Journal of Applied Ecology

Journal of Applied Ecology 2011, **48**, 980–988 doi: 10.1111/j.1365-2664.2011.02000.x

Estimating and influencing the duration of weed eradication programmes

F. Dane Panetta[1]*, Oscar Cacho[2], Susie Hester[2], Nikki Sims-Chilton[1] and Simon Brooks[3]

[1]*Alan Fletcher Research Station, Biosecurity Queensland, Department of Employment, Economic Development and Innovation, PO Box 36, Sherwood, Qld 4075, Australia;* [2]*School of Business, Economics and Public Policy, University of New England, Armidale, NSW, Australia; and* [3]*Tropical Weeds Research Centre, Biosecurity Queensland, Department of Employment, Economic Development and Innovation, PO Box 187, Charters Towers, Qld 4820, Australia*

Summary

1. Weed eradication efforts often must be sustained for long periods owing to the existence of persistent seed banks, among other factors. Decision makers need to consider both the amount of investment required and the period over which investment must be maintained when determining whether to commit to (or continue) an eradication programme. However, a basis for estimating eradication programme duration based on simple data has been lacking. Here, we present a stochastic dynamic model that can provide such estimates.

2. The model is based upon the rates of progression of infestations from the active to the monitoring state (i.e. no plants detected for at least 12 months), rates of reversion of infestations from monitoring to the active state and the frequency distribution of time since last detection for all infestations. Isoquants that illustrate the combinations of progression and reversion parameters corresponding to eradication within different time frames are generated.

3. The model is applied to ongoing eradication programmes targeting branched broomrape *Orobanche ramosa* and chromolaena *Chromolaena odorata*. The minimum periods in which eradication could potentially be achieved were 22 and 23 years, respectively. On the basis of programme performance until 2008, however, eradication is predicted to take considerably longer for both species (on average, 62 and 248 years, respectively). Performance of the branched broomrape programme could be best improved through reducing rates of reversion to the active state; for chromolaena, boosting rates of progression to the monitoring state is more important.

4. *Synthesis and applications*. Our model for estimating weed eradication programme duration, which captures critical transitions between a limited number of states, is readily applicable to any weed. A particular strength of the method lies in its minimal data requirements. These comprise estimates of maximum seed persistence and infested area, plus consistent annual records of the detection (or otherwise) of the weed in each infestation. This work provides a framework for identifying where improvements in management are needed and a basis for testing the effectiveness of alternative tactics. If adopted, our approach should help improve decision making with regard to eradication as a management strategy.

Key-words: branched broomrape, chromolaena, *Chromolaena odorata*, eradication feasibility, *Orobanche ramosa*, stochastic dynamic model

Introduction

A number of studies have been undertaken in recent years to determine when eradication is an appropriate response to a weed invasion (Rejmánek & Pitcairn 2002; Cunningham *et al.* 2004; Panetta & Timmins 2004; Woldendorp & Bomford 2004; Gardener, Atkinson & Rentería 2010). Eradication is an appealing strategy for serious weeds because other alternatives (such as containment or control to a level below an impact threshold) require permanent, ongoing investment of resources, unless a species can be brought under effective biological control. Eradication of a weed may be more cost-effective than any other form of control but should only be attempted if it is considered feasible (Wittenberg & Cock 2001).

The interplay of many factors can determine whether eradication is a feasible objective. These can be broadly categorized as sociopolitical, economic, biological and

*Correspondence author. E-mail: dane.panetta@deedi.qld.gov.au

operational (Bomford & O'Brien 1995; Myers *et al.* 2000; Simberloff 2003; Panetta & Timmins 2004; Panetta 2009). For informed decision making, a systematic approach to the estimation of eradication feasibility is required, whereby the importance of each factor, as well as the scope for dealing with any difficulties posed by this factor, is assessed. Regardless of other detail, sustained institutional and public support are essential for any eradication programme (Myers *et al.* 2000; Simberloff 2003; Mack & Foster 2009). Without these, a programme can easily founder, because in many cases eradication efforts must be maintained for decades (Mack & Lonsdale 2002), owing to the common occurrence of persistent seed banks, among other reasons. Sustaining the allocation of funding and other resources over such time frames may be problematic and decision makers need to know for how long an eradication programme must run to achieve its objective. Equally, over the course of an eradication programme, there is a need to assess progress towards the objective (Panetta & Lawes 2007) and to identify the ways of improving programme performance.

There have been several attempts to estimate the duration of weed eradication programmes on theoretical grounds. Cacho *et al.* (2006) demonstrated the critical effects of detectability and search effort on the duration of a weed eradication programme and 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 prioritize weeds for control (Cacho, Hester & Spring 2007). These studies have shed light on the influences of the biological and operational factors that determine eradication feasibility and provide the foundation for a 'first-pass' estimation of programme duration. They also led to the development of software that can be used by decision makers to generate such estimates (Cacho & Pheloung 2007; Panetta *et al.* 2011). However, in terms of the periodic assessment of ongoing eradication programmes, there remains a need for an approach that can be used to estimate programme length using simple indices (see Panetta 2007) derived from field observations.

We have recently developed a stochastic dynamic model that can be used to estimate eradication programme duration from fitted functions describing the temporal patterns of detection of a weed (Panetta *et al.* in press). On the basis of observed trends, it was estimated that a programme lasting for > 50 years would be required to eradicate a branched broomrape *Orobanche ramosa* L. invasion in South Australia. In this study, we simplify the model and extend its application to identify the areas of management where improvements would lead to reductions in the time required to achieve eradication. As branched broomrape is atypical in the sense of being a parasitic annual species, we apply the same approach to a nonparasitic perennial, chromolaena *Chromolaena odorata* (L.) King and Robinson, which is targeted for eradication in the north Queensland tropics. Finally, because there is a degree of uncertainty regarding seed persistence for both weeds, the implications of varying seed persistence for eradication programme length are explored.

Materials and methods

THE ERADICATION PROGRAMMES

Branched broomrape

Branched broomrape is an annual obligate parasitic species that has a wide range of broadleaved crops and weeds as hosts (Jupp, Warren & Secomb 2002). In 2006, the annual value of Australian crops at risk from branched broomrape was *c.* AUD1·87 billion (Econsearch 2008). Furthermore, contamination of products with branched broomrape seed could have a major impact on export markets, because many of Australia's trading partners are free of this species.

