**Summary**  The damage that weeds inflict on natural ecosystems over time reduces the flow of services from these areas, thus reducing the flow of benefits to society. A simulation model of a natural ecosystem is a useful tool to analyse the effects of an alien plant invasion over time. Such an approach is developed here to apply the theory of production economics to value the damage through a dynamic bioeconomic model. The approach integrates the principles of benefit-cost analysis to value the costs of the incursion and the benefits of control.

**Keywords**  Weed incursion, natural environment, simulation model, production economics, benefit-cost analysis, biodiversity.

**INTRODUCTION**

When weeds invade natural ecosystems there can be profound effects on the native habitat. Weeds compete with indigenous plants for nutrients, soil and light, commonly replacing native flora and preventing regeneration of natural vegetation. In addition, fire regimes, hydrology, water quality and animal habitat may also be adversely affected.

The damage that weeds inflict reduces the flow of services from natural areas, thus reducing the flow of benefits to society. Ecosystem services may include recreation, eco-tourist visitation, grazing, and non-use outputs such as the existence of endemic species and genetic storage services. Weed control will reduce these losses but such activities cost money to implement.

The objective of this paper is to integrate bioeconomic concepts with production economics theory to develop a conceptual model that describes the effect of a weed invasion on natural ecosystem outputs over time. Such a model may be used to make decisions about the management of weeds in natural ecosystems.

A review of the literature shows the major difficulties in developing this approach (Barbier 1994). We need to model (a) the different kinds of resource and outputs (stocks and flows) that are derived from the environment, (b) the way a weed invasion affects outputs from natural ecosystems and (c) the way outputs interact with each other. In order to understand these relationships a conceptual model is described in this paper and ways in which the model can be implemented are discussed.

**MODEL DESCRIPTION**

In order to make decisions about the management of natural ecosystems, economists value the social benefits and social costs associated with their use. The flow of goods and services from a natural ecosystem is likely to be reduced by a weed invasion. To value these losses directly, we start from the assumption that the community wishes to maximise the present value of the flow of benefits (community welfare) from the natural environment. The community would then maximise:

\[ CW = \sum_{t=1}^{T} [V(Q_1, Q_2, \ldots, Q_n) - C] (1 + d)^t \]  

where \( CW \) is the present value of the flows of welfare from the natural environment, \( V \) is a function of each of \( n \) goods or services \( Q_i \), \( C \) are the costs of producing these outputs, \( d \) is the social rate of discount, \( t \) is time and \( T \) is the planning horizon.

A conventional production function can capture the nature of an ecological function that models the provision of a good or service when inputs are combined with the environment (Barbier 1994):

\[ Q_i = f_i(I_i, E) \quad i = 1, \ldots, n \]  

where \( Q_i \) denotes each of the \( n \) outputs produced, \( I_i \) is a vector of input classes (namely public inputs, private inputs and weed control inputs), and \( E \) represents the state of the environment. \( E \) is exogenous to the system at time \( t \) and is affected by weeds. The environment is described by a set of attributes, and weeds affect the output of goods and services through their effect on these attributes. These attributes are more fully described below, starting with environmental quality. The conceptual model is presented in Figure 1.

**Environmental quality**  Environmental quality is identified through two characteristics. These are the area of native plants \( (A_n) \) and the number of native plant species or biodiversity \( (B) \). A major effect of

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**Figure 1**

Valuation of the cost of a weed incursion in a natural environment: a simulation approach

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area occupied by weeds ($w$) in a natural ecosystem is on the area of native plants, which is measured as the difference between total landscape area and the area occupied by weeds.

The value of $A_n$ depends on the area of weeds and any clearing that might take place as a result of actions that occur with particular types of natural ecosystem output (i.e. mining). It is assumed that native plants are competitively inferior to alien plants so that the area of native plant species decreases as alien plants invade natural ecosystems. This decrease may or may not simultaneously result in native plant extinctions. It is possible for weed invasions to occur in such a way that isolated pockets of an ecosystem, containing the full range of native plant species, remain. In this situation, weed control may lead to restoration of the
environment to its original state. Ultimately however, left unchecked, the spread of the weed will cause native plant extinctions, and weed control, no matter how substantial, will not be able to restore the landscape to its original pre-invasion state.

For most weeds, native plant extinctions are an indirect consequence of weed spread, and are caused by a reduction in the area of native plants. In some cases, however, there will be a direct link between the area of weeds and the loss in native plant species. This additional relationship, between the area of weeds and the number of native plant species, recognises that a small number of weeds have a growth characteristic that results in elimination of native plants through ‘smothering’. This direct effect on native plants is contrasted with the indirect way that most weeds affect the number of native plant species.

Biodiversity ($B$) is represented by the number of native plants species in the natural ecosystem relative to the number that existed at the start of the simulation period, and has values ranging from zero to one. A value of one indicates the natural ecosystem is in a pristine state with the full range of native plant species present, and a value of zero suggests the ecosystem has been completely overrun with weeds.

The value of $B$ in a given year depends on the number of native plants in the previous year and on the number of native plants species lost as the area of native plants is reduced from increasing weed density. When biodiversity levels fall below a critical value, native plant species are lost from the ecosystem and it is assumed that this extinction is irreversible. If weed density is subsequently reduced by weed control the area of native plants will increase, however the number of native plants will remain constant. The value of biodiversity is therefore the minimum of two values: its value in the previous year or its value in the previous year minus any current-year native species losses. This temporal relationship becomes important when weed management strategies are chosen to optimise net benefits to society of natural ecosystem outputs.

