



Improving decisions for invasive species management: reformulation and extensions of the Panetta–Lawes eradication graph

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ABSTRACT

Aim Effective decisions for managing invasive species depend on feedback about the progress of eradication efforts. Panetta & Lawes (2007) developed the eradograph, an intuitive graphical tool that summarizes the temporal trajectories of delimitation and extirpation to support decision-making. We correct and extend the tool, which was affected by incompatibilities in the units used to measure these features that made the axes impossible to interpret biologically.

Location Victoria, New South Wales and Queensland, Australia.

Methods Panetta and Lawes' approach represented delimitation with estimates of the changes in the area known to be infested and extirpation with changes in the mean time since the last detection. We retain the original structure but propose different metrics that improve biological interpretability. We illustrate the methods with a hypothetical example and real examples of invasion and treatment of branched broomrape (*Orobancha ramosa* L.) and the guava rust complex (*Puccinia psidii* (Winter 1884)) in Australia.

Results These examples illustrate the potential of the tool to guide decisions about the effectiveness of search and control activities.

Main conclusions The eradograph is a graphical data summary tool that provides insight into the progress of eradication. Our correction and extension of the tool make it easier to interpret and provide managers with better decision support.

Keywords

Decision support, delimitation, eradication, eradograph, extirpation, weeds.

INTRODUCTION

Weed invasions threaten ecosystems and productive enterprises globally. Tools to support decision-making are a critical element of successful weed management (Pheloung *et al.*, 1999; Cacho *et al.*, 2006; Hauser & McCarthy, 2009; Regan *et al.*, 2011; Hester *et al.*, 2013; Potts *et al.*, 2013; Whittle *et al.*, 2013; Yemshanov *et al.*, 2013). Panetta & Lawes (2007) developed an intuitive tool to graph the progress of eradication programmes, using the South Australian branched broomrape (*Orobancha ramosa* L.) eradication programme as an example. The authors identified two critical criteria: delimitation (determination of the full spatial extent of

spread) and extirpation (elimination of individual infestations). They developed a model for delimitation based on the total area infested (A_T), the area searched (A_s) and the area of new infestation (A_d). The authors wanted their delimitation measure, D , to increase with both A_d and A_T , so that an increase in D would indicate deterioration in the situation. The larger the area searched, the more likely new infestations are to be found, so D should also decline with A_s .

With these objectives in mind, they defined

$$D_t = A_d / [P_n + \log(A_s + 1)] \quad (1)$$

where D_t is the value for D in year t and P_n depends on the proportional change in total known infested area between

year $t-1$ and year n , equal to $(A_T - A_d)/A_T$, and A_s is the area searched in year t .

Panetta & Lawes (2007) represented success in extirpation with the mean of the distribution of the time since the most recent detection, E , in monitored infested sites. They recommended plotting D_t versus E_t (the value of E at time t) to generate a graph of progress towards eradication. The trajectory of the graph could be used to indicate the relative need to invest in surveys to further delimit infested sites versus the need to eliminate local populations.

Unfortunately, equation 1 uses physical quantities in ways that lead to units that are not commensurate. The first term in the denominator is unitless, and the second is log hectares. The unit in the numerator is hectares. This arbitrary construction makes D_t difficult to interpret because the units are incompatible. Panetta & Lawes (2007) took the log of $A_s + 1$ to dampen the effect of variability in A_s upon the eradograph trajectory. Our objective in this study is to reformulate and extend the procedure, retaining the intention of the original authors to capture the salient features of delimitation and extirpation, but using a consistent and more intuitive formulation.

REVISION OF THE METHOD

One critical element of equation 1 is the relationship between area searched and the area of new infestations found. This is expressed most simply as

$$D'_t = A_{d,t}/A_{s,t} \tag{2}$$

where the terms are defined as above, with t indicating the time period.

Equation (1) confounds the relative area of new infestations with the total area of infestation. We considered a number of alternative formulations, including expressions showing the total area infested, discounted by the mean time since the most recent detection, giving a weighted estimate of the area infested. However, all alternatives suffer from the fact that, as Panetta & Lawes (2007) pointed out, three parameters are important: delimitation, total area infested and extirpation within the delimited area. This makes all two-dimensional representations ambiguous, in at least some situations.

To resolve this issue and to correct the unbalanced units in equation 1, we suggest an alternative approach in which delimitation and extirpation are plotted separately against the total area infested. This representation is simpler and free of potentially ambiguous signals.

