Evaluating the feasibility of eradication for terrestrial weed incursions

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Summary

The feasibility of eradication of weeds has had little systematic investigation, in contrast to eradication feasibility for pest animals. A fundamental condition for realising the objective of eradication is that the rate of weed removal exceeds the rate of weed increase at all population densities. If this is not so, the eradication program may be prolonged or even fail. We present a decision tree that can be used to determine whether eradication is an appropriate management strategy for a weed incursion. We also investigate various factors in terms of their ability to impede progress towards eradication, and offer a prospective scoring system that captures the influence of logistic, detection, biological and control factors upon the effort required to achieve eradication.

A recent analysis of selected weed projects indicates that eradication feasibility declines rapidly with increasing area of a weed infestation, to the point where eradication is unlikely for infestations of greater than 1000 ha. This generalization is based upon 'gross' infestation size (i.e. the area that must be surveyed in return trips following control treatments), as opposed to 'net' infestation size (the area to which treatment is applied). For species that are readily detectable and combine long pre-reproductive periods with limited seed persistence, it may be possible to eradicate infestations larger than 1000 ha. Certain combinations of weed characteristics and environmental contexts may restrict eradication potential, however. The scope for eradication of some weeds of natural ecosystems may be limited to infestations that are considerably smaller (perhaps by an order of magnitude) than 1000 ha. More examples of successful eradication programs are required in order to develop further our scoring system, particularly as it would apply to weeds of natural ecosystems. Even when eradication is technically possible, it appears that relatively long-term financial and institutional commitment will generally be required for success.

Introduction

Weed invasions constitute one of the leading threats to managed and natural ecosystems worldwide. Estimates of the annual costs of weeds to agriculture in some countries are in the order of billions of dollars (Pimental 2002). The impacts of environmental weed invasions are much more difficult to capture in monetary terms, but are equally, if not more, serious. Weed invasions have been linked with major changes in the structure and composition of natural ecosystems, as well as with disruption of key ecosystem functions. In the absence of intervention and with increasing globalization, these impacts are likely to worsen as species are introduced, both intentionally and unintentionally, to new areas. With recognition of the ever-mounting costs of dealing with widely distributed weeds, there has been a growing interest in the development and adoption of processes aimed to reduce the rates of introduction and establishment of invasive species.

The development of a weed risk assessment (WRA) system that could assess the potential for an intentionally introduced plant taxon to become a weed was a major step forward. Originally designed to assess the weed risk associated with plant introductions to Australia, this system was later modified for New Zealand conditions (Pheloung *et al.* 1999). A subsequent evaluation of the system in the Hawaiian Islands suggested that it was a promising template for designing a globally applicable system (Daehler and Carino 2000). Owing to the inherent difficulties in predicting weediness (Williamson 2001), there are limits to the accuracy of this or, in fact, any system (Lonsdale and Smith 2001). Potentially weedy species may still escape detection. Furthermore, a large number of species that have the potential to naturalize and become invasive have accumulated over many decades, even in the countries where WRA systems have since been introduced. There is a need for procedures to deal with the plants that are beginning to realize their weed potential, or that otherwise elude the quarantine net.

Weed invasions are considered to comprise a series of general phases (Hobbs and Humphries 1995, Williams 1997). The stage of the invasion sequence that follows introduction is naturalization, when a species has overcome various barriers to survival and regular reproduction and has developed populations large enough that the probability of extinction due to environmental stochasticity is low (Mack 1996, Richardson *et al.* 2000). If a species is to become invasive, i.e. spread beyond its initial site of introduction, it must both disperse effectively and be adapted to the prevailing environmental conditions. The early naturalization stage is considered to be the most effective time to attempt to reduce the ultimate impact of a weedy species (Hobbs and Humphries 1995, Williams 1997, Grice and Ainsworth 2003).

Eradication, defined as the elimination of every single individual of a species from an area in which recolonization is unlikely to occur (Myers *et al.* 1998), is a strategy that is favoured wherever possible. It is particularly appealing because the alternatives of containment or broadscale control require permanent, ongoing investment of time and money (Zavaleta *et al.* 2001), unless a species can be brought under effective biological control. However, removing a weed from a natural or agricultural ecosystem, or a cultural setting where human well-being is at risk, is rarely an end in itself. For natural ecosystems, the ultimate goal of an eradication program is either to prevent negative impacts upon diversity and ecosystem function, or to reverse such impacts once they have occurred (Zavaleta *et al.* 2001). Only the first objective is generally achievable for weed incursions (Hobbs and Humphries 1995).

