Optimising weed control by considering disturbance

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Summary Mounting scientific evidence suggests newly imposed disturbance and/or alterations to existing disturbances facilitate invasion. Several empirical studies have explored the role of disturbance in invasion, but little work has been done to fit current understanding into a format useful for practical control efforts. We are working towards addressing this shortcoming by developing a metapopulation model couched in a decision theory framework. This approach has allowed us to investigate how incorporating the negative effects of disturbance on native vegetation into decision-making can change optimal control measures. In this paper, we present some preliminary results.

Keywords Disturbance, weed control, seed bank, stochastic dynamic programming, *Mimosa pigra*.

INTRODUCTION

In Australia, the estimated annual expenditure on weed control in agriculture alone is a staggering $1.4 billion (Sinden *et al.* 2004). Traditional control measures such as the application of herbicides, bulldozing, raking and burning tend to target weeds directly by attempting to either kill or remove them. The underlying assumption behind these actions is that if the weed is removed then more desirable species should establish. This assumption may not always hold true as several studies have identified disturbance as the main mechanism behind some invasions (Seabloom *et al.* 2003, MacDougall and Turkington 2005). Therefore, if the disturbance remains or is even mimicked by control efforts then the target weed may return. If disturbance is found to play a role in facilitating invasion then attempts to reduce or mitigate its effects may improve the efficacy of weed control efforts.

The way in which disturbance facilitates invasion is complicated. The extent of its role will vary depending on the inherent nature of the disturbance, including its frequency, intensity and duration, the abiotic and biotic conditions of the habitat and the presence of propagules of the invading species. Empirical and theoretical studies have shown that disturbance, either newly imposed (exogenous) or alterations in the existing (endogenous) regime (Pickett *et al.* 1989), can directly facilitate invasion by removing or killing native species, thereby freeing up essential resources such as light, nutrients and space for an invasive species to become established (Hobbs and Humphries 1994). Disturbance has also been found to indirectly facilitate invasion by altering resource conditions in a manner which disadvantages the survival of the native community, such as an increase in nutrient levels in soils that were otherwise nutrient poor.

In this paper, we explore how optimal weed control measures change when the effects of disturbance are considered. To do this, we first present a simple model that describes the main processes behind the invasion of *Mimosa pigra* L. (a perennial legume shrub) into wetlands regions of the Northern Territory. Then we couch this model in a rigorous decision theory framework, Stochastic Dynamic Programming (SDP), to solve for the optimal weed control measure.

Invasion of *Mimosa pigra* *M. pigra* (hereafter mimosa) was introduced into the Northern Territory of Australia in the late 1800s for ornamental purposes. Today, it is estimated to cover more than 80,000 ha of the Tropical North wetlands and is predicted to have the capacity to double its range annually. Because of its high level of invasiveness, potential for spread and socioeconomic and environmental costs, it has been labelled one of 20 weeds of national significance within Australia (Thorp and Lynch 2000).

The problem with mimosa is that it forms dense monocultural thickets (reaching heights of up to 6 m) in habitats once dominated by native grasses. Its establishment has greatly impacted on native wildlife, agricultural production and essential ecosystem services such as hydrology and nutrient cycling. The spread and establishment of mimosa is believed to be accelerated by disturbance, more specifically grazing and trampling of native vegetation by feral animals such as buffalo and pigs (Lonsdale and Farrell 1998, Buckley *et al.* 2004). Foraging buffalo and pigs remove native vegetation from a site, creating an opportunity for mimosa, being shade intolerant, to move in and take over.

METHODS

The metapopulation model we have developed is an example of a Markov Chain with discrete time processes. It describes an area comprised of 10 sites, which are under management for the invasion of mimosa. Each site can be in one of five possible states: 1) occupied by native vegetation (N), 2) recently occupied by mimosa, so having a low seed bank (W_L) 3) open with a low mimosa seed bank (O_L), 4) occupied by mimosa for long enough that a high seed bank has accumulated (W_H), and 5) open with a high seed bank (O_H). The overall state of the land area being managed at any given time is described by the number of sites in each of these five possible states.

