Land Use and Water Resources Research

Integrated control of invasive alien plants in terrestrial ecosystems

Brian van Wilgen[1], Dave Richardson[2] and Steve Higgins[3]

[1]Environmentek, CSIR; [2]Institute for Plant Conservation, University of Cape Town; [3]National Botanical Institute.

Abstract

Effective management of invading alien plants in natural and semi-natural systems is imperative if we are to prevent enormous impacts. An integrated approach involving the combined use of a range of methods is usually necessary to control invasive alien plants effectively. The various methods that are available are usually classified as: mechanical methods (felling, removing of invading alien plants, often in conjunction with burning); chemical methods (using environmentally safe herbicides); and biological control (using species-specific insects and diseases from the alien plant's country of origin). Approaches available for integrated control depend on the species under consideration (features of individual species and the number and identity of species that occur together), features of the invaded systems, the availability of resources and other factors. Mechanical and chemical control are short-term activities, whereas rigorous and disciplined follow-up and rehabilitation are necessary in the medium term. Biological control can provide effective control in the short and medium term in some cases, and it is often the only really sustainable solution in the longer term. We suggest that the biological attributes of plants represent a stable set of attributes, which enable managers to devise control approaches, but that such approaches are likely to be upset by stochastic events such as fires, floods or budget cuts. While an approach of adaptive management, based on trial, error and continual improvement is a logical way in which to progress, the advent of powerful computer simulation modelling technologies will allow managers to do hundreds of 'trial and error' runs in order to explore the consequences of certain courses of action. This should represent an improvement on the current state of affairs, and should allow for better decision-making. We present a series of simulations to illustrate this point.

Introduction

Invasive alien plants are a problem of global significance, causing impacts running into billions of dollars annually. In South Africa, at least 161 species cause serious problems in natural and semi-natural systems (Henderson, 1995), impacting on 10 million hectares (8%) of the country (Le Maitre *et al.*, in press). Impacts associated with invasive alien plants include reduced surface water runoff and groundwater reserves, increased biomass and fire intensity, markedly reduced biodiversity and many economic consequences. Water use increases where short vegetation is replaced by dense stands of invasive alien trees; the latter use an estimated 7% of the South Africa's runoff (Le Maitre *et al.,* in press). Fuel loads at invaded sites are increased up to ten-fold, increasing fire intensities and causing soil damage, increased erosion and decreased germination from indigenous seed pools. South Africa has unusually high levels of biodiversity, and alien plants could eliminate several thousand species of plants if spread is not controlled, seriously affecting the delivery of ecosystem services.

Environmental managers recognise the need for effective control programmes to counter these impacts, and many attempts have been made to institute such programmes in many parts of the world. Some have been relatively successful but many others have been dismal failures. It would be useful if the factors that determine success or failure could be understood and documented to guide management in future.

By and large, ecologists and ecosystem managers understand the biology and ecology of the most important weed species. However, this understanding does not always mean that a programme of integrated control will be easy to put together. There are many factors that complicate management: these include the occurrence of unplanned events such as fires, drought, excessive rainfall and flooding; uncertainties around budgets and the levels of funding that will be available to carry clearing programmes forward once they have begun; uncertainties around the impacts of treatments such as felling or burning that may lead to unexpected results; and differences in the levels of capability and commitment amongst the workers tasked with carrying out clearing programmes. These complicating factors often mean that clearing programmes become an exercise in trial-and-error, which can be expensive and may have consequences that can be ill afforded — there is a clear need to develop a set of best practices guidelines that draw on a wide range of past experience, and that will assist in at least avoiding mistakes that have been made elsewhere. There is also a great deal of potential for combining our ecological understanding with these lessons to develop computer-based simulations that will assist managers in making decisions.

In this paper we examine the elements of integrated control in relation to their usefulness in controlling a range of invasive alien plants, and we place these control options within a wider holistic framework aimed at alien plant control. We review the different control options and define appropriate integrated options. We provide examples of where these approaches have been used successfully, and identify problem areas where further solutions need to be developed. We also examine the concept of adaptive management, and show how computer simulation models can assist managers in dealing with the complications inherent in implementing integrated control programmes.

