Estimating the duration and cost of weed eradication programmes

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Abstract Two prerequisites for realistically embarking upon an eradication programme are that cost-benefit analysis favours this strategy over other management options and that sufficient resources are available to carry the programme through to completion. These are not independent criteria, but it is our view that too little attention has been paid to estimating the investment required to complete weed eradication programmes. We deal with this problem by using a two-pronged approach: 1) developing a stochastic dynamic model that provides an estimation of programme duration; and 2) estimating the inputs required to delimit a weed incursion and to prevent weed reproduction over a sufficiently long period to allow eradication of all infestations. The model is built upon relationships that capture the time-related detection of new infested areas, rates of progression of infestations from the active to the monitoring stage, rates of reversion of infestations from the monitoring to active stage, and the frequency distribution of time since last detection for all infestations. This approach is applied to the branched broomrape (Orobanche ramosa) eradication programme currently underway in South Australia. This programme commenced in 1999 and currently 7450 ha are known to be infested with the weed. To date none of the infestations have been eradicated. Given recent (2008) levels of investment and current eradication methods, model predictions are that it would take, on average, an additional 73 years to eradicate this weed at an average additional cost (NPV) of $AU67.9m. When the model was run for circumstances in 2003 and 2006, the average programme duration and total cost (NPV) were predicted to be 159 and 94 years, and $AU91.3m and $AU72.3m, respectively. The reduction in estimated programme length and cost may represent progress towards the eradication objective, although eradication of this species still remains a long term prospect.

Keywords: Branched broomrape, eradication feasibility, Orobanche ramosa, stochastic dynamic model

INTRODUCTION

One requirement for eradication is that sufficient funding is available to complete the programme (Myers et al. 2000; Panetta 2009; Simberloff 2009; Gardener et al. 2010). For weeds, programme duration may be in the order of decades (Mack and Lonsdale 2002) owing, among other reasons, to the persistence of seed banks. However, weed eradication programmes have often been initiated without realistic estimates of the resources required to achieve their objective. This is understandable up to a point, because during the early stages of an incursion there may be uncertainty about the extent of spread and critical biological attributes of the target species. However, we maintain that subsequent reviews have often been undertaken without sufficient consideration of likely duration of the programme and hence future requirements for resources.

In simple terms, a weed eradication comprises the search effort required to delimit an incursion plus the additional search and control effort required to prevent reproduction until extirpation is achieved over the entire infested area (Panetta 2009). The feasibility of eradication depends upon such disparate factors as: 1) the number, area and spatial distribution of infestations; 2) detectability of the weed, and 3) biological characteristics such as time to reproduction and seed persistence (Panetta and Timmins 2004). Cacho et al. (2006) demonstrated the crucial effects of weed detectability and search effort on the duration of a weed eradication programme. They also showed that for a given level of detectability and search effort, search speed, control effectiveness, germination rate and seed longevity had the greatest influence on eradication programme length. Later work provided preliminary estimates of the cost and duration of eradication programmes that could be used to prioritise weeds for control (Cacho et al. 2007).

The attempted eradication of some major weeds in Australia has involved cost-sharing arrangements whereby the federal government provides 50% of total funding and the states and territories provide the remainder on the basis of the relative risk posed to each by the incursion (Panetta 2009). Major reviews of these programmes are undertaken at three year intervals, but tend to have an operational focus, without due regard to how long it might take to achieve the eradication objective and hence funding requirements over the long term. In this paper we present an estimate of the duration and future cost for an eradication programme against branched broomrape (Orobanche ramosa L.) in South Australia. We also demonstrate retrospectively how, on the basis of available information, estimates of both programme duration and cost can change over time.

METHODS

The eradication programme

Branched broomrape is an annual obligate parasite that has a wide range of broadleaved crops as hosts (Jupp et al. 2002). It has been estimated that in 2006 the annual value of Australian crops at risk from branched broomrape was approximately $AU1.87b (Econsearch 2008). An economic evaluation of an eradication scenario for branched broomrape suggested a benefit-cost ratio of 3.4 over 30 years. This assessment assumed that it would take 60 years for 100% infestation of susceptible crops and 15 years for a maximum yield loss (35% for all host crops) in any given area of infestation (Econsearch 2008). However, contamination of products with branched broomrape seed could have a major impact on export markets, since many of Australia’s trading partners are free of this species. This was not factored into the analysis.

