and economics of mountain fynbos

Mountain fynbos ecosystems are home to a major part of the Cape flora, one of the six plant kingdoms of the world. The Cape flora consists of 8574 species crammed into a mere 90 000 km^2. There are 989 genera of plants, of which 19.5% are endemic; 5847 (68.2% of the total) species are endemic (Bond and Goldblatt, 1984; Cowling et al., 1992). Local endemism is extremely pronounced, especially in the southwestern part of the region (Cowling and Holmes, 1992; McDonald and Cowling, 1995; Trinder-Smith et al., 1996), making this region an unparalleled center of endemic plant diversity (Myers, 1990). Although florally spectacular, the mammalian diversity of fynbos is unimpressive (Bigalke, 1979; Johnson, 1992).

The Cape flora occurs in a mediterranean climate area that is characterized by cool wet winters and warm dry summers. Fynbos is a fire-prone vegetation type, and regular fires are considered necessary for the maintenance of diversity (van Wilgen et al., 1992). Prescribed burns are conducted at intervals of around 12–15 years in the late summer to early autumn period in order to rejuvenate the vegetation.

The value of mountain fynbos ecosystems can be classified in a number of ways. We choose six categories: water production, wildflower harvest, hiker visitation, ecotourist visitation, endemic species and genetic storage. Water production is the major indirect use value of mountain fynbos. As fynbos has a lower biomass than would be predicted by its bio-climate (Richardson and Cowling, 1992), mountain fynbos ecosystems are highly productive in terms of their water yield per unit area (Boucher and Marais, 1995). This water yield is of particular relevance in the Western Cape, where the rapid population expansion of the metropolis of Cape Town (Richardson et al., 1996) threatens to create a regional water crisis within the foreseeable future (Preston et al., 1995). The harvesting of wildflowers is a lucrative consumptive use of fynbos (Greyling and Davis, 1989; Coetzee and Littlejohn, 1994; Higgins et al., 1997). Recreational use of mountain fynbos is presently confined to hiker visitation and limited but growing ecotourist visitation. The exceptional species richness of fynbos means that the option value of fynbos ecosystems is high: fynbos has already provided the source of many cultivated species and varieties for the cut flower, floriculture and herbal industries, and the future economic potential of its genetic variety is far from fully explored (Cowling and Richardson, 1995). The establishment of a fynbos gene bank (Littlejohn, 1995) is indicative of this option value. We divide this option value into endemic species value and genetic storage value to distinguish between the value of species (combinations of genetic material) and the value of populations (genetic material).

Although the value of mountain fynbos ecosystems is not presently well articulated, it is increasingly recognized that poor management, particularly poor alien plant management, is leading to a decrease in the value of mountain fynbos ecosystems (Boucher and Marais, 1995; van Wilgen et al., 1996). The most important invaders of montane areas are serotinous (canopy seed storage) plants such as *Pinus pinaster*, *Pinus radiata* and *Hakea sericea* that are killed by fire and release their seeds on the death of the parent plant (Richardson et al., 1992). Populations of these fire-adapted plants substantially expand their coverage after each fire (see Le Maitre et al., 1996; Higgins et al., 1996). The weeds are competitively superior to the native vegetation, hence the risk of local extinction of many fynbos species is increased by the invasion process (Richardson et al., 1989; Musil, 1993; Richardson et al., 1996). Plant invasions are also likely to reduce the productivity of the wildflower industry and the value of hiking and ecotourism. In addition, a stand of alien plants has a biomass of between 50 and 1000% greater than a stand of native plants (Versveld and Wilgen, 1986). As a result, it is estimated that water production from invaded systems is reduced between 30 and 100%, depending on the nature of the alien invasion and the system's characteristics (Burgers et al., 1995; Le Maitre et al., 1996). Despite the fact that effective techniques for alien plant control exist, invasions in mountain fynbos ecosystems is widespread. Alien control programs are limited by the narrow perception of the value of fynbos mountain ecosystems and the need to allocate government funding to social upliftment programs.

3. Model description

A dynamic simulation model was built with the aim of integrating our ecological and economic knowledge of fynbos ecosystems. The model was developed in STELLA (High Performance Systems, 1993), a high-level programming language, which facilitated the interactive and collaborative development of the model. Using STELLA also allowed the rapid development of a friendly and interactive user-interface, which will allow managers and policy makers to experiment with the model. In order to facilitate the integration of information from different study sites into a single model and to make the model generic, we modelled a hypothetical fynbos ecosystem. The model has a spatially aggregated structure and therefore assumes a homogenous study site. A monthly time step was selected in order to simulate the seasonal dynamics of the system.