Eradication programs are generally very expensive. Before committing to such a strategy it is preferable to be confident that eradication can be achieved. This highlights the need to evaluate the circumstances under which eradication is feasible (Bomford and O'Brien 1995, Rainbolt and Coblenz 1997, Myers *et al.* 2000). It could be argued that the best measure of feasibility of weed eradication is an estimation of the dollar cost of achieving this objective. However, the process of estimating costs is complex and time-consuming, requiring the preparation of management plans in which all the factors that affect cost are considered. Our main focus here is to develop a means of determining whether one weed incursion is more feasible to eradicate than another. We attempt to avoid direct measures of monetary cost, so as to give the model a wider applicability, but the criteria we address do relate to eradication costs.

In this paper we first present a decision tree that can be employed to decide whether eradication is an appropriate management strategy for a particular incursion. A central element of this procedure is an estimate of the amount of effort (and hence resources) that would be required to achieve eradication. Building upon recent attempts to derive general principles for the eradication of weeds, we then identify the primary factors that must be considered when estimating eradication effort (E) and propose a procedure for deriving a measure of E.

Leads from pest animal eradication programs

The final outcome of an eradication program is determined by an interplay of biological, economic and social factors. This has been expressed in the form of criteria that must be met if eradication is to be a feasible management option for pest animals (Table 1). These criteria appear to be equally relevant to the prospects for weed eradication. We also note that quantification of the effort required to achieve eradication of pest animals seems not to have been attempted. Rainbolt and Coblenz (1997) observed that effort was not dealt with explicitly in the criteria listed by Bomford and O'Brien (1995), but rather was dispersed among several of these (Table 1). Myers *et al.* (2000) state that resources must be sufficient to fund a program to its conclusion (Table 1), but provide no guidance as to how the requisite level of resourcing should be determined. Lastly, the use of discounted cost-benefit analysis to determine whether eradication should be favoured over other management strategies (Table 1) also presupposes that there has been a reliable estimate of the costs that would be incurred by an eradication program that extended over a number of years.

Major differences between plants and animals that have a bearing on conformance with the criteria listed in Table 1 include:

1. Some weeds develop large, persistent seedbanks. Maximum seed longevity can be of the order of decades, although it is highly variable between species and even between different populations of the same species. Moreover, control methods employed to target vegetative individuals commonly leave seeds unscathed. Since a weed cannot be considered to have been eradicated until all plants are removed and no viable seeds remain, an eradication program for a species with very long-lived seeds must necessarily extend for a number of decades.
2. Plants cannot deliberately escape detection by evasive behaviour or be detected at low densities with the use of baits or lures — they must be located *in situ*. Some species can be extremely difficult to detect in the vegetative state, especially as juveniles, and most species are undetectable as propagules.
3. Interference with the reproductive process through mating disruption or the sterile male release method has proven so effective with some insect pests that it has been possible to eradicate rather large and extensive infestations (Myers *et al.* 2000). No analogous methods are available for weeds.

These differences can be expected to affect the relative prospects for eradication of weeds versus pest animals. Owing to these and other plant-specific characteristics, it is likely that funding and institutional commitment will generally need to be relatively long-term when compared to that required for pest animal eradication programs.

Determining if a weed is a suitable target for eradication

The first decision with regard to incursion management is whether a weed is a suitable target for eradication (Figure 1). We note a basic dichotomy between the socio-political and the technical/economic considerations of this decision-making process. The framework presented in this paper relates primarily to the latter, although the effects of the former may be crucial to the success of an eradication program. One such social consideration is whether the potential target is widely cultivated. Just as livestock and domestic animals provide a source of new infestations of pest animals (Bomford and O'Brien 1995), so cultivation of plant species functions as a source of new weed infestations. For a plant species to be eradicated from a region, it must be removed from cultivation, as well as from the wild. Conflicts of interest arise when such species are considered weedy in one context, but are valued in another, e.g. as a garden or hedging plant, for landscape values, for honey production or as a food source for native animals. Depending on the species, more or less social resistance can be anticipated. For this reason, we believe that widely cultivated plants are not suitable targets for eradication. Another 'make or break' socio-political consideration involves the tenure(s) of the land over which control must occur — the more agencies involved in the eradication effort, the higher risk of failure should one party not wish to participate, remembering that for eradication to be successful *all* infestations must be subject to control.