Integrated control in the context of an overall strategy for weed control

In the approaches toward the control of invasive alien weeds, the responses of society in general, and of ecosystem managers in particular, need to be aligned with the different stages of spread. The stages can be divided into four broad categories: arrival; adaptation and establishment; an exponential growth phase; and a phase where alien plants have invaded and dominated the available area (Table 1). It is in the exponential growth stage of weed spread that integrated control programmes find a logical home. Prevention, and early detection and eradication, are more appropriate for the first two stages, while options may be severely limited once weed populations reach the final stage of total ecosystem domination (Figure 1).

Elements of integrated control

Integrated weed control usually involves a combination of at least two of the primary elements of control — mechanical, chemical and biological. Each of these is described briefly.

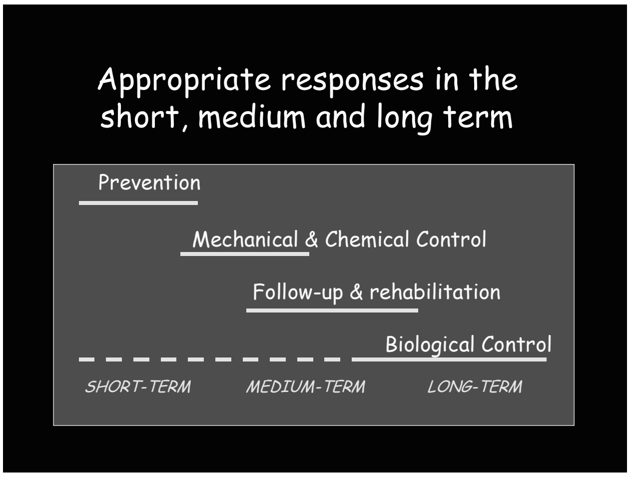

Figure 1. Appropriate responses to weed control programmes in the short, medium and long term

Mechanical control

Mechanical control options include the physical felling or uprooting of plants, their removal from the site, often in combination with burning. When fire is used, it can be applied in conjunction with physical control (for example fell and burn, or burn and follow-up with hand weeding). The equipment used in mechanical control ranges from hand-held instruments (such as saws, slashers and axes) to power-driven tools such as chainsaws and brushcutters, and even to bulldozers in some cases. Mechanical control is labour-intensive and thus expensive to use in extensive and dense infestations, or in remote or rugged areas.

Chemical control

Herbicides can be applied to prevent sprouting of cut stumps, or to kill seedlings after felling or burning. Herbicides can target, for example, grasses or broad-leaved species, leaving other plants unharmed. However, there are legitimate concerns over the use of herbicides in terms of potential environmental impacts. Although newer herbicides tend to be less toxic, have shorter residence times, and are more specific, concerns over detrimental environmental impacts still remain. The use of chemical control is often governed by legislation, and the effective and safe use of herbicides requires a relatively high level of training; both of these factors can restrict the use of chemical control on a large scale.

Biological control

Biological control (or 'biocontrol') involves using species-specific insects or other invertebrates, and diseases, from the alien plant's region of origin. Most invasive alien plants show no 'weedy' behaviour in their natural ranges — their ability to grow vigorously and produce huge amounts of seeds is kept in check by a host of co-evolved organisms. Some species, when transported to a new region without the attendant enemies, grow more vigorously and produce many more seeds than in their native ranges, and become aggressive invaders. Biocontrol aims to reduce the effects of this phenomenon, and to achieve a situation where the

Table 1 Stages in the spread of invasive alien weeds, the factors that encourage spread, and the appropriate management responses (Adapted from Hobbs and Humphries 1995).

Stage of spread	Weed status	Factors encouraging spread	Appropriate management response
Arrival in a new environment	Not present	Introduction (deliberate or accidental)	Prevention (quarantine priority stage)
Adaptation and establishment	Localised populations	Adjustment to local conditions Selection for invasive attributes Developing links with local biota	Early detection (eradication priority stage)
Exponential growth	Multiple populations, exponential increases in affected area.	Dispersal, disturbance. Mismanagement through inappropriate or late management.	Integrated mechanical and chemical control. Management of ecosystem dynamics. Assessing socio-economic drivers (control priority stage)
Dominance	Large, widespread problem	As above, but populations approaching carrying capacity of the environment.	Massive inputs needed for effective control. Biocontrol the only effective solution in some cases.

formerly invasive alien plant becomes a non-invasive naturalised alien. Biological control has many potential benefits, including its potential cost-effectiveness, and the fact that it is (usually) environmentally benign. Some interest groups have expressed concern about the potentially negative effects on non-target plants, or on weeds that may have important commercial value, such as the pines, which are important for timber production but invade large areas outside plantations.