The state of each site can change depending on the probability of five transition processes occurring: 1) the probability that disturbance acts to kill and/or remove native or mimosa plants ($N \rightarrow O_L$; $W_L \rightarrow O_L$; $W_H \rightarrow O_H$), 2) the probability of a decrease in the size of the seed bank due to either natural seed decay and/or accelerated decay because of the effects of disturbance ($W_H \rightarrow W_L$; $O_H \rightarrow O_L$), 3) the probability of an increase in the size of the seed bank due to a wide-scale flood or a global seed dispersal event ($W_L \rightarrow W_H$; $O_L \rightarrow O_H$), 4) the probability that mimosa seeds germinate and the seed bank size is reduced and simultaneously mimosa establishes or re-establishes ($O_L \rightarrow N$; $O_L \rightarrow W_L$; $O_H \rightarrow W_L$; $O_H \rightarrow W_H$) and 5) the probability that the size of the seed bank increases from low to high because of reproduction ($W_L \rightarrow W_H$). In the case of each transition, we use a binomial distribution to find the probability that a site changes to another state.

Disturbance created by feral animals Grazing and trampling by feral animals such as buffalo and pigs can act to remove native vegetation from a site. This reduces competition for resources, which acts to increase the probability that mimosa becomes established at the site. It is assumed that sites occupied by native vegetation have a low weed seed bank because of the prolific seed production and dispersal of mimosa seed.

Disturbance created by weed control measures Within the model, control measures are treated as a type of disturbance because they open up sites by killing and/or removing mimosa plants. The effects of four different control measures (and subsequently management decisions) are described within the model and are optimised in the stochastic dynamic program described below.

The four control measures are: 1) no control, 2) the aerial application of herbicides, 3) the aerial application of herbicides plus mechanical measures and 4) the aerial application of herbicides plus a prescribed burn. The control measure chosen changes: the probability that a site occupied by mimosa will become open, the probability of a decrease in the weed seed bank due to accelerated seed decay and the probability of weed establishment as a result of a change in germination rate from the weed seed bank.

Each control measure has both advantages and disadvantages, which makes it difficult to decide which one to implement. The advantage of control option 2, the aerial application of herbicides, is that it has the lowest probability that mimosa will re-establish at the site if the seed bank is low (29%). The main disadvantage of this control measure is that it also has the lowest probability of killing mimosa (65%) because of the broad scale spectrum of its application.

Control measure 3, the combined use of herbicides and mechanical measures, has the highest probability of killing mimosa (75%) because of the higher specificity of the application. It also has the advantage of a moderate probability of accelerating the decay of the seed bank (15%) because of the disruptive nature of using bulldozers and raking the soil. It also has a moderate probability of reducing the seed bank from high to low through stimulating germination (45%). Its disadvantage compared to control measure 2 is that it has a moderate probability of the weed re-establishing after disturbance if the seed bank is low (45%).

Control measure 4, the combined use of herbicides and prescribed burning, has a moderate probability that it will effectively kill and remove adult mimosa plants from a site (70%). This is because the practitioner has less control over which areas are reached. It has the disadvantage of having the highest probability that the weed will re-establish (80%) because fire is known to stimulate germination of mimosa seeds. Its main advantage is that it has the highest probability of accelerating the decay of the seed bank (29%) due to the effects of smoke and heat, and the seed bank size will be reduced from high to low (80%) as fire stimulates germination.