The model comprises five interactive sub-models, namely hydrological, fire, plant, management and economic valuation (Fig. 1). The plant sub-model determines the area of alien and native plants, and traces the current vegetation age. The area of native plants is used to calculate the number of native species, the number of endemic species and with vegetation age, harvestable

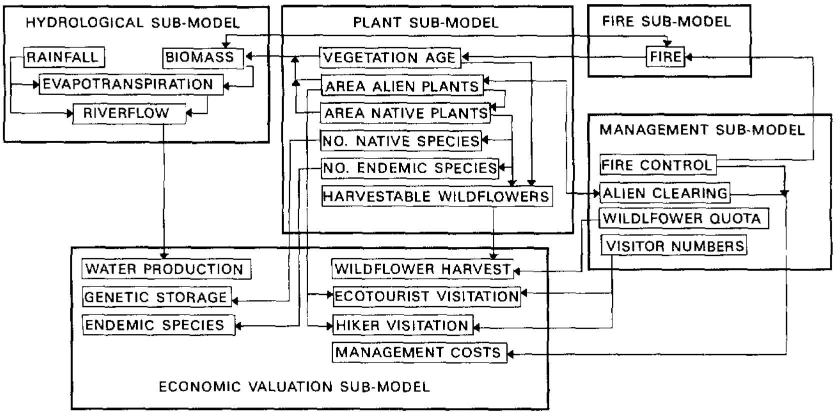

Fig. 1. Conceptual diagram of the fynbos model.

wildflowers. Vegetation age and the areas of native and alien plants are used to calculate the above-ground biomass for the hydrological model. Plant biomass is used to estimate the probability of fire occurrence. Fire occurrence in turn reduces plant biomass. Rainfall and above-ground biomass determine the evapotranspiration which with rainfall determines the river flow. Management is able to manipulate the fire regimes, remove alien plants and control visitor numbers and wildflower harvesting. The extent of alien plants, however, influences management response to alien plant clearing, the visitation rates and the extent of native plants. The economic valuation sub-model calculates the value of the wildflower harvest, ecotourist visitation, hiker visitation, water production, genetic storage, endemic plant species as well as the management costs. Each of the sub-models is discussed in more detail below. Parameter names, units, symbols and estimates are listed in Appendix A.

3.1. Hydrological sub-model

The hydrological model simulates the movement of water through a simple precipitation, interception, run-off, infiltration, evapotranspiration and ground water base-flow cycle. Potential evapotranspiration losses (E_t, mm/month) were estimated using an empirical relationship between plant biomass and evapotranspiration (Le Maitre et al., 1996), such that:

$$E_t = 10^{(0.1\log_{10}(1+B'_n)+2.119}\frac{E_p}{1948.6} + 10^{(0.2335\log_{10}(1+B'_a)+2.119}\frac{E_p}{1948.6} \qquad (1)$$

where E_p is pan evaporation (mm/month, Versveld et al., 1992), B'_n and B'_a are relative native and alien biomass (g) as estimated by the plant sub-model (described below). This relationship accounts for seasonal patterns of canopy interception and evapotranspiration of native biomass relative to alien biomass. The difference between precipitation (P) and evapotranspiration (E_t) determines surface run-off ($R = P - E_t$). Inter-annual differences in rainfall were not investigated (Le Maitre et al., 1996). An empirically-derived infiltration constant (I_f, Scott and van Wyk, 1992) determines the proportion of surface run-off which moves into the ground water reservoir (G_i). The remainder of the surface run-off enters river flow (F_r, m^3/month). A proportion of ground water is lost to evapotranspiration (E_g), and another proportion, the groundwater base flow (F_g), enters the river flow (F_r).

River flow data from a mountain fynbos ecosystem (Scott and van Wyk, 1992) was used to calibrate the model. The calibration procedure involved adjusting the parameters E_g and F_g. The calibrated model's river flow and the observed river flow are illustrated in Fig. 2.

3.2. Fire sub-model

Two types of fires can occur in the system, managed fires and wildfires. Once ignition occurs, both these fire types burn the entire area (Kruger and Bigalke, 1984). If the model is run with fire management ($MF? = 1$), fires occur at a frequency determined by the managed fire frequency (MF_f). If fire management is turned off ($MF? = 0$), then the wildfire rules determine fire frequency. The probability of wildfire occurrence in fynbos is primarily a function of biomass accumulation rates and weather (van Wilgen and van Hensbergen, 1992; Richardson et al., 1994). Empirical data on the relationship between biomass and fire frequency (van Wilgen and van Hensbergen, 1992) allowed the construction of a simple fire probability model,

$$\begin{aligned} p &= -0.00214 - 1.42 \times 10^{-}5B_t \\ &= 6.24 \times 10^{-8}B_t^2 - 8.60 \times 10^{-12}B_t^3 + 3.42 \\ &\quad \times 10^{-16}B_t^4 \end{aligned} \tag{2}$$

where p is the probability of a fire and B_t is total plant biomass (g/m²). To incorporate the seasonal pattern of wildfire occurrence we constrained wildfire occurrence to low rainfall ($P < 50$ mm) months. In summary, the wildfire rule allows a fire if rainfall is < 50mm and if the product of a uniformly distributed random number and the probability of a fire (p) is greater than a fire threshold constant (F_t).

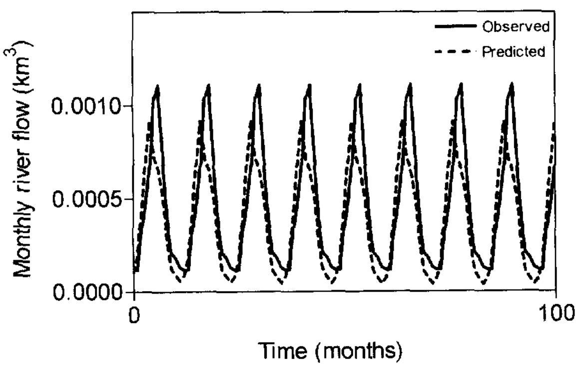

Fig. 2. Predicted and observed river flow from a 4 km² fynbos mountain ecosystem.