The requirement for indefinite prevention of reinvasion imposes a lower limit to the spatial scale over which eradication should be contemplated; in this paper we consider scales from regional to national, and where there are natural barriers to reinvasion, such as water bodies surrounding islands. Timely availability of effective control measures is essential. The aim of eradication is to drive a weed species to extinction wherever it occurs, so a variety of control methods may be required. The remaining two decision points in Figure 1, namely whether cost-benefit analysis favours eradication over other management strategies and whether resources are sufficient to fund an eradication program

Table 1. Criteria used by two different attempts to address the feasibility of pest animal eradication programs.

Criterion	Bomford and O'Brien (1995)	Myers *et al.* (2000)
Strategic/operational		
Immigration prevented	+	+
Pests can be detected at low densities	+	+
Rate of removal exceeds rate of increase at all population densities	+	
Biological		
Biology of target organism must make it susceptible to control procedures OR All reproductives must be at risk [A]	+	+
Economic		
Discounted cost-benefit analysis favours eradication over control	+	
Resources sufficient to fund the program to its conclusion		+
Socio-political		
Suitable socio-political environment OR Lines of authority clear and allow individual or agency to take all necessary actions [A]	+	+

[A] The wording for these criteria differs in the two schemes but is essentially equivalent.

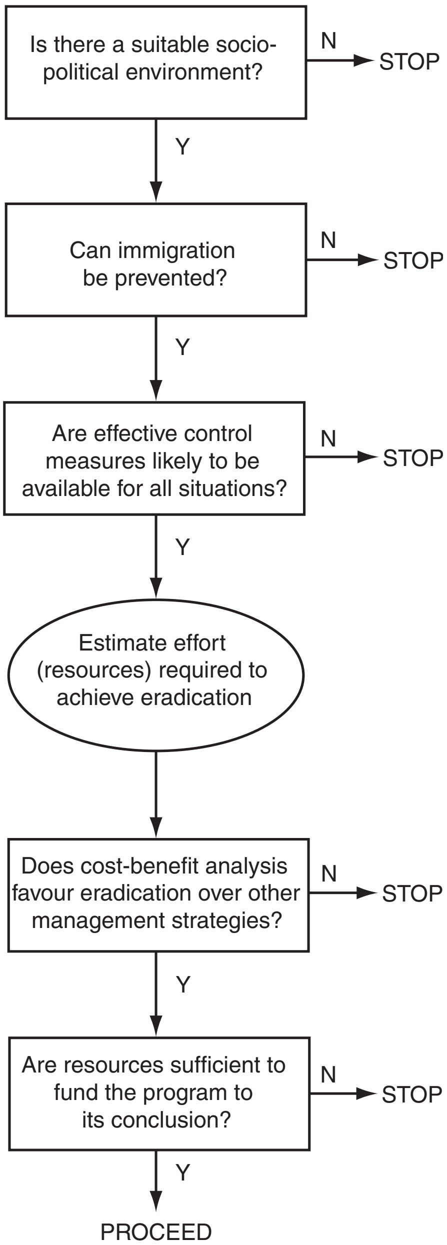

Figure 1. A decision tree for determining the suitability of an eradication management strategy for potential weeds at an early stage of the invasion process.

to its conclusion, are basically economic considerations and cannot be addressed without an estimate of the amount of resources required to achieve eradication.