Examples of invasive plants and control strategies

The success of some alien plants as invaders is, at least partly, attributable to their life-history traits that allow them to establish, grow, reproduce, spread, and eventually dominate in the new environment. For example, many very widespread and damaging invaders produce large numbers of highly dispersible seeds and can capitalise on disturbance events such as fire or floods to enhance reproduction and spread. Alien plants are often present in a new environment for some time before they start spreading. During this lag phase, there may be selection for certain attributes that enhance invasive potential, or it may take some time to develop the necessary interactions with local biota (such as pollinators or seed dispersal agents) that facilitate invasion. Some examples of invasive species are given in Table 2, together with the biological and physical factors that affect their spread, and the control strategies that have been adopted for their control.

The examples given in Table 1 cover a range of weed types that can be used to illustrate the range of control options. *Hakea sericea*, a shrub introduced to South Africa from Australia, has invaded thousands of hectares of fire-prone fynbos shrublands. Shrubs mature quickly after germination and produce large numbers of seeds, held in serotinous follicles, well before another fire could be expected. Plants are killed by fire, after which the winged seeds are released and dispersed by wind. Invading shrubs form dense monospecific stands that increase biomass and displace the rich native vegetation. Control programmes use a combination of mechanical control, fire and biocontrol. The shrubs are felled using chainsaws or slashers, and left for 12 to 18 months before burning. During this time seeds are released where they are either germinate or are eaten by rodents. The practice has been successful in clearing large areas of invasions, but problems with the impact of fire do occur where the felling of particularly dense stands results in high loads of dead dry fuel, high fire intensities, and physical damage to the soil. Biological control is available in the form of several seed-feeding insects (Gordon, 1999); however, these insects do not disperse readily or over long distances, and managers of mechanical control programmes should leave ‘reserves’ of uncleared shrubs to harbour populations of biocontrol agents if they are to be effective. This mechanical control strategy is also successfully applied to other invasive hakea species (*H. drupacea* and *H. gibbosa*) and to pines (*Pinus* species).

The Australian tree *Acacia mearnsii* was introduced to South Africa where it now forms the basis of a small but important component of the forest industry. The tree invades landscapes around the country, mainly along river courses. The trees grow and mature quickly, and produce large numbers of hard-coated seeds, which accumulate in the soil below the tree and are spread rapidly down rivers and streams. Seeds are also dispersed in soil transported by humans, and new invasions develop wherever there is

Table 2 Examples of widespread invasive alien plant species, the factors that influence their invasive potential and spread, and the strategies adopted for their control

Invasive alien species	Characteristics	Spread mechanisms	Ecosystem characteristics	Control strategy
Hakea sericea (Proteaceae)	Fire-sensitive, non-sprouting shrub with short juvenile period and serotinous follicles that open after fire.	Winged seeds spread long distances by wind after fir.	Invades fire-prone shrublands; rugged inaccessible terrain	Fell shrubs and burn within a year to kill resultant seedlings; biocontrol to reduce seed production.
Acacia mearnsii (Fabaceae)	Sprouting tree with hard-coated, soil-stored seeds.	Seeds spread down water courses and through the transport of soil.	Invades shrublands, grasslands and savannas, especially along water courses.	Fell and treat stumps with herbicide. Follow-up removal of seedlings essential. Biocontrol to reduce seed output.
Opuntia stricta (Cactaceae)	Succulent cactus with edible fruits.	Animals eat fruits and spread seeds; also vegetative reproduction.	Invades savanna ecosystems.	Injections of herbicides in isolated individuals; biological control effective in denser stands.
Melaleuca quinquinervia (Myrtaceae)	Fire-adapted tree that produces large quantities of seed.	Spreads after fire or seasonal flooding.	Invades wetlands, often in inaccessible areas.	Felling and burning to kill seedlings. Biological control options being investigated.
Chromolaena odorata (Asteraceae)	Shrub with small, light seeds.	Seeds dispersed by wind.	Invades forest margins, water courses, road verges and plantations.	Fell and apply herbicide. Some promising biological control agents have been identified.
Bromus tectorum (Poaceae)	Fire-adapted annual grass.	Changes in fuel characteristics brought about by invasions of this species favour frequent fires, which in turn assist further spread.	Invades shrub-steppe ecosystems.	Herbicides followed by rehabilitation of sites. Large infestations very expensive to control.
Psidium guajava (Myrtaceae)	Small tree with edible fruits.	Animals eat fruits and disperse seeds.	Invades savannas, forest margins and watercourses.	Mechanical felling only.
Centaurea solstitialis (Asteraceae)	An annual thistle.	Http://tncweeds. ucdavis.edu/esadocs/ documnts/centsol.html		Mechanical removal, herbicide application, burning and establishment of perennial vegetation. Biocontrol agents show good promise.