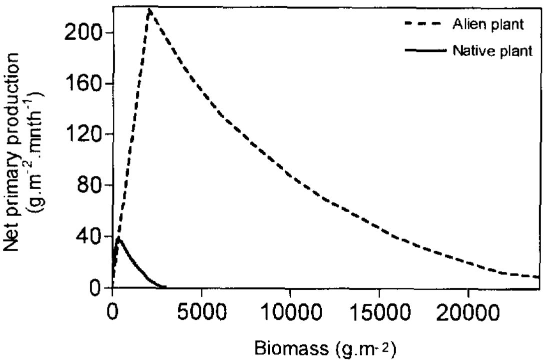

Fig. 3. Net primary production-biomass relationship for alien and native plants.

3.3. Plant sub-model

Two groups of plants are considered by the model, alien plants and native plants. The spread of alien plants in fynbos systems is driven by fire events (Richardson et al., 1992): this is simulated in the model by preventing alien plant spread between fires. The invasion rate (I_r) determines the increase in areal extent of alien plants ($I_r^* A_a$, where A_a is the area of alien plants) that occurs during each fire. This ignores the details of the invasion process (Higgins and Richardson, 1996; Higgins et al., 1996). The area to be cleared of aliens (management parameter A_c) determines the decrease in the areal extent of alien plants. Empirical data (Rutherford et al., 1986) were used to estimate a biomass (B_a)-net primary production (NPP_a) relationship (Fig. 3). This relationship was used to calculate the monthly increase in alien biomass, and fire was assumed to reduce alien biomass by 85% (Richardson, 1988).

Native plants are competitively inferior to alien plants (Witkowski, 1991; Musil, 1993; Holmes and Cowling, 1997). Consequently, the area occupied by native plants (A_n) was assumed to be the difference between the total area of the landscape (A) and alien area (A_a). Empirical data (Kruger, 1977) were used to estimate a biomass (B_n)-net primary production (NPP_n) relationship (Fig. 3) for native plants. This relationship was used to calculate the monthly native biomass increment, and fire was assumed to reduce native biomass by

99% (Kruger and Bigalke, 1984; Le Maitre and Midgley, 1992).

To model native plant species extinction events that would accompany alien invasion of a landscape (Musil, 1993), we constructed a regression model based on empirical data (Cowling et al., 1992; McDonald and Cowling, 1995; Trinder-Smith et al., 1996) which predicts number of endemic species (N_e) as a function of area (a, km^2),

$$N_e = \frac{153.6a}{414.5 + a} \tag{3}$$

In the model we substitute A_n for a, thereby assuming that as the area invaded increases, the endemic species pool will decrease. This assumption is based on the observation of reduced native plant diversity (Richardson et al., 1989) and increased chances of native plant extinction (Musil, 1993) under stands of alien plants. A plant species-area regression for the western fynbos biome, where our mountain fynbos ecosystem is located, (Cowling and Holmes, 1992) was used to estimate the total number of indigenous plants that could go extinct as the invasion process proceeds;

$$N_s = \frac{1676.2a}{10.42 + a} \tag{4}$$

where a is area (km^2) and N_s is number of native plant species. The native plant extinction process is modelled in the same way as endemic plant species extinction (described above). Modelling extinctions in this way ignores the resilience of some fynbos species to extinction and the sensitivity of others to extinction (Musil, 1993; Holmes and Cowling, 1997).

Native plants can be harvested for an existing wildflower market (Greyling and Davis, 1989; Coetzee and Littlejohn, 1994; Higgins et al., 1997). Since productivity, particularly of reproductive material, of fynbos decreases as biomass accumulates (Le Maitre, 1992) we estimated the potential wildflower harvest as,

$$H_h = -0.00640 - 5.64 \times 10^{-5} B_n + 5.84 \times 10^{-7} B_n^2 - 1.62 \times 10^{-10} B_n^3 \tag{5}$$

where H_h is the potential wildflower harvest (m^2/month) and B_n is native plant biomass (g/m^2). This relationship ignores details of the spatial and temporal variation in wildflower productivity.

3.4. Management sub-model

A number of options are available for the management of mountain fynbos ecosystems, namely fire control, alien plant clearance, wildflower harvesting, and controlling the access of hikers and ecotourists. The management sub-model allows the definition of the fire management strategy (through parameters $MF?$ and MF_f) and the area of aliens to be cleared (parameter A_c): the mechanics of these management options are described above in the fire and plant sub-models. The proportion of native plants available for wildflower harvesters can be defined by the manager (parameter H_p). The manager also defines the potential visitation rate (PV) of ecotourists and hikers. It is envisaged that ecotourist potential visitation rates (PV_t) would be lower than hiker visitation rates (PV_h); potential visitation rates were estimated from a typical hiking trail located in mountain fynbos (Ms A. Eager, Cape Nature Conservation, personal communication). The realized visitation rates (RV) would be a function of alien plant density, with hiker visitation rates (RV_h) being less sensitive than ecotourist visitation rates (RV_t) to alien plant density (Fig. 4). Hence we assume that ecotourists are primarily