Branched broomrape was initially detected in South Australia during 1911, but this single infestation appears to have gone extinct shortly afterwards (Jupp, Warren & Secomb 2002). The first infestation of the current invasion of branched broomrape was detected in 1992. It was eradicated by fumigation with methyl bromide, but an additional 22 infestations were found within 15 km over the next 7 years. Broadscale surveys were then undertaken, and in November 1999, a quarantine area, which included all known infestations, was declared 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 & Bowran 2002). As of 2008, 260 infestations had been detected, with an annual programme expenditure of *c.* AUD4 million.

Infestations are controlled by a combination of host denial (including control of the weeds that are hosts for branched broomrape) and, to a much lesser extent, soil fumigation of roadside and smaller satellite infestations (Wilson & Bowran 2002). This approach is largely in agreement with theory developed by Regan, Chades & Possingham (2011). Surveys for branched broomrape have been conducted consistently at yearly intervals within and adjacent to the quarantine area, as well as on properties in other areas with links to infested properties. Surveys are undertaken between late winter and early summer. While there is uncertainty regarding potential seed persistence for this species, the operational criterion for the eradication of an infestation is the lack of detection for 12 consecutive years (Panetta & Lawes 2005).

Chromolaena

Chromolaena is a fast-growing perennial shrub, with long branching stems that can clamber up to 20 m on supporting vegetation. It has a pantropical distribution and is considered a weed in over 50 countries throughout Africa, Asia and the western Pacific (Zachariades *et al.* 2009). It was first reported in Australia in 1994, most probably introduced via contaminated pasture seed (Waterhouse 1994).

Chromolaena flowers prolifically and its achenes (hereafter 'seeds') are dispersed to a minor extent by wind (Witkowski & Wilson 2001) and more so by water, on stock and machinery, as well as by people, through the attachment of seeds to clothing and possessions (Zachariades *et al.* 2009). In open areas, it can form dense monocultures, suppressing all other species and out-competing preferred pasture species. However, it tolerates partial shade such as under plantation crops, where it can become the dominant species. During the dry season, chromolaena dies back to become a fire hazard. If left uncontrolled in north Queensland, chromolaena could invade cropping and grazing areas, reducing productivity, and could also invade many natural ecosystems, becoming the dominant understorey species and reducing biodiversity.

Chromolaena has been the target of a national cost-shared eradication programme since 1995, currently costing over AUD1·3 million pa (DEEDI 2009). As of 2008, 418 infestations had been detected. A cost-benefit analysis of this programme undertaken in 2008 indicated accumulated benefits to agriculture of AUD2·9 billion, and combined benefits to agriculture and the environment (in terms of maintenance of ecosystem services) of AUD4·5 billion (Goswami 2008).

A range of control measures is employed in the eradication programme. Isolated plants are removed physically. For large infestations, herbicides (e.g. triclopyr + picloram, and fluroxypyr) are effective as foliar sprays. Fire is used in some areas to reduce plant and seed numbers to the point where other control measures can be implemented. Surveys for chromolaena are conducted annually between May and July, although not all infestations have been visited consistently, owing to operational constraints (see Discussion). The criterion for the eradication of an infestation is the lack of detection for seven consecutive years, based upon evidence obtained from a single feld study of seed bank depletion (Setter, Graham & Patane 2007).

THE MODEL

Model structure

A model (Fig. 1) was developed for predicting the trajectory of total infested area and hence programme duration. It differs from that of Panetta *et al.* (in press) in that no allowance is made for new infested areas that might be detected in the future. Accordingly, it is assumed that the invasion has been delimited, but should new areas be detected, the model can simply be run again.

Total infested area is divided into two states: active (in which the weed is detectable above-ground) or monitored (where no recruits have been detected for at least 12 months; Panetta 2007). The proportion of area in the active state vs. the monitored state changes each year based on transition rates (i.e. *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) that are estimated from programme data. 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 an amount of time exceeding maximum seed persistence, the infestation is considered to be eradicated and hence the area of the infestation is subtracted from the total infested area.

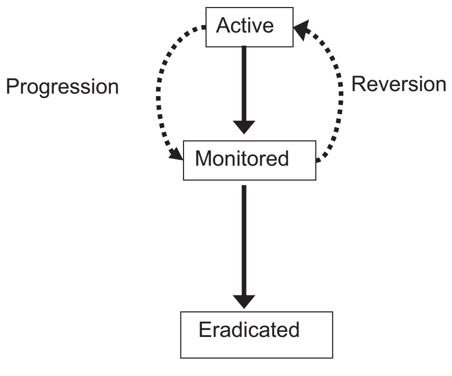

Fig. 1. Schematic diagram illustrating the functions upon which the stochastic dynamic eradication model was based. Active weed infestations progress to monitored status when plants have not been detected for at least 12 months; monitored infestations revert to active status upon further detection of plants. A monitored infestation is considered to be eradicated when plants have not been detected for a period equal to or exceeding maximum seed persistence for the species (in this case, 12 years for branched broomrape and 7 years for chromolaena).

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

1. The rate of progression of infested area (considering all infestations) from active status to monitored status

2. The rate of reversion of infested area (considering all infestations) from monitored to active status.

The total area infested at any time t is given by the sum of active area (A_t) and the area under monitoring (M_t). The active infested area at any time t is calculated as:

$$A_t = A_{t-1} - A_{Pt} + A_{Rt} + A_{Nt} \qquad \text{eqn 1}$$

where A_t is the total active area at time t, A_{Pt} is the area that has progressed from the active stage to the monitoring stage since the previous time step, A_{Rt} is the area that has reverted from the monitoring state to the active state since the previous time step, and A_{Nt} is new infested area detected since the previous time step. Here, we assume that the invasion has been delimited and hence $A_{Nt} = 0$.

The progression area is calculated as:

$$A_{Pt} = (\gamma + \varepsilon_P)A_t \qquad \text{eqn 2}$$

where γ is the progression factor that indicates the rate of progression from the active state to the monitoring state and ε_P is a normally distributed error term with mean zero and standard deviation σ_P. The factor γ is calculated from the data as the proportion of the total number of infestations that transitions from the active phase (plants detectable) to the monitoring phase (no plants detectable) for each year of the programme.