human access as a result. The tree is a vigorous resprouter, and soil-stored seed pools are stimulated to germinate after fire or other disturbance such as clearing. Control operations usually involve mechanical felling of trees, followed by the application of herbicides to the stumps to prevent sprouting. Fire is sometimes applied after these measures to aid germination of soil-stored seeds. For control to be effective, regular follow-up treatments are required to remove seedlings, either by spraying with an appropriate herbicide, or by hand-pulling the seedlings. Biological control has been introduced in the form of a seed-feeding weevil (Dennill *et al.*, 1999), but is restricted to seed-feeding insects at present due to the commercial value of the species. The above approach is effective for other Australian

Acacia species, as well as other sprouting tree species with similar life-history traits. For species without major commercial value (such as *Acacia cyclops* and *Acacia longifolia*), biocontrol agents that reduce the vigour of the plants and result in their death have also been imported (Dennill *et al*., 1999).

Opuntia stricta is a South American cactus that has recently become a weed of significance in South African savanna conservation areas. Early attempts at mechanical control were ineffective as the species was spread widely by baboons and elephants that consumed the fruits and spread seeds over large distances. The large areas concerned, and the difficulty of locating scattered individuals prevented effective control. However, the introduction of biological control agents in the form of a *Cactoblastis* caterpillar and a cochineal insect (Hoffmann, Moran and Zimmermann, 1999) has improved the situation substantially. An approach of combining herbicide control on scattered populations and the release of biocontrol agents on to larger infestations (Lotter and Hoffmann, 1998) shows much promise for bringing the weed under control.

Melaleuca quinquinervia (Myrtaceae) from northern Australia was introduced to the USA in about 1900. In the last quarter of the 20th century this tree invaded thousands of hectares of freshwater wetlands in southern Florida. Impenetrable stands of these trees completely replace native wetland vegetation and degrade wildlife habitat, notably in the Big Cypress National Preserve and the Everglades National Park. The attributes that have contributed to its success in these systems include its massive seed production, adaptation to fire, and tolerance to flooding. Controlling these species is greatly complicated by the inaccessibility of the habitat. Mechanical control, involving hand pulling, cutting, removal of seed capsules and follow-up is applied in more accessible sites. In less accessible sites, cut stumps are treated with herbicide. Prescribed burning is also applied to kill seedlings in wetlands (Hammer, 1996). Biological control in the form of the snout weevil *Oxyops vitiosa* has been applied since 1997, and several other potential insects have been identified.

Chromolaena odorata is a shrub of Neotropical origin that has become a serious invader in many humid tropical and subtropical areas, including South Africa. The plant produces large numbers of light seeds, which are readily dispersed over long distances by wind. Establishment is aided by disturbances such as clearing, logging, fires and flooding, and the shrub is a serious pest in agricultural, forestry and conservation areas. Mechanical control or the application of herbicides can be used to clear areas, but unless nearby seed sources and ecosystem disturbances are eliminated, cleared areas become re-invaded over time. The introduction of a range of promising biological control agents is currently being investigated and one has already been released (Zachariades, Strathie-Korrubel and Kluge 1999).