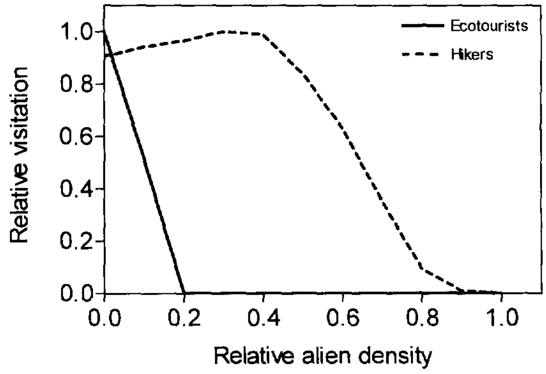

Fig. 4. Hypothesized relationship between hiker and ecotourist visitation rates and alien plant cover.

interested in pristine ecosystems and would avoid lightly invaded systems and conversely that hikers are not motivated by pristine systems but would shun densely invaded areas.

3.5. Economic valuation sub-model

The economic sub-model calculates the benefits of the mountain fynbos ecosystems as well as the costs associated with different management scenarios. Benefits are derived from consumptive use (wildflower harvest), non-consumptive use (hiker and ecotourist visitation), indirect use (water production), and future use or option value (endemic plants and genetic storage). The existence value of the ecosystem is not included in the model. Costs include direct and indirect management costs. The values are calculated as follows, using variable unit values which are quantified in the scenario analysis section.

The monthly value of wildflowers (V_f) is the product of the area of native plants, the potential harvest, the proportion of total ecosystem available to harvesters and the unit value of flowers ($A_n^*H_h^*H_p^*UV_f$). The monthly value of hikers (V_h) and ecotourists (V_t) is $A^*RV_h^*UV_h$ and $A^*RV_t^*UV_t$, respectively, where A is the ecosystem area, the RV terms are realized visitation rate per unit area and the UV terms are the unit values. The monthly value of water (V_w) is $UV_w^*F_r$, where F_r is river flow as determined by the hydrological sub-model and UV_w is the unit value of water. The value of plant species endemic to the mountain fynbos ecosystem (V_e) is $UV_e^*N_e$, where UV_e is the unit value of an endemic species and N_e is the number of endemic species. The monthly value of the genetic storage service (V_s) provided by mountain fynbos ecosystems is $UV_s^*N_s$.

Management costs are divided into capital infrastructure maintenance costs (MC_c), alien clearing costs (MC_a), wildflower harvesting costs (MC_{fh}) and fire management costs. If fire management is selected, the fire management costs are A^*MC_f plus the cost of extinguishing the fire (MC_{wf}). If there is no fire management, the cost of fire management is only the cost of extinguishing a wildfire (MC_{wf}). The records of the regional conservation authority (Cape Nature Conservation; Anon., 1992) were used to estimate MC_c, MC_f and MC_{wf}, while MC_a was estimated from Burgers et al. (1995). The cost of flower harvesting (MC_{fh}) was based on the generalization that harvesting costs amount to 40% of the gross wildflower harvest income (Mr R. Middleman, South African Protea Producers and Exporters Association, personal communication).

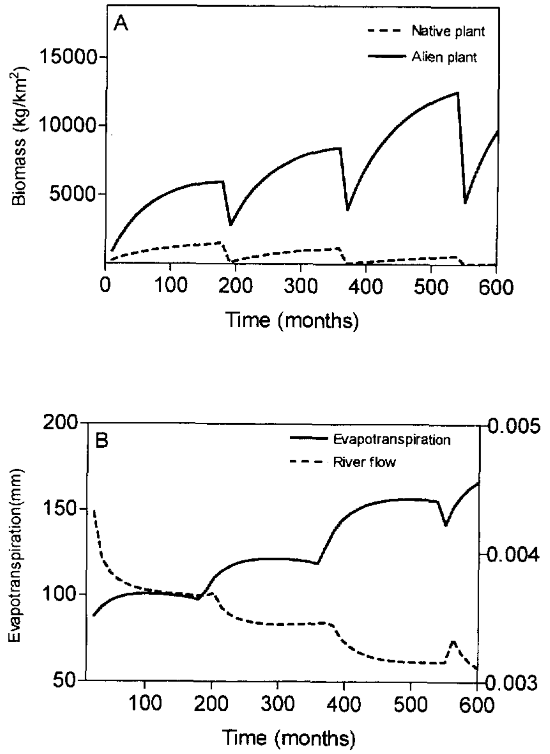

Fig. 5. Changes in (A) alien and native plant biomass and in (B) evapotranspiration and river flow over time (including four fire cycles) for an invaded mountain fynbos ecosystem.

The static (one-off values of endemic plant species) and dynamic values (costs and benefits cumulated on a monthly basis) are combined to form the total value of the mountain fynbos ecosystem over the 50-year period. In order to calculate the net present value of the mountain fynbos ecosystem, static values are taken at the end of the 50-year period, while costs and benefits were discounted at a rate of 3%.

Table 1
Model scenarios defined by management and economic factors

Factor[a]	Scenario combination					
	M1,E1[b]	M2,E1	M3,E1	M1,E2	M2,E2	M3,E2
A_a	2	2	0	2	2	0
A_c	0.003	0.01	0	0.003	0.01	0
UV_s	200	200	200	20 000	20 000	20 000
UV_e	100 000	100 000	100 000	1 000 000	1 000 000	100 000
UV_w	0.15	0.15	0.15	0.45	0.45	0.45
UV_f	1984	1984	1984	41666	41666	41666
UV_h	12.5	12.5	12.5	25	25	25
UV_t	80	80	80	1000	1000	1000

[a] Names and units of symbols are in the text and in Appendix 1.