Building on the approach outlined by Panetta & Lawes (2007), E_{mean} is the mean of the frequency distribution of the time since the most recent detection for all populations, including those where eradication has been declared, and E_{max} is the time it takes to conclude that a population has been extirpated. The quantity E_{max} may be, for example, the maximum longevity of soil-stored seed. Progress towards eradication at time t , Ex_t , can be represented by the difference between E_{max} and E_{mean} ,

$$Ex_t = E_{\text{max}} - E_{\text{mean}} \tag{3}$$

The values of D'_t and Ex_t may then be plotted against the total area ever infested to show the progress of eradication efforts, with declines in both D'_t and Ex_t expected under good management. Under ideal conditions in which delimitation is effective and populations within the delimited area are eliminated permanently, both curves will fall to zero on the y -axes. It is worth noting that Ex_t can go negative where searches in sites continue beyond E_{max} .

It is important to note that being 'infested' is treated as a permanent state, meaning that data points for successive years cannot have lower x -axis values because the total infested area can never decrease. It may be counterintuitive to think that a site contributes to the total area infested even when the time since last detection has exceeded the maximum longevity of the soil seed bank. The reasons for taking this approach are to ensure the curves do not fold back on themselves, enhancing visual interpretation, and because the total area ever infested is valuable information. The total area currently infested is important additional information that should be considered alongside the graphs described here.

The revised eradograph does not have the same general properties as those in the original eradograph outlined by Panetta & Lawes (2007). Trajectories in the two curves (D'_t and Ex_t in Fig. 1) towards the bottom right would indicate that management is effective. A trajectory towards the upper right quadrant in the delimitation curve (D') suggests that increased search effort should be considered. A trajectory towards the upper right quadrant in the extirpation curve (Ex) suggests that increased control effort should be considered (Fig. 1).

Panetta & Lawes (2007) plotted a trajectory for branched broomrape for the period 1999–2006. We analysed the data in their article to illustrate the two approaches (Fig. 2).

The graphs in Fig. 2 show that the revised formulation retains the essential features of the original. It provides a visual representation of the progress of the eradication effort. As noted above, the objective of management in Fig. 2(b) is

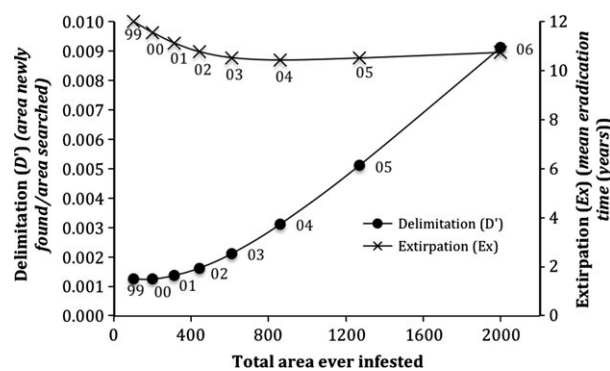


Figure 1 Revised eradograph for an idealized scenario in which 100 ha are discovered initially to be infested. A total of 90 ha are successfully treated annually but the population grows exponentially, doubling in size every year, so that the overall pattern is one of an exponential increase in the infested area.

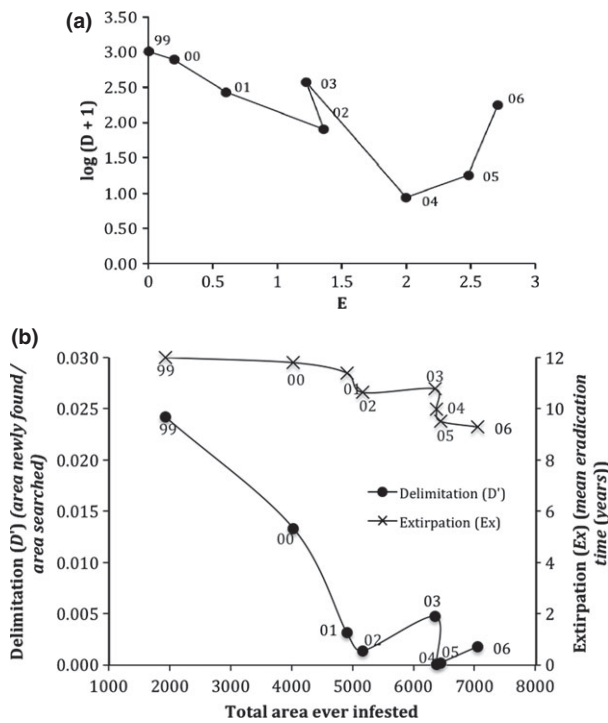


Figure 2 Comparison of eradograph plots for the branched broomrape data (Panetta & Lawes, 2007) using (a) the original formulation, and (b) the revised eradograph.

to reduce both curves to zero on the y -axes. The advantage of the revised formulation, apart from the use of consistent units in the construction, is that it clearly separates the contributions of delimitation and extirpation to the overall objectives. This separation is consistent with the distinction between investments in learning about the invasion and investment in eradicating it (Baxter & Possingham, 2011).