Bromus tectorum is an erect winter- or spring- annual grass that dominates disturbed ground in shrub-steppe ecosystems of western North America. It occurs in a wide variety of habitats but is most abundant in disturbed sagebrush steppe communities (Rice and Mack, 1991). Cheatgrass has a 'compressed phenology' and usually dries out and casts seeds by mid-June. These dry plants fuel wildfires which, if they occur regularly enough, lead to the formation of communities dominated by cheatgrass and other annuals (West, 1983). The self-induced change in fire frequency is probably the species' greatest competitive advantage. Although fire is a natural part of sagebrush grasslands, those fires usually occurred at intervals between 60-100 years. Areas invaded by cheatgrass often burn every 3-5 years (Whisenant, 1989). At this frequency, native shrubs and perennial grasses cannot recover and after a few wildfire cycles a cheatgrass monoculture develops. This monoculture further increases the frequency of fires and increases the dominance by cheatgrass in the area.

An effective management programme needs to control existing infestations and to develop land management plans to prevent reinvasion. Since cheatgrass reproduces entirely by seed, the key to controlling existing infestations is to eliminate new seed production and deplete the existing seed bank. *Bromus tectorum* is most commonly controlled with herbicides, and a two to three-year combination of burning, herbicide application, and reseeding can be used to control and re-vegetate areas is almost exclusively dominated by cheatgrass. Hand pulling cheatgrass is very labour intensive and is only feasible for very small infestations.

Lasting control of cheatgrass requires a combination of chemical and mechanical control, vegetative suppression, and proper livestock management where land is grazed. This integrated (or 'cumulative stress') stress approach keep the plants under constant stress, reducing their ability to flourish and spread. This integrated approach also provides a level of redundancy in case one type of treatment is not implemented or proves to be ineffective (Carpenter and Murray, 1999). *Bromus tectorum* must be one of the most difficult of all invasive alien plants to manage. In the words of Richard Mack, authority on the ecology of this species, 'cheatgrass isn't controlled, it's just fate'.

Selecting an appropriate weed control strategy

The above examples of integrated control programmes utilise mechanical, chemical or biological solutions aimed at the characteristics of the particular plant species (Hobbs and Humphries, 1995). Such approaches may ignore other important aspects of an effective weed control programme; these include the characteristics and dynamic processes in the ecosystem being invaded, and the effects of human activities on these components. In this section we review the effectiveness of conventional approaches in relation to these additional considerations, and explore ways in which they can be dealt with.

Considerations relating to the biological attributes of a species

The selection of an appropriate weed control strategy is often determined primarily on the attributes of the plant species, as shown above. The correct combination of felling, burning, herbicide application and follow-up schedules is dependant on the attributes of the species, such as seed biology, dispersal characteristics, age to maturity, sensitivity to fire, and ability to sprout. It is beyond the scope of this paper to attempt to list all of the possible combinations (although this has been done elsewhere — see van Wilgen, Bond and Richardson, 1992, for invasive plants in the fynbos). In many cases, there are no 'right' answers, and managers have to make judgements about a course of action based on a limited understanding of the consequences. There is therefore always an element of adaptive management (Holling, 1978) in such approaches, where managers learn from previous experiences and adjust management practices accordingly (see also http://tncweeds.ucdavis.edu/products.html).

The case of the use of fire to control pines and hakeas is an example here. Where the infestations are light or moderate, trees can be felled and the site burned with little or no adverse effects. But where dense infestations are cleared, excessive amounts of dead, dry fuel are created, and fire intensities are so high that physical damage to the soil can result. There are options to deal with this situation. First, the conditions for burning can be selected to reduce the fire intensity (Richardson and van Wilgen, 1984). There are also options around burning standing, or felling and removing the fuel loads before burning (Holmes *et al*., 2000), although each has its own drawbacks, such as excessive seed spread following fires in standing plants, or the impractical realities of removing vast amounts of fuel from inaccessible areas prior to burning.

Additional considerations affecting control programmes

The factors affecting control programmes can be grouped into three broad categories. The biological attributes of the invasive species form the first group, and are often the primary factors considered by managers (as described above). These attributes could be viewed as relatively stable, and therefore as 'givens' in the equations of choice facing a manager. The second group is made up of a range of environmental factors such as variations in climate (including drought and floods), fire, and pest outbreaks. This group of factors is stochastic. While they have a profound effect on the outcome of control programmes, they are largely beyond the control of managers. The final group is made up of human activities, and includes the management interventions themselves, and the ways in which they are implemented. This in turn depends on budgets, the levels of skill and knowledge of managers and workers, and the commitment to deal with the problem. This last group represents the activities over which we have some degree of control.