[b] M1 = present management (invaded, inadequate clearing); M2 = proactive management (invaded, intense clearing); M3 = pristine management (uninvaded, no clearing required); E1 = low economic valuation; E2 = high economic valuation.

3.6. Model behavior

Here we illustrate the model's behavior by initiating a simulation run with 50% of the mountain fynbos ecosystem invaded and run the simulation for 50 years. Both alien and native biomass increase between fires and are reduced by fires, but alien biomass accumulates at a faster rate (Fig. 5a). Since the real extent of alien plants increases after each fire, the alien biomass shows a steady increase over the simulation period. As the native plants are competitively inferior to alien plants, the expansion of alien plants leads to a decrease in native plant biomass after each fire. The increase in total biomass through the invasion process leads to higher plant transpiration and hence higher evapotranspiration: increases in evapotranspiration rates result in a corresponding decrease in river flow (Fig. 5b).

4. Scenario analysis

4.1. Scenario definition

Scenario analyses are used to articulate the ecosystem services and the value of these services that flow from mountain fynbos ecosystems. We do this for three management scenarios and for two levels of economic valuation, providing six scenarios in total (Table 1). The three management scenarios are pristine (uninvaded), poor (invaded and no alien clearing) and proactive (invaded and alien clearing); the two valuation levels (low and high valuation) allow the quantification of the observed variation in values and the uncertainty of estimating values. The objective of these scenarios is therefore to investigate whether expenditure on clearing alien plants (proactive management) is justified in terms of an increased flow of ecosystem services and hence ecosystem value.

All management strategies assume that fire management is implemented ($MF? = 1$), that ecotourist ($PV_t = 1$) and hiker ($PV_h = 2.8$) visitation occurs and that 50% of the ecosystem is available for wildflower harvesting. The first management scenario (present management: M1, Table 1) simulates present state of mountain fynbos ecosystems: invaded by alien plants and an inadequate alien clearing strategy. The second management scenario (proactive management: M2, Table 1) examines the consequences of a proactive management strategy that is capable of clearing alien plants faster than they spread. The third management scenario (pristine: M3, Table 1) investigates an uninvaded mountain fynbos ecosystem. This third scenario provides an estimate of the ecosystem services that flow from pristine mountain fynbos ecosystems which are uninvaded by alien plants.

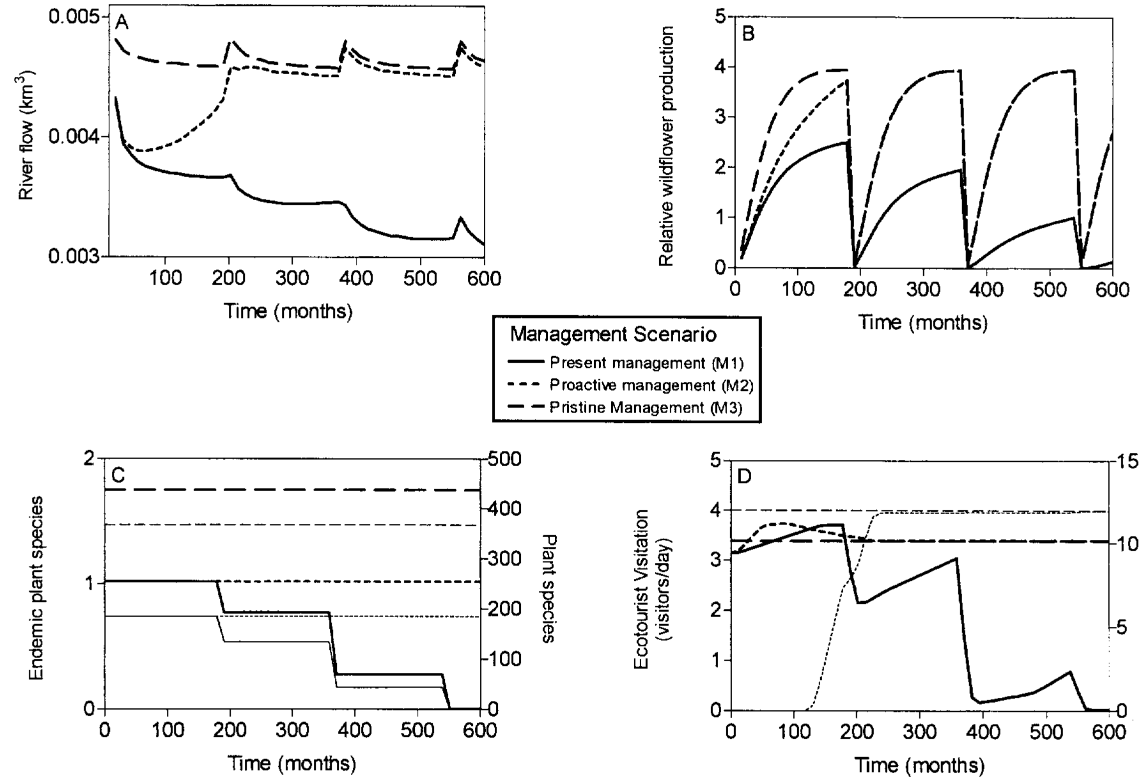

Fig. 6. Changes in (A) river flow and (B) relative wildflower production, (C) endemic plant species (thin lines) and native plant species (thick lines), (D) Ecotourist visitation (thin lines) and hiker visitation (thick lines) with time for three management scenarios for a 4 km^2 mountain fynbos ecosystem. Scenarios are defined in Table 1.