EXTENSIONS

The time since the last detection, the quality of potential habitat, distance to the nearest infested site and the detectability of the invasive species may all affect the eradication graph. The reformulation outlined above provides an opportunity to develop the approach further, for circumstances in which information about these aspects of the invasive species is available.

Time since the last detection at each infested site may vary depending on its discovery and treatment. If we simply use E , the average time since last detection, then the index may be misleading. For example, if E_{max} is 6 years and we have two sites for which E is 0 and 14 and another two for which E is 7 and 7, equation 3 would rate these situations the same, whereas a manager might be more concerned about the former scenario, in which there is definitely at least one extant population. To take account of the time since last detection in a range of sites, one may use the revised eradograph and plot the extirpation curve separately for each site. Alternatively, the manager could estimate the probability of

the invasive species being present at each site, based on detections and effort (Rout *et al.*, 2009), and this quantity might be averaged across sites. Accounting for inconsistent search effort among sites would require the application of more complicated analyses. We discuss this further below.

Detectability will affect the interpretation of eradographs. Detectability is never 100% (Garrard *et al.*, 2008; Moore *et al.*, 2011), and Panetta & Lawes (2007) noted that values of E should be regarded as upper bounds, as a result. Assuming the species is equally detectable in all the patches, the probability of detection, p_d , may be introduced to D_t straightforwardly, as follows:

$$D'_t = A_d / (A_s * p_d) \tag{4}$$

In this equation, the area searched is discounted by the detectability of the species in question. We note, however, that this is only useful if detectability varies between patches, so that $p_{d,i}$ would differ for different patches, i .

The area searched should be weighted by the probability of occurrence of the invasive species. That is, if the search includes areas that are relatively unlikely to harbour infestations because they are relatively unsuitable or are very far from the current infestation, then they should weigh less in the overall assessment of progress towards eradication. For example, assuming the probability of occurrence of the species is the same in all patches, this value may be included in the calculations as follows:

$$D'_t = A_d / (A_s * p_d * p_o) \tag{5}$$

The probability of occurrence (p_o) is itself a function of two main factors: the suitability of the habitat (see Elith *et al.*, 2006) and the distance to currently infested sites. Likelihood of occurrence as a function of distance from current infestations (p_m) may be included by calculating the geographic (or ecological) distance between the searched location and the nearest infested site. The distance function may be calibrated by the dispersal mechanisms of the species or any particular knowledge of dispersal dynamics, as was done for orange hawkweed (*Hieracium aurantiacum* L.) (Williams *et al.*, 2008) and citrus canker (Potts *et al.*, 2013). To combine distance and habitat quality, we need to specify the relationship between them. Here, we use the product of two numbers, which implies we consider their relative importance to be equal in determining the occurrence of the invasive species.

Finally, as noted above, detectability and the probability of occurrence typically vary between sites. Thus, for an area comprising n pixels, each with its own detectability and probability of occurrence,

$$D'_t = \sum_{i=1}^n A_{d,i} / \sum_{i=1}^n (A_{s,i} * p_{d,i} * p_{o,i}) \tag{6}$$

Note that the optimal surveillance strategy of Hauser & McCarthy (2009) provides a solution that maximizes the effective area searched (the denominator in equation 6), by

balancing spatial variation in the probability of occurrence and detectability under a given search budget.

As D'_i (from equation 6) is inversely proportional to the sum of area searched weighted by probability of occurrence (we assume equal detectability in each patch), by searching in those areas with greater $P_{o,i}$ values, we are able to achieve a greater reduction in D'_i for the same search effort – that is, equation 6 reflects the fact that targeting those areas with greater probabilities of occurrence equates to maximizing our search effort.

To illustrate the effect on search effort priorities of these extensions, we consider a hypothetical scenario where a new incursion is detected in the study region on the southern coast of NSW shown in Fig. 3. The shading in Fig. 3 reflects the relative habitat suitability of the region for the guava rust complex (*Puccinia psidii* (Winter 1884)), calculated from a habitat suitability model (Elith *et al.*, 2012). Figure 4(a) shows the priority for search effort of each patch within the study region on the basis of log distance from incursion alone. Calculating the probability of occurrence of each site $p_{o,i}$ as the product of habitat suitability index and log of the distance from incursion, we can then contrast this with Fig. 4(b), which shows the revised search priorities when we also take into account the information on the habitat suitability of each patch.

DISCUSSION

Panetta & Lawes (2007) introduced a useful idea, unfortunately compromised by an arbitrary construction that made one of the axes impossible to interpret. The reformulation here results in consistent axes and patterns for delimitation and extirpation that are clearly separated. The changes make trajectories following eradication efforts more readily interpretable.