The reversion area is calculated as:

$$A_{Rt} = \sum_i M_{i,t}R(i) \qquad \text{eqn 3}$$

where $M_{i,t}$ is the area that has been monitored i years at time t and $R(i)$ is a reversion function. Note that $M_{i,t}$ is the monitored area for each year and each stage (i) of the monitoring state (i = 1, 2, 3…n years since last detection), and therefore, the total area monitored in any given year is calculated as:

$$M_t = \sum_i M_{i,t} \qquad \text{eqn 4}$$

The area of any infestation that remains in the monitoring state for a time step automatically advances to the next category of years since last detection (stage i + 1), and this is adjusted by the reversion rate. The area of the first monitoring stage is the progression area. These transitions are represented as:

$$M_{i,t} = (1 - R(i))M_{i-1,t-1}; \text{for } i = 2, \ldots n \qquad \text{eqn 5}$$

$$M_{1,t} = A_{Pt} \qquad \text{eqn 6}$$

Eradication of an individual infestation occurs when the monitoring period exceeds maximum seed persistence (n). Eradication of the invasion is achieved when all infestations have been extirpated (i.e. when $A_t + M_t = 0$).

The reversion function used in eqns (3) and (5) gives the rate of reversion of monitored area to the active state in relation to its monitoring stage i. $R(i)$ is calculated from the data by expressing the number of infestations reverting as a proportion of the total number of infestations in that stage. These rates are then regressed against the number of years without detection, and the resulting relationship is used to model the reversion of infestations from the monitoring to the active state (using eqn 3). The reversion function is represented as:

$$R(i) = \alpha + \beta \ln(i) + \varepsilon_R \qquad \text{eqn 7}$$

where α and β are intercept and slope coefficients, respectively, and ε_R is a normally distributed error term with mean zero and standard deviation σ_R. These coefficients are estimated through linear regression. For short, β is referred to as the reversion coefficient given elsewhere.

Numerical model

The numerical implementation of the model allows deterministic or stochastic simulations to be undertaken. The user can specify both the maximum time period and the number of Monte Carlo simulations to be employed. Stochasticity is introduced by sampling randomly from normal distributions based on the variance of the progression coefficient γ and the mean square error of the linear regression of the reversion function (eqn 7). More specifically, in deterministic simulations, the expected progression and reversion rates for each iteration of the model are calculated from eqns (2) and (7) with $\varepsilon_P = \varepsilon_R = 0$. In stochastic simulations, a number of Monte Carlo iterations are run, with ε_P and ε_R drawn randomly for each iteration from normal distributions with means of zero and standard deviations of σ_P and σ_R, respectively.

The model operates on annual time steps, corresponding to annual searches for the weed. It simulates the process for any given set of parameters given by the user, rather than optimizing an objective function. We specified a maximum time frame for simulations of 250 and 280 years for branched broomrape and chromolaena, respectively, with 250 iterations for the stochastic results presented herein.

The model was applied to the two case-study species, and probability distributions of time to eradication were generated. Once the analysis for the current programmes was completed, additional simulations were undertaken to determine the combinations of progression and reversion rates that would be able to achieve eradication in a given (target) number of years. This analysis was based on the deterministic model and consisted of deriving isoquants showing the possible combinations of progression factor (γ) and reversion coefficient (β) values that result in a given target time to eradication T_E.

To derive the isoquants, the model was embedded into an iterative search algorithm where the target T_E is set by the user and a table of (γ, β) pairs that satisfy this target is determined by the model. The search was based on a simple bisection root-finding algorithm (Press *et al.* 1986, pp. 246–247).

Data acquisition

Records for both species were acquired for each infestation for each year of the respective eradication programme from 1999 to 2008 (nonexistent or poor records precluded the use of a longer time series for chromolaena). For branched broomrape, infestations in cultivated situations were defined by the total area of a paddock in which plants had been detected; in other situations, they were defined by minimum convex polygons (IUCN 1994) that incorporated the outermost plants. For chromolaena, infestations incorporated a 200-m buffer beyond the outermost plants of an infestation. Infestations were designated as active in any year that the weeds were detected; otherwise, they were assigned to the appropriate stage of the monitoring state. Total gross infestation area (area over which the weed is distributed; Rejmánek & Pitcairn 2002) in 2008 was 7450 ha for branched broomrape and 14 778 ha for chromolaena.

Results

Progression factors (γ) for branched broomrape varied considerably between years (range 0·414–0·853), as did those for chromolaena (range 0·050–0·139), but on average, γ was almost six times higher for branched broomrape (Table 1). As of 2008, only 10·2% of the total infested area for chromolaena was in the monitoring stage (i.e. ≥1 year since last detection), as compared with 78·1% of the total infested area for branched broomrape (Table 2).

The reversion coefficient (β) for branched broomrape infestations was lower than that for chromolaena infestations, as was the intercept (α) of the respective function (Fig. 2;

Table 1. Progression factors (proportion of infestations progressing from the active to the monitoring state; γ) for branched broomrape and chromolaena

	Proportion progressing	
Years	Branched broomrape	Chromolaena
1999–2000	0·616	0·0506
2000–2001	0·667	0·0495
2001–2002	0·853	0·0806
2002–2003	0·414	0·0970
2003–2004	0·838	0·1389
2004–2005	0·628	0·0935
2005–2006	0·686	0·0778
2006–2007	0·771	0·0559
2007–2008	0·795	0·1176
Mean (γ)	0·696	0·118
SD (σ_P)	0·137	0·130

Table 2. Categorization of infested area relative to the time since last detection of branched broomrape and chromolaena in 2008

	Area (ha)	
Years since last detection	Branched broomrape	Chromolaena
0	1634	13 276
1	1769	402
2	871	148
3	1 003	321
4	20·1	197
5	744	200
6	5·3	109
7	558	62·5
8	816	12·5
9	29·4	37·5
10	–	12·5
Total	7450	14 778

Note that 0 year since last detection denotes active infestations and that the criterion for eradication is 12 and 7 years since last detection for branched broomrape and chromolaena, respectively.