Both valuation levels assume that hikers, ecotourists, native plants, endemic plants, wildflowers and water contribute to the value of mountain fynbos ecosystems, but use different unit values (Table 1). The estimation of hiker willingness to pay (UV_h) was based on the amount currently charged for hiking in mountain fynbos (Ms A. Eager, Cape Nature Conservation, personal communication). Estimation of the potential benefit from ecotourism (UV_t) was made with the help of an ecotourist consultant (Dr P.J. Mustart, Institute for Plant Conservation, personal communication). The wildflower net income per unit area (UV_f) (Dr P.J. Mustart, personal communication) was used to estimate the unit value of wildflowers. The value is dependent on the species composition of the vegetation, the UV_f estimates (Table 1) illustrate the observed variation of this value. The tariff for bulk untreated water from a state water supply scheme (Burgers et al., 1995) was used to assess the minimum unit value of water (UV_w) to society. The values used (Table 1) reflect the tariffs for different supply schemes. The cost of maintaining indigenous plant gene banks was used to estimate value of the genetic storage service, the values used for the two valuation levels (Table 1) reflect the cost of two South African schemes (Ellsenberg Gene Bank, Agricultural Research Council and Cycad Gene Bank, National Botanical Institute). The value of an endemic species was estimated as the cost of producing a new floricultural variety (Dr J.H. Coetzee, Fynbos Research Unit, Agricultural Research Council, personal communication).

4.2. Scenario results

The ecological responses of the hypothetical mountain fynbos ecosystem to the three management scenarios (Table 1) are shown in Fig. 6. Under present management (scenario M1) the model predicts a steadily decreasing water yield from the system (Fig. 6a). Proactive management (scenario M2) can, however, restore the water yield to that produced by a pristine system (scenario M3). The index of relative wildflower production (Fig. 6b) decreased under present management (M1); proactive management (M2) could restore production levels to those observed in pristine ecosystems (M3). The number of both endemic and indigenous plant species present in the ecosystem (Fig. 6c) decreased as the invasion process proceeds under present management (M1). Proactive management can only halt but not reverse this species loss process (M2). It is, however, conceivable that species restoration projects could re-establish some plant populations (e.g. Holmes and Cowling, 1997; this was not considered in this version of the model), although the number of species threatened by invasions suggest that substantial restoration projects would be required. The sensitivity of ecotourists to alien plants means that few would be expected to visit under the present management regime (Fig. 6d, M1). Proactive clearing of alien plants would be needed to attract ecotourists, as is illustrated by scenario M2. Hikers, being less sensitive to alien trees, would visit the ecosystem under the present management regime (M1), but their numbers are predicted to dwindle as the level of alien plant infestations increased. Clearing of alien plants (M2) would guarantee the long-term visitation of hikers. Pristine ecosystems (M3) are predicted to attract a constant (i.e. manager regulated) number of visitors (Fig. 6d).

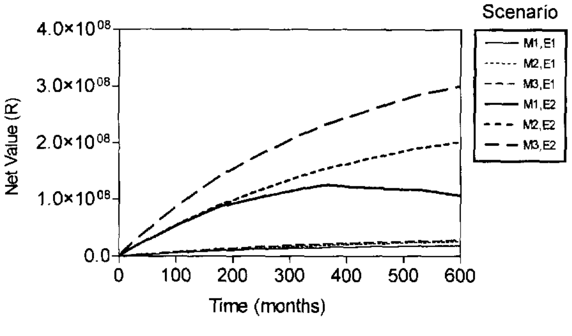

Fig. 7. Changes in net value (R4.50 = US$1) with time for three management scenarios (M1–M3) and for two economic valuations (E1–E2) for a 4 km^2 mountain fynbos ecosystem. M1 = present management (invaded, inadequate clearing); M2 = proactive management (invaded, intense clearing); M3 = pristine management (uninvaded, no clearing required); E1 = low economic valuation; E2 = high economic valuation. Scenarios are defined in Table 1.

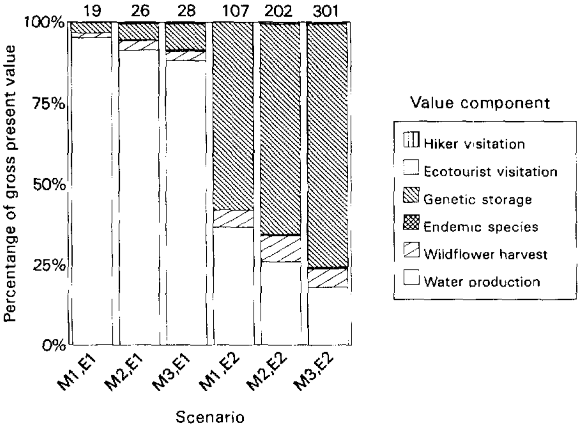

Fig. 8. Stacked bar diagram of the percentage gross present value of six sub-components (hiker visitation, ecotourist visitation, plant species, endemic plant species, flower harvesting, and water production) of fynbos ecosystem value under three management (M1–M3) and two economic valuations (E1–E2) for a 4 km^2 mountain fynbos ecosystem. Numbers are the total gross value in millions of rand (R4.50 = US$1) for each scenario. M1 = present management (invaded, inadequate clearing); M2 = proactive management (invaded, intense clearing); M3 = pristine management (uninvaded, no clearing required); E1 = low economic valuation; E2 = high economic valuation. Scenarios are defined in Table 1.