Management inputs and ecosystem outputs The model presently illustrates three of the types of outputs (services) that flow from natural ecosystems: recreational outputs such as camping (type 1); outputs of endemic species services such as genetic storage, medicinal products and knowledge (type 2); and non-renewable resource outputs such as minerals (type 3).

Weeds affect the level of output from the natural ecosystem through their effect on biodiversity and area of native plants. The number of visitors to a natural ecosystem will be influenced by the amount of weeds present in camping and hiking areas. The higher the weed density, the less attractive will be the locations that were once sought out because of their pristine nature, although this may be worth testing empirically.

There is an obvious and very direct link between the state of the environment and the level of non-use type outputs. As biodiversity levels fall so too does the number of endemic species ($N_e$) and hence the output of services ($Q_e$) provided by these endemic species.

There is a less obvious relationship between the state of the environment and non-renewable outputs such as mining. It is assumed that mining can only occur in areas where there are no endangered or endemic plant species. In turn, we assume the amount of mining that occurs has a direct effect on the area of native plants and ultimately biodiversity values. In order to extract mineral resources from the ground there is always some level of destruction of habitat, although there may be the legal requirement that the mine site be restored once mining is completed.

Authorities responsible for management of natural ecosystems may influence the flow of certain outputs from the environment, through the development and maintenance of infrastructure that may serve to either increase or decrease flows of visitors to the ecosystem. Public inputs ($I_p$) are included in the model through the production function discussed as equation (2). When visitors are encouraged to visit a natural ecosystem their activities (e.g. walking, four-wheel driving) may lead to the disturbance and dispersal of weed seed banks thus promoting the further spread of weeds. Annual increases in weed spread, and the resulting impacts on the environment, would therefore be larger with tourists than without. If it is likely that tourists will promote the spread of weeds, authorities may choose to exclude them, by closing off roads or closing camping grounds (reducing inputs) in areas where the weed is present. This action will indirectly benefit the output of endemic species services, which would otherwise decline as biodiversity decreases and lead to costs resulting from loss of recreational outputs.

Private inputs enabling accommodation and travel to natural ecosystems also affect the flow of outputs. If visitors are not prepared to travel to the ecosystem, paying necessary sustenance and accommodation costs, then visitor numbers (output) will be reduced. Public and private inputs also influence the use of the natural ecosystem by mining companies. Public inputs such as mining permits, monitoring and road access will modify the use of the environment by mining companies as will private expenditure on inputs such as capital, labour and other costs such as pollution control.
**Benefits of weed management** The impacts on natural ecosystems of weed infestations occur over time and may be slowed, halted or possibly reversed, through weed control activities (\(u\) in Figure 1). These activities may include manual pulling of weeds, use of herbicides, control of feral animals and biological control. Weed control activities aim to either remove or kill the weed, or to stop spread, disturbance and subsequent germination of weed seeds and therefore have a direct impact on the annual change in weed spread.

Benefits from ecosystem outputs or services (summed as \(CW\) in equation (1)), can be evaluated using appropriate prices. Prices and quantities of each type of output are denoted \(P_{rec}, Q_{rec}, P_{mg}, Q_{mg}, P_{es}\) and \(Q_{es}\) in Figure 1. Prices and quantities are combined to give a measure of benefits from the system. Costs are incurred (\(C_u\)) through the various weed control activities, through public provision and maintenance of infrastructure and private inputs (\(PI_i\)). Benefits and costs of ecosystem management are compared using equation (1) to give a net present value of community welfare from the natural environment.

**DISCUSSION**

An outline of the model has been presented and the challenge is now to estimate parameters and calibrate the model. Relationships that may be difficult to parameterise are those between the area of weeds (or area of native plants) and the number of native plant species and the relationship between the number of native plant species and the number of endemic species. In addition, appropriate production functions for the environmental outputs must be chosen and parameters derived. Interaction between environmental outputs must also be adequately described.

Values (prices) will need to be placed on each unit of the different types of outputs produced by the interaction of the environment and inputs. This will be particularly challenging for biodiversity type inputs, where such values are rare. Nevertheless, recent work by Sinden et al. (2004), using data from Thorp and Lynch (2000), indicates the value of saving a threatened species is (at least) A$68 700 per year, which may be used as a lower bound for the value of each endemic species. Another useful study (van Bueren and Bennett 2004) gives a method of assessing non-market values associated with land and water degradation in Australia, and shows the importance of accounting for differences in attitudes at the local and national level to these issues. Using a survey, the authors show that, on average, respondents households are willing to pay 67 cents per annum over the next 20 years for every species that is protected from extinction. The authors assume that this can be safely extrapolated to 37% of the 7.2 million Australian households, giving an annual value of $1,784,880 for every threatened species that is protected from extinction. This may give an upper limit.

Progress to date includes the selection of three different types of outputs from the natural environment and conceptualisation of the way weeds affect each of these. Interactions between each output have also been described conceptually.

Finally, uncertainty needs to be incorporated into the bioeconomic model. Elements of weed growth will have a range of possible values expressed as probabilities. This will allow for more realistic changes in weed spread.

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