Table 3). The relatively high rate of reversion at 7 years within the monitoring phase for chromolaena (Fig. 2b) is anomalous, but the number of infestations involved was small ($n = 7$). Regardless, these data highlight the need for caution in designing stopping rules (see Discussion).

Given programme performance as of 2008, the model predictions were that it would take, on average, an additional 62 years to eradicate branched broomrape and an additional 248 years to eradicate chromolaena (Fig. 3). Without a major improvement in programme performance, therefore, the chromolaena invasion would have to be considered ineradicable.

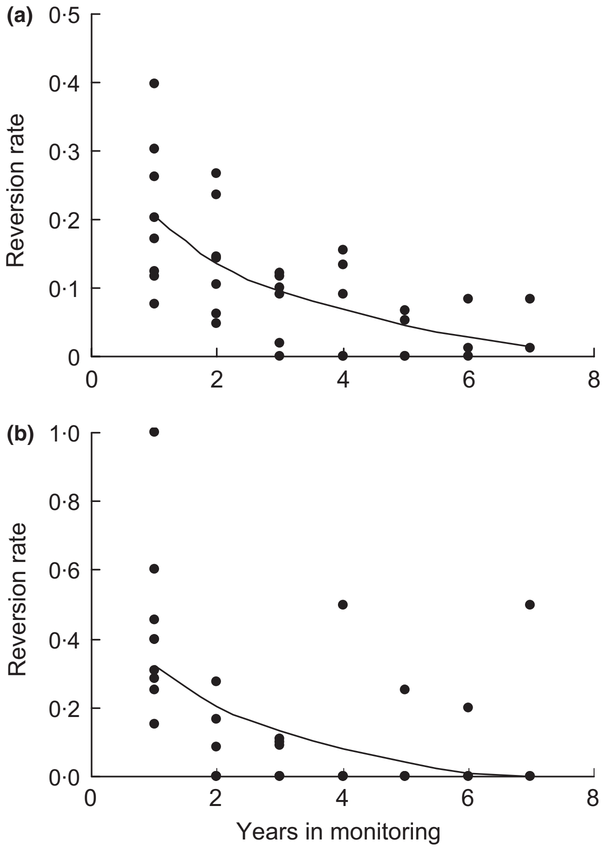

Fig. 2. Reversion from the monitoring to the active state as a function of time in the monitoring state for (a) branched broomrape and (b) chromolaena.

Table 3. Parameters estimated through linear regression for the reversion function (eqn 7) of the two species

	Branched broomrape	Chromolaena
α	0·204	0·323
β	−0·098	−0·174
σ_R	0·073	0·191
R^2	0·446	0·270

Data are for the period 1999–2008; all parameter values were significant ($P < 0{\cdot}01$).

As could be expected, earlier eradication for both species was associated with low rates of reversion and high rates of progression (Fig. 4a,b). For longer time frames (e.g. 40–60 years), eradication programme length was more sensitive to β where γ was low; as time frames became tighter (e.g. ≤25 years), the isoquants became less curvilinear. Generally, as time frames decreased, the minimum value for γ at which eradication was achievable increased.

Under the best conceivable programme performance, the earliest that eradication could be achieved post-2008 was 22 and 23 years for branched broomrape and chromolaena, respectively. As was stated earlier, however, values derived from the field suggested that eradication would take considerably longer. Only for values obtained during 2003–2005 was there any suggestion that the branched broomrape programme might be completed within 40 years (Fig. 4a). Eradication of this weed in the minimum possible time required $\gamma > 0{\cdot}7$, which was achieved in over 50% of the years, although the values of β were too high to permit eradication within this time frame.

The situation for chromolaena was considerably worse: owing to very low values of γ, none of the field data suggested

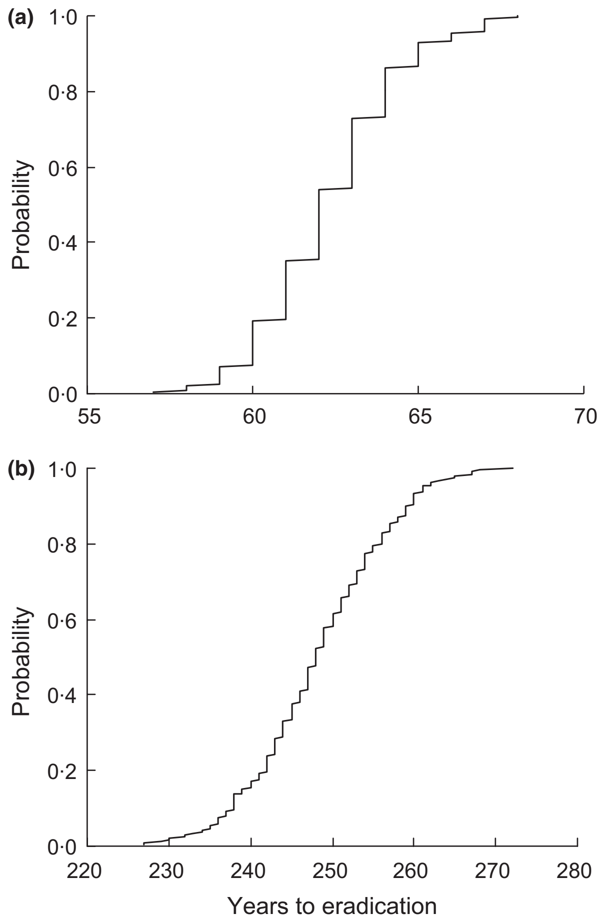

Fig. 3. Cumulative distribution functions for time to eradication for the (a) branched broomrape and (b) chromolaena eradication programmes.