The net value, discounted at 3% over 50 years, of the mountain fynbos ecosystem was strongly influenced by both the management scenario and the economic valuation level (Fig. 7, Fig. 8). The present management scenario (M1) was the least sensible strategy to follow. Although the pristine, uninvaded mountain fynbos systems (M3) have the greatest value under both economic contexts, clearing alien plants (M2) can increase the value of a mountain fynbos ecosystem. Water production, genetic storage and the wildflower harvest are the main contributors of the value of mountain fynbos ecosystems; water production dominates for the low valuation level (E1), whereas native plants dominate for the high valuation level (E2). Although the hikers, ecotourists and endemic plants only made a relatively small contribution to the total value, this value is still substantial in well-managed scenarios (M2 and M3).

5. Discussion

The need for tools to articulate the value of natural ecosystems has led many to advocate the development of trans-disciplinary, integrative and dynamic models of ecological economic systems (e.g. Bockstael et al., 1995). This paper documents an explicit attempt to take up this challenge. It recognizes that all models represent a trade-off between realism, generality and precision (Levins, 1966). The model developed here compromised precision and to a lesser extent realism in producing a general model of the ecological economics of fynbos. The disadvantage of this is that the predictions reported here will differ in quantitative detail from site to site. The advantage of the strategic approach adopted is that the results have broad implications for mountain fynbos ecosystems. Furthermore the model's user-friendly interface means that managers and policy makers can easily modify the model's parameters to suit local conditions.

5.1. Management and economic determinants of value

The model integrates the most important ecosystem services that flow from mountain fynbos ecosystems. These include, under pristine conditions (management scenario 3), substantial volumes of water, wildflowers and recreational services indexed by ecotourist and hiker visitation. In addition mountain fynbos ecosystems serve as an excellent reservoir of floral genetic diversity and endemic plant species. The flow of these ecosystem services is influenced by the presence and spread of alien plants, and the effectiveness of alien plant management. The model predicts that the present poor management (management scenario 1) of mountain fynbos ecosystems will substantially reduce the flow of ecosystem services from mountain fynbos, but that proactive management (management scenario 2) can restore ecosystem services to a level that would be expected of pristine systems. The cost of this proactive management strategy is from 0.6 (under high economic valuation) to 4.76% (under low economic valuation) of the value of the system. The relative values of a poorly-managed (management scenario 1) and a well managed eocsystem (management scenario 3) illustrate that proactive clearing can increase the value of an invaded ecosystem by between 138 (under low economic valuation) and 149% (under high economic valuation). The proactive management strategy (management scenario 2) also shows the value of an intensive alien clearing strategy that rapidly eliminates alien plant infestations while they are still manageable. It follows that any effort devoted to clearing alien plants that cannot clear aliens faster than they are spreading is a wasted effort.

The current realization of the value of mountain fynbos ecosystems among managers and policy makers is limited to hiker visitation revenue. It follows that they cannot justify allocating funds to clear alien plants and thereby increase the flow of ecosystem services from mountain fynbos ecosystems. This study, however, articulates the value of mountain fynbos ecosystems and shows that this value is between 21 (under low economic valuation) and 164 (under high economic valuation) times greater than the cost of clearing alien plants.

5.2. Future research needs

Owing to a lack of existing information on the value of components of mountain fynbos ecosystems and the novelty of valuing some of these components, our valuation is uncertain. We dealt with this uncertainty in economic information by examining two economic valuation levels and by adopting a conservative approach to valuation. For instance, the financial yield of dense stands of *Brunia albiflora*, a highly desirable cut-flower, may be substantially higher than the estimate of wildflower yield incorporated in this version of the model. The high value of a species such as *B. albiflora* means that a decrease in abundance, local extinction or extinction of a single plant species may have substantial economic implications. Furthermore the potential for new discoveries of economically valuable aromatic oils, new floricultural species and the potential of medicinal plants (Cowling and Richardson, 1995) suggests that our option value of endemic plant species is extremely conservative. The value of water produced by mountain fynbos ecosystems is a controversial issue. At present the value of water is a function of the capital and operating costs and the potential yield of the water supply scheme. This means that, in terms of current policy, water itself has a value only in context of its water supply scheme. We conservatively estimated the value of water in this context, although the scarcity of water in the southwestern Cape suggests that the value of water should be higher (Preston et al., 1995). In addition to the conservative estimation of the unit values of ecosystem services, we assumed negligible multiplier effects for all economic activities. More research on quantifying the unit values of fynbos ecosystem services is needed.