When looking for best practices, we need to understand the effects of our interventions as they interact with the stable and stochastic factors that affect the final outcome. While an approach of adaptive management, based on trial, error and continual improvement, is a logical way in which to progress, the advent of powerful computer simulation modelling technologies will allow managers to do hundreds of 'trial-and-error' runs to explore the consequences of certain courses of action. This should represent an improvement on the current state of affairs, and should allow for better decision-making. In the next section, we present an example of such an approach; we also provide an example of how such an approach could be used to select an appropriate combination of control options.

Modelling the effects of combining different control options

Effective control of invasive alien plants requires the integration of different options. The way in which control measures are integrated is critically important but the outcomes of different permutations are often difficult to predict. Until now, the only way of developing effective control programmes was through trial and error. When one is dealing with long-lived trees and shrubs over thousands of hectares of terrain and when control is extremely expensive and the potential implications of taking the wrong decision are serious, then trial and error is not a viable option.

Recent advances in computer technology and ecological modelling now enable us to model the likely outcomes of different management options in isolation and in various combinations. This affords us the opportunity of optimising the integration of different options to achieve desired results.

To illustrate the utility of this approach, we present a range of outcomes that would be predicted to follow different control approaches for the invasive alien shrub *Acacia saligna* in South African fynbos. The modelling approach is described by Higgins *et al*. (1999, 2000). The model simulates population dynamics of individual *A. saligna* trees in an area of 1.5 km × 1.5 km adjacent to a large source population. The examples we chose to run show the growth of *A. saligna* populations with no management (as control), two approaches of mechanical control (prioritising dense and scattered stands) with two budget levels, and the combination of one mechanical option with bio-control that reduces seed production.

In a scenario of no management, the model predicts that the site would become fully invaded after 100 years (Figure 2). We then modelled the outcomes of management interventions that begin after 40 years. Figures 3 and 4 show the differences after 70 and 100 years that can be achieved by using two basic approaches to mechanical control: prioritise dense stands (close to the founder population) for clearing, or prioritise outlying plants (furthest from the founder population) for clearing. In these scenarios, the available budget would first be used to clear the priority areas, and if any funds remained after that, the rest of the invasions would be cleared.

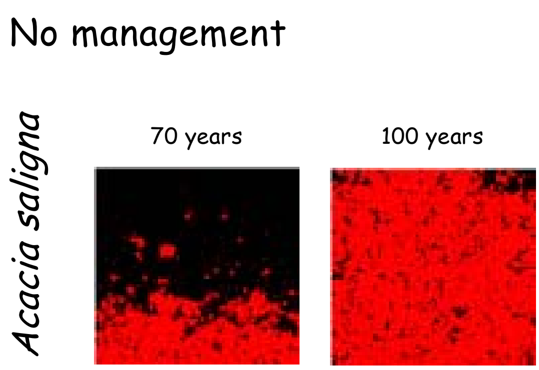

Figure 2. The simulated extent of invasion of an area (1.5 x 1.5 km) adjacent to a dense invasion of *Acacia saligna* at two stages (70 years and 100 years) under a scenario of no management.

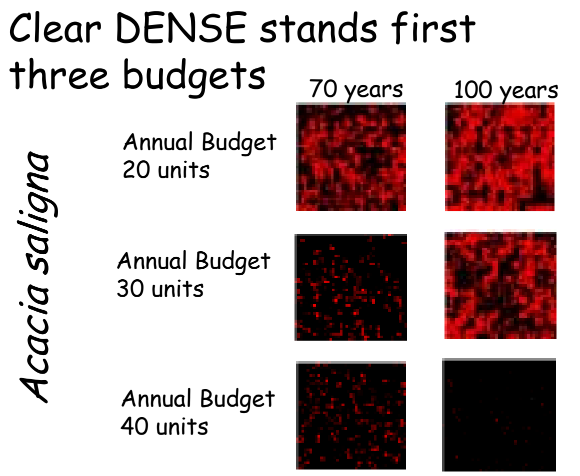

Figure 3. The simulated extent of invasion of an area (1.5 x 1.5 km) adjacent to a dense invasion of *Acacia saligna* at two stages (70 years and 100 years), in a situation where dense stands are given priority for clearing. The effects of three levels of budget availability are also shown.