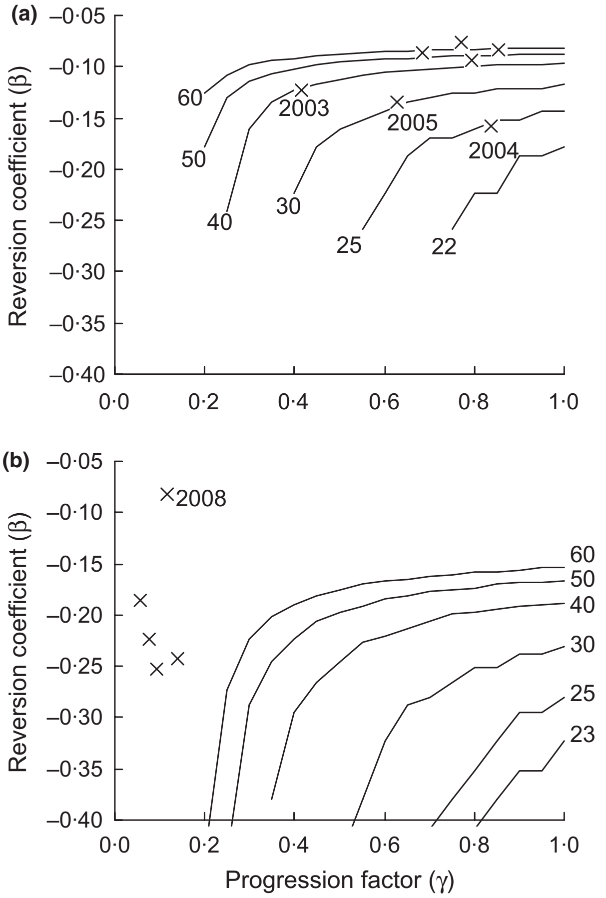

Fig. 4. Isoquants demonstrating the combinations of progression factors (γ) and reversion coefficients (β) that will allow eradication within specified time frames (denoted by numbers next to each curve) for (a) branched broomrape and (b) chromolaena. Minimum possible times to eradication are 22 and 23 years for branched broomrape and chromolaena, respectively. Each isoquant denotes the upper limit of all parameter space allowing eradication within the respective time frame. ×-symbols represent values from different years of the eradication programmes. For these values, γ is as presented in Table 1; β is derived from regressions based on data relevant to the individual year. Years corresponding to outlying values are indicated.

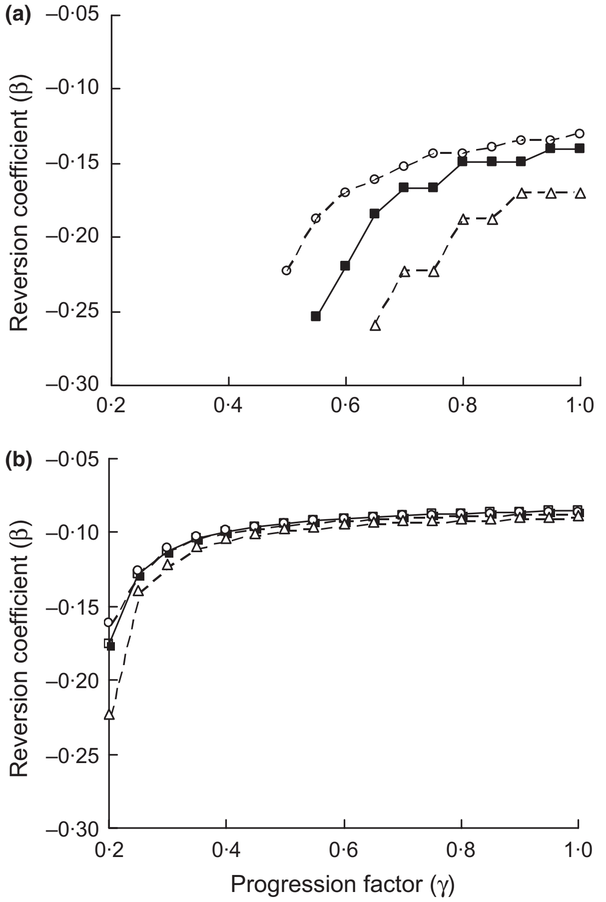

Fig. 5. Isoquants demonstrating the effects of increasing (open circles) and decreasing (open triangles) maximum branched broomrape seed persistence by 2 years for programmes that will achieve eradication within (a) 25 and (b) 50 years. Estimated seed persistence (closed squares) is 12 years.

that eradication could be achieved within 60 years. For this, a value of $\gamma = 0{\cdot}2$ would be required (Fig. 4b). Overall, the programme data suggested that performance in the branched broomrape eradication programme is most limited by rates of reversion from the monitoring to the active state and for chromolaena, the opposite holds – the critical process requiring improvement is the transition from the active to the monitoring state.

Within a 25-year time frame for eradication, increasing maximum seed persistence for branched broomrape by 2 years had the effect of decreasing the values of β required to achieve eradication. Decreasing maximum seed persistence had the opposite effect (Fig. 5a). However, within a substantially longer time frame (50 years), changes in maximum seed persistence had minimal effects (Fig. 5b). Results (not presented) for chromolaena were similar. This suggests that as the temporal scope of weed eradication programmes is allowed to increase, the accuracy of estimates of seed persistence becomes less important.

As the frequency of reversion to the active state is highest during the first year of monitoring (Fig. 2), the intercept of the reversion function (α) was varied to investigate the influence of variations at this stage on programme duration. Reducing α by 50% meant that eradication within the same time frame could be achieved with higher values of β (Fig. 6). Increasing α had the opposite effect. These effects were more marked within the 25-year time frame for eradication. Thus, there is a trade-off between α and β in that if the rate of reversion can be minimized early in the monitoring state, reversions later on become less important.

Discussion

By comparing model outputs with data from eradication programmes, we have been able to identify that programme duration could be best reduced by increasing rates of progression from active to monitoring status (γ) for chromolaena and by decreasing rates of reversion from monitoring to active status (β) for branched broomrape. These are different management