Future research should be orientated towards developing a spatially-explicit version of the model developed here. The current model could serve as a unit-model in such a spatially-explicit model. This model should ideally be calibrated for a number of sites in order to explicitly test the validity of the simplifying assumptions made here. This would allow the simulation of spatial processes known to be important in the dynamics of plant invasions (Higgins and Richardson, 1996; Higgins et al., 1996) and ecosystem models in general.

5.3. Conclusions

We have shown that mountain fynbos systems provide many valuable ecosystem services. Effective management can maintain the value of pristine systems and substantially increase the value of degraded mountain fynbos ecosystems. However, poor management can substantially decrease the value of mountain fynbos ecosystems. Since the cost of management is small relative to the value that these services provide, it is clear that proactive and effective management of these ecosystems is justified.

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Appendix A. Parameter names, units, symbols and estimates for the model

Parameter name	Symbol	Estimate
Hydrological sub-model		
Potential evapotranspiration (mm/month)	E_t	Eq. (1)
Pan evaporation (mm/month)	E_p	Empirical sequence
Precipitation (mm/month)	P	Empirical sequence
Surface run-off (mm/month)	R	$P-E_t$
Infiltration constant (proportion)	I_f	0.1
Base-flow constant (proportion)	F_g	0.001
Ground-water evapotranspiration constant	E_g	0.4
Ground-water inflow (km^3/month)	G_i	$I_f^{*}R$
Ground-water outflow (km^3/month)	G_o	$F_g^{*}G_r+E_g^{*}E_t$
Ground-water reservoir (km^3/month)	G	$G_{t-dt}+(G_i-G_o)*dt$
River flow (km^3/month)	R_f	$(1-I_f)*R*A+G_o$
Fire sub-model		
Fire probability	p	Eq. (2)
Fire threshold	F_t	0.85

Appendix A (continued)

Parameter name	Symbol	Estimate
Plant sub-model		
Invasion rate (proportional increase)	I_r	if fire = 1 then 0.75 else 0
Area alien plants (km^2)	A_a	$A_{t-dt}+(I_r^* A_a - A_c)*dt$
Alien biomass increment (g/m^2 per month)	B_{ai}	Fig. 3
Alien biomass burn-off (proportion)	B_{ab}	If fire = 1 then 0.75 else 0
Alien biomass (g/m^2 per month)	B_a	$B_{at-dt}+(B_{ai}-B_{ab})*dt$
Area native plants (km^2)	A_n	$A-A_a$
Native biomass increment (g/m^2 per month)	B_{ni}	Fig. 3
Native biomass burn-off (proportion)	B_{nb}	If fire = 1 then 0.99 else 0
Native biomass (g/m^2 per month)	B_n	$B_{nt-dt}+(\mathrm{B}_{ni}-\mathrm{B}_{nb})*dt$
Number of endemic plant species	N_e	Eq. (3)
Number of native plant species	N_s	Eq. (4)
Potential wildflower harvest (m^2/month)	H_h	Eq. (5)
Management sub-model		
Management area (km^2)	A	4
Fire management	$MF?$	1 (1 = yes; 0 = no)
Managed fire frequency	MF_f	15
Area of alien plants to be cleared (km^2)	A_c	Table 1
Wildflower harvest (proportion harvested)	H_p	0.5
Potential visitation hikers (visitors/km^2 per month)	PV_h	2.8
Potential visitation ecotourists (visitors/km^2 per month)	PV_t	1
Realized visitation hikers (visitors/km^2 per month)	RV_h	Fig. 4
Realized visitation ecotourists (visitors/km^2 per month)	RV_t	Fig. 4
Economic valuation sub-model		
Flower harvesting cost (R^a)	MC_{fh}	$0.4*V_f$
Alien clearing cost (R/km^2 per month)	MC_a	204 500
Fire management cost (R/km^2 per month)	MC_f	30
Wildfire management cost (R)	MC_{wf}	If fire = 1 then 20 000 else 0
Capital equipment maintenance cost (R/km^2 per month)	MC_c	30
Unit value endemic plant species (R)	UV_e	Table 1
Unit value native plant species maintenance (R)	UV_s	Table 1
Unit value hiker (R/visitor per day)	UV_h	Table 1
Unit value ecotourist (R/visitor per day)	UV_t	Table 1
Unit value water (R/km^3)	UV_w	Table 1
Unit value wildflowers (R/km^2)	UV_f	Table 1
Discount rate	DR	0.03/12
Value endemic plants (R)	V_e	$N_e^* UV_e$
Value native plants (R)	V_s	$N_{st-dt}+(N_s^* UV_s - DR*V_s)*dt$
Value hikers (R/month)	V_h	$V_{ht-dt}+(RV_h^* UV_h^* A - DR*V_h)*dt$
Value ecotourists (R/month)	V_t	$V_{tt-dt}+(RV_t^* UV_t^* A - DR*V_t)*dt$
Value water (R/month)	V_w	$V_{wt-dt}+(F_r^* UV_w - DR*V_w)*dt$
Value wildflowers (R/month)	V_f	$V_{ft-dt} + (A_n^* H_h^* H_p^* UV_f - DR*V_f)*dt$
Total value (R)	TV	$V_e+V_s+V_h+V_t+V_w+V_f$
Total cost (R)	TC	$C_{t-dt}+((MC_{fh} + A_c^* MC_a + A*MC_f + MC_{wf} + A*MC_c - DR*TC)*dt$

[a] R = R4.50 = US$1

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