The probability values used are primarily based on a study by Buckley *et al.* 2004. We have found, however, that the model is more sensitive to the relative differences between the control options rather than the values of the individual probabilities

Stochastic Dynamic Program (SDP) To determine the optimal control strategy in relation to the probability of disturbance, we set the metapopulation model into an SDP framework (Mangel and Clark 1988). The advantage of using an SDP algorithm is that the exact optimal state-dependent decision can be found despite the uncertain effects of each control measure. Our objective was to find the optimal control measure that maximises the number of sites occupied by native vegetation at the end of the planning time frame, which was set at 10 years. The optimal decision at each time step *t* is the action with the highest value, as given by the equation:

$$V\left(t, w_L, w_H\right) = \max_{j=\{1,2,3,4\}} \sum_{x=0}^{Z} \sum_{y=0}^{Z-x} a^{j}_{w_L, w_H, x, y} V\left(t+1, x, y\right).$$

$V(t,w_L,w_H)$ is the value of having w_L low seed bank weed sites and w_H high seed bank weed sites at time *t*, and $a^{j}_{W_L,w_L,x,y}$ is the element of the transition matrix, which contains the probability that w_L low and w_H high seed bank weed sites at time *t* become *x* low and *y* high seed bank weed sites at time $t+1$. $V(t+1,x,y)$ is the value of having *x* low seed bank weed sites and *y* high seed bank weed sites at time $t+1$.

To investigate how disturbance changes optimal control measures, we ran the SDP twice, once where the probability of feral animal disturbance to native vegetation was set at 0% and again at 10%.

RESULTS AND DISCUSSION

Our results (Figure 1) highlight the importance of considering disturbance in weed management programs. Accounting for the negative effects of disturbance can alter which control measure is optimal, particularly if the invasion is extensive. Each box in Figures 1a and b represents the management scenario, that is, the number of sites occupied by mimosa with a low seed bank (w_L) and/or occupied by mimosa with a high seed bank (w_H). The shade of each box indicates the control measure found to be optimal for that scenario. For example in Figure 1a when the invasion is extensive (most of the 10 sites are occupied with mimosa with a high seed bank) and the probability of disturbance to native vegetation is 0%, the optimal control measure is the use of herbicides and mechanical control (number 3). However, if the probability of disturbance is set at 10%, the optimal control measure is instead the herbicide and prescribed burn combination (number 4).

Overall, we found if there is a small probability of disturbance to native vegetation (10%) and the invasion of mimosa is extensive, then control measures should shift focus from the current population to future populations (managing seed bank size). This can be done by choosing the control measure that maximises the probability that the weed seed bank is reduced in size, even if the short-term trade-off is a high probability that the weed re-establishes (method 4: herbicide and burn). This decision may be counterintuitive because the first instinct of a resource practitioner may be to select the control measure that has the highest probability of killing the current population and a lower probability of stimulating germination. In the long-term this may not be an effective strategy for a weed such as mimosa, whose establishment and persistence is favoured heavily by disturbance, as the next disturbance event might encourage re-establishment regardless of control efforts. Instead, reducing the size of the seed bank may be more effective, although also more labour intensive.

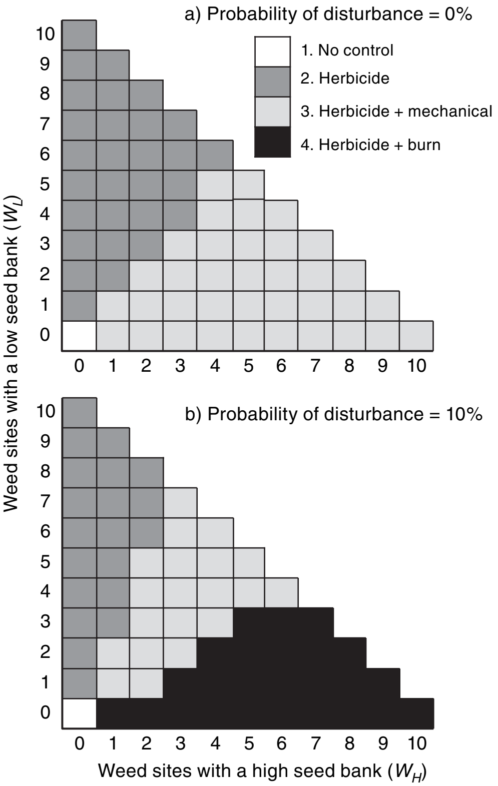

Figure 1. The optimal set of control measures. Each box represents the possible management scenario at the start of the planning period. The shade of the box indicates the optimal control measure if the system is in that state at time 0.

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