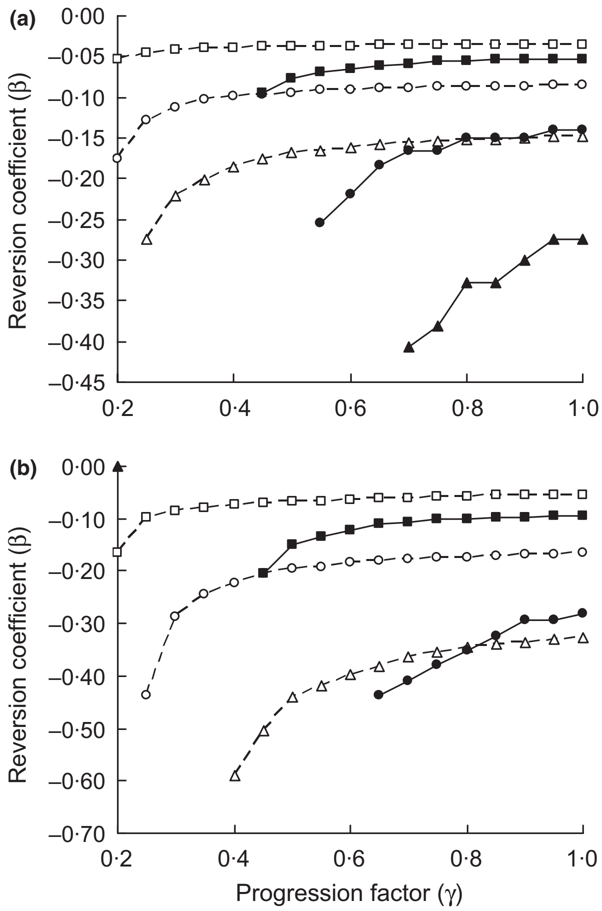

Fig. 6. Isoquants demonstrating the effects of increasing (triangles) and decreasing (squares) the value of α by 50%, relative to the value derived from field data (circles) in the (a) branched broomrape and (b) chromolaena eradication programs during 2008. Isoquants are for either 50-year (open symbols) or 25-year (closed symbols) programmes. Chromolaena could not be eradicated within 25 years when α was increased by 50%.

objectives and could conceivably require different tactical approaches.

Failure to progress to the monitoring state could occur for several reasons, including failure to control established plants and recruitment arising either from an *in situ* seed bank or via seed immigration. Failure to control established plants could result either from ineffective control techniques or from a failure of detection, the latter being a function of search effort.

With the exception of a restricted employment of soil fumigation, branched broomrape is not targeted directly by control measures. The most widely applied method of controlling infestations is preventing the establishment and growth of host plants. Cereal crops are not hosts, and the broadleaved weeds that are parasitized are controlled effectively with herbicides within this management context. However, it is difficult to control branched broomrape hosts without also eliminating the legume component in the pasture phase of cropping rotations. This is when it is most difficult to achieve progression to the monitoring state and also when most reversions to the active state occur (Panetta & Lawes 2007). For this species, therefore, identical control methods are used to influence both transitions. The use of herbicides that are less deleterious to legumes or the incorporation of less-sensitive species/varieties in rotations could potentially lead to significant improvements in both γ and β. Seed production of branched broomrape occurs < 2 weeks after emergence, so broadscale detection and control before seed set is not possible (Wilson & Bowran 2002). In practice, little attempt is made to control emerged plants, and the objective of monitoring (and surveillance) activities is to determine presence/absence; following detection, an entire paddock is considered to be infested and is treated accordingly.

In contrast, the juvenile phase of chromolaena persists for at least 4 months (S.J. Brooks, unpublished data). So long as plants are controlled before they can produce viable seed, the eradication objective will not be compromised. However, there is potentially less control over reversion to the active state for chromolaena than there is for branched broomrape. Apart from limiting seed immigration (the amount of which will depend upon the distribution of neighbouring infestations and the effectiveness in preventing reproduction and dispersal from these), reversion will be a function of recruitment from the soil seed bank. Emergence is essentially a 'double-edged sword' in that it contributes to seed bank depletion in the short term, but either contributes to or detracts from the eradication objective depending upon the effectiveness of management in preventing reproduction. To this extent, the system on which our model is based is conservative when applied to most eradication targets, because monitored infestations automatically revert to active status upon detection of plants, but the eradication objective is not actually compromised unless these plants reproduce.

Historically, very low rates of progression for chromolaena infestations have been a reflection of inconsistent visits to some infested sites and the difficulty of timely control on others (DEEDI 2009). It is reasonable to assume that plants have been able to reproduce freely under these circumstances. When site visits occur during flowering, it has been difficult to eliminate the production of viable seed by herbicide application (Setter & Campbell 2002), although seed-kill effectiveness has increased significantly through the use of different herbicides (Patane, Setter & Graham 2009). Consistent prevention of seed production is the key to reducing soil seed banks and reducing recruitment, eventually leading to the monitoring state (Panetta 2007). A recent doubling of the annual programme budget to AUD1·3 million pa (Department of Employment, Economic Development and Innovation (DEEDI) 2009) has provided an opportunity to increase operational staff numbers, which should contribute to improved monitoring and control of infestations, thereby increasing γ.

More rapid eradication of both species could be achieved through implementing methods that directly target their soil seed banks. The use of ethylene as a germination stimulant, combined with treatments that prevented reproduction, made it possible to eradicate an infestation of another parasitic weed, witchweed *Striga asiatica* L. (Kuntze) in about 3 years (Eplee 1992). Unfortunately, seeds of branched broomrape do not respond to ethylene, and it has not been possible yet to develop a reliable, cost-effective method for rapidly reducing soil seed populations. Until such a method becomes available, this programme will remain largely reliant upon natural attrition of the seed bank, in conjunction with sustained prevention of its replenishment. Where chromolaena infestations occur in seasonally dry areas, burning may significantly deplete their seed banks. For example, 89% of the chromolaena soil seed bank was located on the soil surface at an infestation near Townsville, Queensland, and a single fire caused a 72·5% reduction of this component (S.J. Brooks, unpublished data).

As eradication is approached, programmes could potentially be accelerated by the application of control methods that earlier would have been economically prohibitive. For example, fumigation with methyl bromide, which destroys branched broomrape seed banks, currently costs *c.* AUD20 000 ha^{-1} (Williams *et al.* 2006). Should total infested area for this weed eventually be reduced to *c.* 200 ha, the intention is to employ such fumigation exclusively (P. Warren, personal communication). On the basis of the model parameters for 2008, this could reduce a 50-year programme by 20 years.