Branched broomrape was first detected in Glenelg, South Australia in 1911, as a single infestation that disappeared within a few years of detection. The species was not observed again until 1992, in the vicinity of Bowhill, 90 km E of Glenelg (Jupp et al. 2002) and was considered to have resulted from a separate introduction. This second infestation was eradicated by fumigation with methyl bromide, but over the next seven years, an additional 22 infestations were found within a 15 km radius. Broadscale surveys were then undertaken and in November 1999 a quarantine area covering all known...
infestations was declared in order to contain and eradicate the weed. A cost-sharing arrangement between the federal and state governments for an eradication programme was initiated in 2000 (Wilson and Bowran 2002).

Surveys between late winter and early summer have continued at yearly intervals within and adjacent to the quarantine area, as well as on properties in other areas with links to infested properties. The highest densities of branched broomrape’s weed hosts inhabit the perimeter of paddocks, so searches target this area, with a few additional transects across each paddock (Jupp et al. 2002). Only about 3% of a paddock is searched each year (N. Secomb pers. comm.), which accounts for the low search cost when expressed on a per hectare basis (Table 1). The total area over which the weed is distributed is currently 7450 ha.

Infestations are controlled by a combination of host denial (including control of the weeds that are hosts for branched broomrape) and soil fumigation of roadside and smaller satellite infestations (Wilson and Bowran 2002). Although there is still some uncertainty regarding potential seed persistence for this species, the operational criterion for eradication of an infestation of branched broomrape is the lack of detection for 12 consecutive years (Panetta and Lawes 2005).

Records were acquired for each infestation for each year of the eradication programme from 1999 to 2008. In cultivated situations, infestations were defined by the total area of a paddock in which branched broomrape plants had been detected; in other situations they were defined by minimum convex polygons (IUCN 1994) that incorporated the outermost plants. Infestations were designated as active in any year that branched broomrape was detected. The total area of newly detected infestations was calculated for each year as was the total cumulative infested area. Records were also maintained of the area searched for each year.

### The model

#### Model structure

We developed a stochastic dynamic model (Fig. 1) for predicting the trajectory of total infested area, and hence programme duration. In this model, total infested area is divided into: 1) an active state in which the weed is detectable above ground; and 2) a monitored state where no recruits have been detected for at least 12 months (Panetta 2007). Data from the programme are used to estimate progression from the active state to the monitored state and reversion from the monitored state to the active state upon the further detection of plants. Given these transition rates, at the end of each time step the amount of infested area that is in the active or the monitored state is updated. When the weed has not been detected in an infestation for 12 years, the infestation is considered to be eradicated and hence the area of the infestation is subtracted from the total infested area. To date, however, there has not been sufficient time within the programme to eradicate any infestations.

The model is based upon three functions (Fig. 1):

1. The predicted discovery of new infested area
2. The rate of progression of infested area (considering all infestations) from active status to monitored status
3. The rate of reversion of infested area (considering all infestations) from monitored to active status.

### Table 1 Economic and associated information employed in model run for 2008.

<table>
<thead>
<tr>
<th>Description</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Search ($AU/ha)</td>
<td>2.77</td>
</tr>
<tr>
<td>Area searched (ha)</td>
<td>333,000</td>
</tr>
<tr>
<td>Control ($AU/ha)</td>
<td>341.27</td>
</tr>
<tr>
<td>Area treated (ha)</td>
<td>1634</td>
</tr>
<tr>
<td>Administration ($AU)</td>
<td>532,831</td>
</tr>
<tr>
<td>Research and communication ($AU)</td>
<td>352,269</td>
</tr>
<tr>
<td>Discount rate</td>
<td>0.06</td>
</tr>
</tbody>
</table>

### Table 2 Categorisation of infested area relative to the time since last detection of branched broomrape for the three years for which the model was run. Note that zero years since last detection denotes active infestations and that the criterion for eradication is 12 years since last detection.

<table>
<thead>
<tr>
<th>Years since last detection</th>
<th>2003</th>
<th>2006</th>
<th>2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4113</td>
<td>3150</td>
<td>1634</td>
</tr>
<tr>
<td>1</td>
<td>167</td>
<td>1134</td>
<td>1769</td>
</tr>
<tr>
<td>2</td>
<td>1097</td>
<td>345</td>
<td>871</td>
</tr>
<tr>
<td>3</td>
<td>886</td>
<td>831</td>
<td>1003</td>
</tr>
<tr>
<td>4</td>
<td>70.8</td>
<td>11.3</td>
<td>20.1</td>
</tr>
<tr>
<td>5</td>
<td>-</td>
<td>929</td>
<td>744</td>
</tr>
<tr>
<td>6</td>
<td>-</td>
<td>579</td>
<td>5.3</td>
</tr>
<tr>
<td>7</td>
<td>-</td>
<td>68.6</td>
<td>558</td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>-</td>
<td>816</td>
</tr>
<tr>
<td>9</td>
<td>-</td>
<td>-</td>
<td>29.4</td>
</tr>
<tr>
<td>10</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>6334</td>
<td>7048</td>
<td>7450</td>
</tr>
</tbody>
</table>

**Fig. 1** Schematic diagram illustrating the functions upon which the stochastic dynamic branched broomrape eradication model was based. See text for description of the progression and reversion functions.