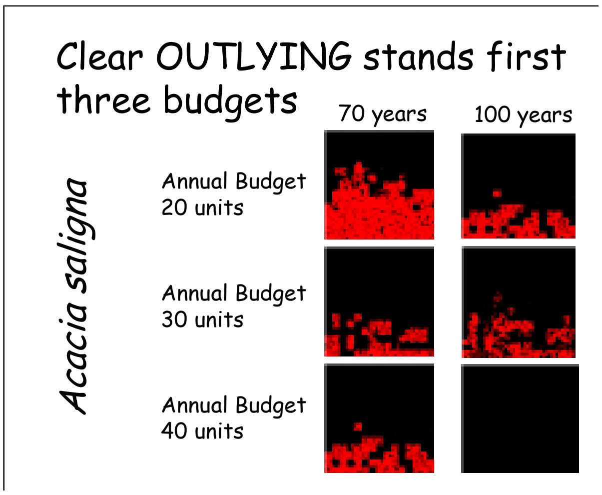

Figure 4. The simulated extent of invasion of an area (1.5 x 1.5 km) adjacent to a dense invasion of *Acacia saligna* at two stages (70 years and 100 years) in a situation where outlying, scattered stands are given priority for clearing. The effects of three levels of budget availability are also shown.

Comparing Figures 3 and 4 shows that for smaller budgets (20 and 30 units in our example), focusing on outlying plants results in a sparser population at the end of the modelling period. As the available budget increases, the differences between the two approaches become less. If the budget is sufficient, focusing on dense stands may be preferable to reduce the likelihood of damage to the native biota and/or particular ecosystem functions. However, where budgets are smaller, it would be better to focus on the scattered, outlying populations.

The effect of combining biological control with mechanical clearing is illustrated in Figure 5. Here, an

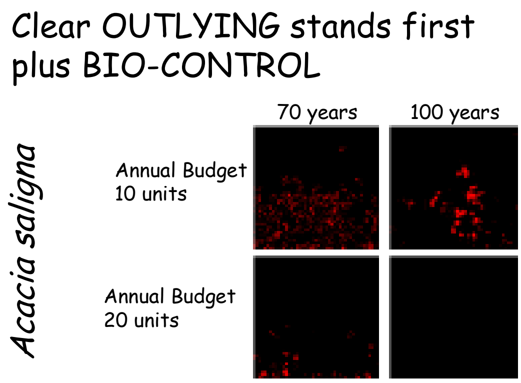

Figure 5. The simulated extent of invasion of an area (1.5 x 1.5 km) adjacent to a dense invasion of *Acacia saligna* at two stages (70 years and 100 years) in a situation where outlying, scattered stands are given priority for clearing, and where biocontrol agents are released simultaneously on the site. The effects of two levels of budget availability are also shown.

annual budget of 20 units would achieve the same result as a budget of 40 units without biocontrol, illustrating the savings that could be brought about by biocontrol in this case.

This modelling approach has great potential for planning control strategies to optimise cost-effectiveness. The approach has also been used to model impacts of different spread and spread-control scenarios on native biodiversity (Higgins *et al.*, 1999).

Conclusions

The challenge for the scientists who have developed models such as those described above lies in their implementation on a large scale. Such models are often developed as an academic exercise, and they seldom find widespread use. There are therefore two priorities. The first is the obvious need for further research to refine and test the models, and the second is in developing a programme for their implementation. An implementation programme would have to take place within the framework of a national strategy for weed control. A national strategy should provide the resources for a technology transfer exercise in which research scientists train managers in the use of modelling techniques that will improve the efficiency of their management. If we are able to achieve widespread use of simulation models, a great deal of progress can be made in integrated weed control.

Acknowledgements

BvW thanks the Department of Water Affairs and Forestry for funding in support of this paper, provided through the Department's Working for Water Programme. We also thank Karin Burns for her assistance in the preparation of the illustrations.

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