The minimum duration of a weed eradication programme will be determined by seed persistence, but what constitutes a 'realistic' time frame for eradication? The present model should allow decision makers to determine the most appropriate time frame, particularly when the model is used in conjunction with informed estimates of required investment (Panetta *et al.* in press). A significant potential contribution to deviation from any stipulated time frame is the detection of new infested area, as weed invasions have been rarely delimited at the inception of eradication programmes (Panetta & Lawes 2005). Otherwise, having nominated a time frame, it would clearly be prudent to maintain the values of γ and β below the respective isoquant. It is an open question, however, as to what extent values exceeding an isoquant can be compensated for by subsequent improved performance.

In this study, our focus is on time to eradication rather than cost, but an agency facing budget constraints may be more concerned with costs. If it is possible to achieve cost savings (without substantially reducing the probability of eradication) by adopting strategies that result in a longer expected programme duration, longer programmes may be desirable. This can be partially addressed in our isoquant model by incorporating a budget constraint in the form of an equal cost line; the combination of β and γ that achieve a given time to eradication at minimum cost is then found at the point where the equal cost line is tangent to the isoquant (see Varian 1992, pp. 49–52). However, derivation of the equal cost line for our model may be challenging, as it would implicitly include assumptions about the effectiveness of control, the detectability of the plant, the spatial and temporal allocation of search and control effort and other factors that affect the relative costs of reducing β against increasing γ.

Cacho, Hester & Spring (2007) have shown that the minimum cost of eradication (in present value terms) does not normally coincide with the minimum time to eradication. Attempting eradication in the minimum time possible involves a cost and, in deciding whether to spend additional funds to achieve early eradication, an agency will need to take into account the opportunity cost of these funds not being allocated to other projects. As suggested previously, probability of success is another important factor; the risks associated with intentionally extending eradication programmes need to be considered against the possibility of allowing a longer time to minimize costs. In addition to the usual problems associated with lengthy eradication programmes (e.g. maintenance of institutional commitment and funding, continuity of trained and motivated workers), there are other ways for programmes to go off track, such as failure to prevent reproduction, and dispersal leading to the establishment of new foci of infestation.

Both of our case studies currently utilize stopping rules based upon the estimates of maximum seed persistence. The importance of accuracy in such estimates will vary according to the time frame under consideration (Fig. 5). However, recent work has generated more refined stopping rules that incorporate sighting records and the relative costs of continued monitoring vs. those arising from weed escape should monitoring be terminated prematurely (Rout, Salomon & McCarthy 2009; Rout, Thompson & McCarthy 2009). Undoubtedly, there is scope to increase the efficiency of weed eradication programmes through improved allocation of investment between different activities (Panetta *et al.* in press), thereby leading to shorter, less costly programmes. This study has established a framework that can be utilized to identify where tactical improvements could be made; further research is required to determine how best to achieve targeted parameter values and to analyse the cost-time trade-offs.

When taken in conjunction with considerations of programme cost and probability of success, our approach has broad applicability to decisions concerning whether to embark upon or continue a weed eradication programme. A particular strength of the approach lies in its minimal data requirements, which comprise estimates of the area of each weed infestation, consistent annual records of the detection (or otherwise) of the weed in each infestation and an estimate of maximum seed persistence. The last data type is the only one that may vary intrinsically with the targeted species, and methods are under development for obtaining rapid, if crude, estimates of seed persistence (e.g. Schoeman *et al.* 2010). Our approach can be employed to determine whether a programme is on track to achieve eradication within a nominated time frame and, if otherwise, can indicate potential rectifications. If programme performance cannot be improved readily within budgetary and technical constraints, decision makers may opt to switch to a more economically optimal strategy, such as containment or sustained control.

Acknowledgements

We are grateful to Nick Secomb and Phil Warren for their provision of data from the branched broomrape eradication programme and to two reviewers for their constructive comments. Funding for this work was provided by the Australian Department of Agriculture, Fisheries and Forestry.

References

Bomford, M. & O'Brien, P. (1995) Eradication or control for vertebrate pests? *Wildlife Society Bulletin*, **23**, 249–255.

Cacho, O.J., Hester, S. & Spring, D. (2007) Applying search theory to determine the feasibility of eradicating an invasive population in natural environments. *Australian Journal of Agricultural and Resource Economics*, **51**, 425–433.

Cacho, O. & Pheloung, P. (2007) *WeedSearch: Weed Eradication Feasibility Analysis, Software Manual*. CRC for Australian Weed Management Project 1.2.8, August 2007. University of New England, New South Wales.

Cacho, O.J., Spring, D., Pheloung, P. & Hester, S. (2006) Evaluating the feasibility of eradicating an invasion. *Biological Invasions*, **8**, 903–917.

Cunningham, D.C., Barry, S.C., Woldendorp, G. & Burgess, M.B. (2004) A framework for prioritising sleeper weeds for eradication. *Weed Technology*, **18**, 1189–1193.

Department of Employment, Economic Development and Innovation (DEEDI) (2009) *National Siam Weed,* Chromolaena odorata*, Eradication Program: Annual Report*. *July 2008–June 2009*. Brisbane, Queensland.

Econsearch (2008) Economic evaluation of options for branched broomrape management. A Report Prepared for the Branched Broomrape Eradication Program, Department of Water, Land and Biodiversity Conservation, Adelaide, South Australia.

Eplee, R.E. (1992) Witchweed (*Striga asiatica*): an overview of management strategies in the USA. *Crop Protection*, **11**, 3–7.

Gardener, M.R., Atkinson, R. & Rentería, J.L. (2010) Eradications and people: lessons from the plant eradication program in Galapagos. *Restoration Ecology*, **18**, 20–29.

Goswami, S. (2008) *National Siam Weed (*Chromolaena odorata*) Eradication Program: Economic Cost Benefit Analysis*. Department of Primary Industries and Fisheries, Brisbane, Queensland.

IUCN (1994) *IUCN Red List Categories*. International Union for the Conservation of Nature, Species Survival Commission, Gland, Switzerland.

Jupp, P., Warren, P. & Secomb, N. (2002) The branched broomrape eradication program: methodologies, problems encountered and lessons learnt. *Proceedings of the 13th Australian Weeds Conference* (eds H. Spafford Jacob, J. Dodd & J.H. Moore), pp. 270–273. Plant Protection Society of Western Australia, Perth.

Mack, R.N. & Foster, S.K. (2009) Eradicating plant invaders: combining ecologically-based tactics and broad-sense strategy. *Management of Invasive Weeds* (ed. Inderjit), pp. 35–60. Springer, Netherlands.