In an ideal world, searches would be standardized at a level of effort sufficient to provide a very high probability of

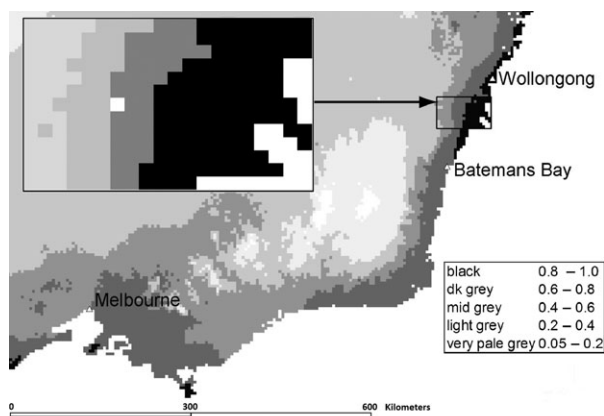


Figure 3 Location of the study region on the Southern coast of NSW between Wollongong and Bateman's Bay. The location of the hypothetical new incursion detected within the study region is indicated by the central white square in the inset.

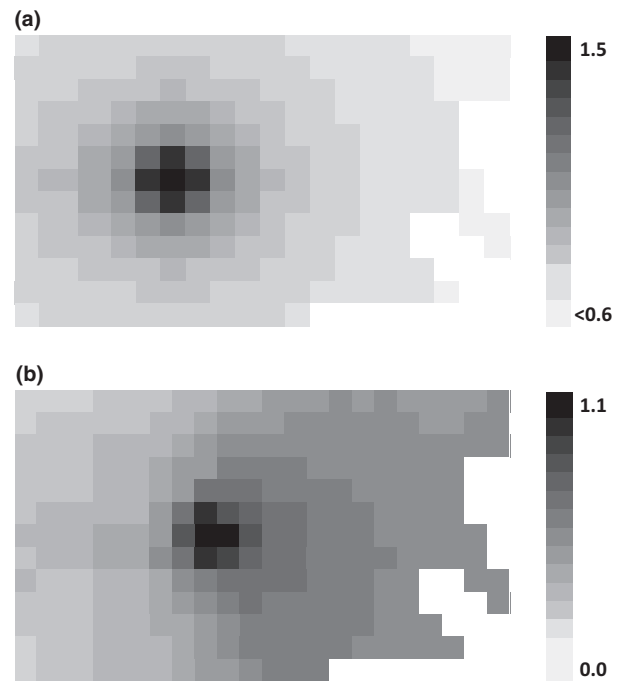


Figure 4 Search area priorities calculated on the basis of (a) log of distance (km) from incursion alone, and (b) probability of occurrence, calculated from the product of log of distance (km) from incursion and habitat suitability. Note the darkest colours are the places that should be searched first.

detection and would be done at the ideal time of year and in ideal weather conditions. In practice, frequently one or more of these conditions is violated; conditions vary, teams have different levels of skills and experience, and budgets or resources limit effort in some locations. As Rout *et al.* (2009) outlined, analysts have the option of weighting the area searched by probability of presence at each site, accounting for variable search effort. This makes the calculations required to produce the eradograph more complex.

In any applications, suggestions for changes in eradication programmes need to be evaluated in a cost-benefit analysis. For example, the information summarized in the eradication graph may be used to decide whether to alter the relative allocations between search and control activities or to discontinue, maintain or intensify an eradication programme. One of the extensions noted above is to calculate probability of occurrence as a function of habitat suitability and distance to current infestations, where the distance function may be calibrated by dispersal mechanisms and dynamics of the species. As an eradication programme proceeds, typically knowledge of habitat suitability and dispersal dynamics improves, creating an opportunity to estimate or adjust these factors. The eradograph could be updated based on the new knowledge, generating continuous improvement in understanding of the progress of an eradication programme. A manager could also include uncertainty in the eradograph parameters by specifying upper and lower plausible limits for each and recalculating the curves using these bounds. This approach

would generate an envelope for each of the eradograph curves. Managers could then exercise their judgement and be more risk averse or more risk seeking than they would be if they were to use the best estimates alone.

The eradograph combines data obtained during an eradication programme to give an overall measure of progress. It is a very general tool and, as such, is not prescriptive about thresholds on the x - or y -axes that may be acceptable or desirable. Such decisions depend on the specific characteristics of the species in question and the manager's context. It is the manager's role to define the eradication objectives. Once this is done, the eradograph should be helpful in representing progress towards those objectives. It should be presented alongside additional visual representation of progress based on simpler measures such as the number of new sites detected annually and maps showing locations of new detections. The steps suggested as extensions above take care of some of the more obvious and important assumptions in the original formulation, but at the cost of additional data and analysis.

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BIOSKETCH

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