**Fig. 2** Detection of new infested area during the course of the branched broomrape eradication programme.
Island invasives: eradication and management

Predictions of future detection of new infested area were based upon regression of historical data for detection of new infestations (Fig. 2).

The rate of progression from the active phase to the monitoring phase (0.696 ± 0.138, mean ± SD) was calculated from the data for all years (1999-2008) of the eradication programme.

Reversion from monitored to active status could be calculated only from 2001 onward, since the first year in which infestations could reach monitoring status was 2000. Thereafter, for each year and each stage of the monitoring phase (e.g., 1, 2, 3...n years since last detection) (see Table 2) the rate of reversion to the active phase was calculated by expressing the number of infestations reverting as a proportion of the total number of infestations in that stage. These rates were then regressed against the number of years without detection and the resulting relationship was used to model reversion of infestations from the monitoring to the active phase (Fig. 3).

The model simulates the active infested area at any time, calculated as:

\[ A_t = A_{t-1} + A_n - A_p \]

where \( A_t \) = total active area at time \( t \)
\( A_{t-1} \) = active area at the previous time step
\( A_n \) = new infested area detected since the previous time step
\( A_p \) = area that has reverted from the monitoring stage to the active stage since the previous time step

\( A_x \) = area that has progressed from the active stage to the monitoring stage since the previous time step. Note that the area of any infestation that remains in the monitoring stage for a time step automatically advances to the next category of years since last detection (Table 2).

The model operates on annual time steps, corresponding to annual searches for the weed. It allows the user to specify both the maximum time period and the number of Monte Carlo simulations to be employed. Stochasticity was introduced by sampling randomly from a normal distribution based on the rate predicted by a regression equation. More specifically, the rate of change for a given iteration of the model were calculated for the three functions as: \( y = \alpha - \beta \ln(x) + \varepsilon \), where (depending on the function) \( y \) represented new infested area, progression rate or reversion rate; \( x \) represented calendar year or years in the monitoring phase; and \( \varepsilon \) is an error term which is normally distributed with mean 0 and standard deviation \( \sigma \). The values of \((\alpha, \beta, \sigma)\) estimated from the data were: (1974, 813.62, 475.25) for new infested area, (0.696, 0.0138) for progression rate, and (0.2004, 0.0936, 0.018) for reversion rate.

The model simulates the process for any given set of parameters given by the user rather than optimising an objective function. We specified a maximum time frame for simulations of 200 years with 50 simulations for the results presented herein. In order to determine how predictions might have changed through time, the model was run initially for 2008 and then for conditions existing in 2006 and 2003. Insufficient data were available to estimate functions 1-3 (above) prior to 2003, and 2006 represented a year in which new detections led to almost a 10% increase in total infested area (Panetta and Lawes 2007).

**Economic data**

Data on programme expenditure between July 2001 and June 2008 were used to calculate model inputs since complete data for the 2008/2009 financial year were not available. Given that we used average values (see below) over a relatively long period, this data deficiency was not expected to have a major effect upon the results. Expenditure was divided between the following activities: treatment, searching, administration, and research and communications. Average values of these allocations (Table 1) were utilised for the purpose of prediction of future programme costs and we assumed that relative allocation between the activities would not change through time. As of June 2009, total programme expenditure was $AU32,548,000 (P. Warren pers. comm.).

In order to make the results modelled for 2006 and 2003 comparable to those for 2008, appropriate deflation factors were incorporated to adjust all costs to net present value (NPV).

**RESULTS**

Given recent (2008) levels of investment and current eradication methods, the model predicts that on average an additional 73 years will be required to eradicate branched broomrape in South Australia (Fig. 4 A) at an average additional cost (NPV) of $AU67.9m (Table 3). Eradication was achieved in less than 100 years in all 50 simulations (Fig. 4 B). Estimates of programme costs varied between $AU63m and $AU75m (Fig. 4 C).