Mack, R.N. & Lonsdale, W.M. (2002) Eradicating invasive plants: hard-won lessons for islands. *Turning the Tide: The Eradication of Island Invasives* (eds C.R. Vietch & M.N. Clout), pp. 164–172. IUCN SSC Invasive Species Specialist Group, Gland, Switzerland.

Myers, J.H., Simberloff, D., Kuris, A.M. & Carey, J.R. (2000) Eradication revisited: dealing with exotic species. *Trends in Ecology and Evolution*, **15**, 316–320.

Panetta, F.D. (2007) Evaluation of the performance of weed eradication programs: containment and extirpation. *Diversity and Distributions*, **13**, 33–41.

Panetta, F.D. (2009) Weed eradication: an economic perspective. *Invasive Plant Science and Management*, **2**, 360–368.

Panetta, F.D. & Lawes, R. (2005) Evaluation of the performance of weed eradication programs: the delimitation of extent. *Diversity and Distributions*, **11**, 435–442.

Panetta, F.D. & Lawes, R. (2007) Evaluation of the Australian branched broomrape (*Orobanche ramosa*) eradication program. *Weed Science*, **55**, 644–651.

Panetta, F.D. & Timmins, S.M. (2004) Evaluating the feasibility of eradication for terrestrial weed invasions. *Plant Protection Quarterly*, **19**, 5–11.

Panetta, F.D., Csurhes, S., Markula, A. & Hannan-Jones, M. (2011) Predicting the cost of eradication for 41 Class 1 declared weeds in Queensland. *Plant Protection Quarterly*, **26**, 42–46.

Panetta, F.D., Cacho, O.J., Hester, S.M. & Sims-Chilton, N.M. (in press) Estimating the duration and cost of weed eradication programs. *Island Invasives: Eradication and Management* (eds C.R. Veitch, M.N. Clout & D.R. Towns). IUCN (International Union for Conservation of Nature), Gland, Switzerland.

Patane, K.A., Setter, S. & Graham, M. (2009) Foliar herbicides that reduce the viability of Siam weed (*Chromolaena odorata*) seeds located on plants at the time of application. *Plant Protection Quarterly*, **24**, 138–140.

Press, W.H., Flannery, B.P., Teukolsky, S.A. & Vetterling, W.T. (1986) *Numerical Recipes: The Art of Scientific Computing*. Cambridge University Press, Cambridge.

Regan, T.J., Chades, I. & Possingham, H.P. (2011) Optimally managing under imperfect detection: a method for plant invasions. *Journal of Applied Ecology*, **48**, 76–85.

Rejmánek, M. & Pitcairn, M.J. (2002) When is eradication of exotic pest plants a realistic goal? *Turning the Tide: The Eradication of Island Invasive* (eds C.R. Vietch & M.N. Clout), pp. 249–253. IUCN SSC Invasive Species Specialist Group, Gland, Switzerland.

Rout, T.M., Salomon, Y. & McCarthy, M.A. (2009) Using sighting records to declare eradication of an invasive species. *Journal of Applied Ecology*, **46**, 110–117.

Rout, T.M., Thompson, C.J. & McCarthy, M.A. (2009) Robust decisions for declaring eradication of invasive species. *Journal of Applied Ecology*, **46**, 782–786.

Schoeman, J., Buckley, Y.M., Cherry, H., Long, R.L. & Steadman, K.J. (2010) Inter-population variation in seed longevity for two invasive weeds: *Chrysanthemoides monilifera* ssp. *monilifera* (boneseed) and ssp. *rotundata* (bitou bush). *Weed Research*, **50**, 67–75.

Setter, M.J. & Campbell, S.D. (2002) Impact of foliar herbicides on germination and viability of Siam weed (*Chromolaena odorata*) seeds located on plants at the time of application. *Plant Protection Quarterly*, **17**, 155–157.

Setter, S., Graham, M. & Patane, K. (2007) Ecology of wet tropics weeds. *Technical Highlights. Invasive Plant and Animal Research 2006–07*, pp. 8–11. Department of Primary Industries and Fisheries, Brisbane, Queensland.

Simberloff, D. (2003) Eradication – preventing invasions at the outset. *Weed Science*, **51**, 247–253.

Varian, H. (1992) *Microeconomic Analysis*, 3rd edn. W.W. Norton and Company, New York.

Waterhouse, B.M. (1994) Discovery of *Chromolaena odorata* in northern Queensland, Australia. Chromolaena odorata *Newsletter*, **9**, 1–2.

Williams, A.M., Virtue, J.G., DeDear, C. & McInerney, T. (2006) Sampling challenges in detecting branched broomrape seed bank decline. *Proceedings of the 15th Australian Weeds Conference* (eds C. Preston, J.H. Watts & N.D. Crossman), pp. 622–625. Weed Management Society of South Australia, Adelaide.

Wilson, B.J. & Bowran, D.G. (2002) *Report on the Review of the Branched Broomrape Eradication Program*, pp. 32. Land, Water and Biodiversity Committee, Canberra.

Witkowski, E.T.F. & Wilson, M. (2001) Changes in density, biomass, seed production and soil seed banks of the non-native invasive plant, *Chromolaena odorata*, along a 15 year chronosequence. *Plant Ecology*, **152**, 13–27.

Wittenberg, R. & Cock, M.J.W. (eds) (2001) *Invasive Alien Species: A Toolkit of Best Prevention and Management Practices*. CAB International, Wallingford, Oxon, UK.

Woldendorp, G. & Bomford, M. (2004) *Weed Eradication: Strategies, Timeframes and Costs*, pp. 30. Bureau of Resource Sciences, Department of Agriculture, Fisheries and Forestry, Canberra, Australia.

Zachariades, C., Day, M., Muniappan, R. & Reddy, G.V.P. (2009) *Chromolaena odorata* (L.) King and Robinson (Asteraceae). *Biological Control of Tropical Weeds using Arthropods* (eds R. Muniappan, G.V.P. Reddy & A. Raman), pp. 130–162. Cambridge University Press, Cambridge.

Received 28 October 2010; accepted 7 April 2011
Handling Editor: Jason Matthiopoulos