When the model was run for the circumstances in 2003 and 2006, the average programme duration and total cost (NPV) were predicted to be 159 and 94 years, and $AU91.3m and $AU72.3m, respectively (results not presented). These results suggest a significant improvement in eradication prospects from 2006 onward, which is likely due to decreases in the amount of infested area in the active phase (Table 2). However, it is clear that eradication of this species has been, and remains, a long term prospect.
Eradication could be achieved more rapidly by directly targeting soil seed banks of this species, an approach used with success against another parasitic weed, witchweed (Striga asiatica L. (Kuntze)). By the end of 2007, witchweed infestations in the United States were reduced from 200,000 ha in the early 1970s (Eplee 2001) to approximately 900 ha (R. Iverson pers. comm.). As for branched broomrape, soil fumigants effectively killed witchweed seeds, but were too expensive for general use. However, when ethylene was used as a germination stimulant, and combined with treatments that prevented reproduction of the target species, it was possible to eradicate infestations of witchweed in about three years (Eplee 1992). A cost-effective method for rapidly reducing soil seed populations of branched broomrape would thus enhance the speed of eradication; this has been an area of considerable research activity in South Australia (Matthews et al. 2006; Virtue et al. 2006; Williams et al. 2006). Until such a method becomes available, however, the programme will remain largely reliant upon natural attrition of the seed bank, in combination with sustained prevention of its replenishment.

Even though our model predicts (on average) that 73 years would be required to achieve eradication, for the last 20 or so years, less than 10 ha of infested area may remain (see long tail of the trace in Fig. 4 A). There may thus be scope to shorten programme duration considerably through the application of expensive methods such as fumigation. This would lead to obvious savings across the various components of programme expenditure.

The allocation of future expenditure between different programme activities is based on several assumptions. For example, administration and the combined costs of research and communication have been treated as fixed costs. We also assume that high investment in control and searching is maintained throughout the programme. Some assumptions are perhaps easier to justify than others. It is unlikely that administrative costs would decrease substantially until at least the final years of the programme. While the need for research might decrease, there could be a compensatory requirement for increased communication so that public awareness and support are maintained through to completion of the programme. The cost of control is a direct function of the remaining infested area, so does not present much scope a priori for manipulation.

Whether searches over hundreds of thousands of hectares for new infestations will be required when only a few hundred hectares (or less) remain infested is debatable. To date there has been limited research on how to optimise investments in the search and control functions (e.g., Hester et al. 2008). Mehta et al. (2007) note that decision-makers often allocate fixed resources to certain activities over multiple time periods; these authors identify possibilities for updating management strategies through varying search effort over time. We believe that there is considerable scope for improving estimates of future costs of eradication programmes by exploring the potential effects of different temporal patterns of investment on both programme duration and cost.

Given the uncertainties that exist when a weed eradication programme commences, methods are needed to evaluate performance in conjunction with tools that
can assist decisions to shift to alternative management strategies should these be warranted. Such decisions require quantitative measures that are utilised at predetermined decision points (Panetta 2009). Some measures of progress towards eradication have been developed (see Panetta 2007; Panetta and Lawes 2005, 2007). The present work adds to these by estimating costs associated with changes in the size and duration of the programme over time.

Feasibility of eradication must be considered in relation to the amount of investment (effort) available (Rainbolt and Coblenz 1997; Panetta and Timmins 2004; Panetta 2009). Increases over time in total known infested area will require increased funding, which has obvious implications for the ongoing assessment of eradication feasibility. The required investment should be estimated iteratively as a programme proceeds, and judgments made regarding whether eradication is still a feasible option given technical limitations and economic constraints (Panetta 2009). If properly informed, decision makers should be able to adopt a dynamic approach that allows switching to more economically optimal strategies (e.g., containment or sustained control) when required.

This study has quantified only the costs of branched broomrape eradication. A full analysis, which considered a 30 year period from the inception of the programme, estimated total incremental costs (NPV) of $AU75.46m and total incremental benefits of $AU258.52m. This yields a benefit:cost ratio (BCR) of 3.43 (Econsearch 2008). Interestingly, the BCR of a containment programme over the same timeframe was 3.85. Our model suggests that a BCR for the programme needs to be estimated over a longer timeframe but this is another exercise. The fact that an alternative management strategy is favoured economically in the shorter term suggests that eradication is not likely to be selected over longer periods, unless it remains advantageous to pursue eradication when potential negative impacts upon international trade are taken into account.

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