The assessment of weed eradication feasibility: progress to date

For some time it has been acknowledged that the chances of eradication are greatest when weed populations are small in number and extent. Moore (1975), perhaps rather pessimistically, stated, "In my experience once a species has been in a region, state or country for several years — the time varying with the species and its characteristics — and is established even sparsely in a number of places, there is little possibility of eradication." Recently a case study approach has been adopted in order to derive principles for successful eradication. Using a dataset on eradication attempts by the California Department of Food and Agriculture, comprising 16 species and 50 infestations, Rejmánek and Pitcairn (2002) showed that eradication of infestations of <1 ha was almost always possible, that approximately 30% of the infestations between 1 and 100 ha were eradicated, and that about 25% of the infestations between 100 and 1000 ha were eradicated. It is important to note that the estimates of infestation area they employed were 'gross' (i.e. the areas over which weeds were distributed, and which had to be surveyed in return trips between treatments), rather than 'net' estimates (the areas to which treatments were applied), which were generally considerably smaller. In the three cases of successful eradications of areas larger than 100 ha, the net areas were all less than 1 ha (Rejmánek and Pitcairn 2002).

Costs increased dramatically with infestation area (see also Rejmánek *et al.* in press). Rejmánek and Pitcairn (2002) maintained, furthermore, that eradication of infestations of >1000 ha was unlikely, given a 'realistic amount of resources'.

Refining the '1000 ha rule'

The generation of such a rule of thumb for eradication feasibility was a major step towards a procedure for making decisions on the allocation of resources to incursion management. However, the generality of this rule is far from established. Given the wide variation in the biology and ecology of weeds, and highly variable environmental contexts, it is likely that the relationship between infestation area and the effort required to achieve eradication will also vary. Our approach consists of an examination of the ability of these other factors to impede progress towards an eradication objective. Thus, we consider the effort required to achieve eradication to be a function of both gross infestation area (A, in ha) and impedance (I). We estimate I, using four broad groups of criteria: logistic considerations (L), weed detectability (D), weed biological characteristics (B), and control effectiveness (C). The sub-criteria for each of these groups are described below, and a prospective scoring system is presented in Figure 2.

Logistic considerations (L)

As the number of discrete infestations (L1) increases, the likelihood of spread, and thus the area over which further surveillance must be conducted, also increases (Moody and Mack 1988). The number of infestations also affects control costs through increasing travel time, especially when infestations are widely dispersed. General accessibility of infestations (L2) has components of travel time, ruggedness of terrain and operational difficulties posed by the type of vegetation in which the infestation occurs.

Weed detectability (D)

Groves and Panetta (2002) concluded that the ease of detection of a weed has not generally been given proper consideration in the evaluation of eradication potential. Detection is critical both in the sense of locating infestations and of locating every individual within known infestations. The ability to detect a weed is a function of its visibility and of search effort, experience and method (Harris *et al.* 2001). Usually weed detection is a slow, labour intensive procedure that is very costly. The search rate (hours/ha) required depends upon characteristics of both the target species and the 'matrix' in which it is found. Based on the experience of weed inventory workers searching for a variety of weed life forms in a broad range of vegetation types, Harris *et al.* (2001) employed a standard effort of 2 h per 10 ha, in order to determine optimal surveillance intervals for weeds of natural ecosystems in New Zealand. During eradication efforts in the Galapagos Islands, four people employing a grid of equidistant points took 7 h to cover between 4–15 ha, depending on the vegetation, terrain and the number plants found and controlled (C. Buddenhagen, personal communication). Cryptic species will be the most costly to detect. Remote sensing may pick up sizeable infestations of weeds, but is unlikely to become sufficiently sensitive to detect very small numbers of plants, particularly if these occur in the understorey.

Detectability is as much a function of the vegetation in which a weed occurs as of the characteristics of the plant. The score for detectability should relate to the vegetation type in which the weed is the least detectable, for eradication cannot be claimed until all populations of the weed, in all situations, have been removed. The surveillance effort required to find both new infestations and all individuals within each infestation is inversely related to the ease of detection of a weed. Weeds that have a conspicuous stage (D1) may be detected relatively readily, with a low search effort. The window of opportunity for detecting such plants is a function of the duration of the conspicuous stage(s). The timing of detection in relation to plant phenology is also important. It is critical that a plant is detected and controlled before it reproduces, since reproductive escape can establish (or, more commonly, replenish) a soil seed bank and contribute to further spread. Detectability is, therefore, also scored on how conspicuous the plant would be prior to reproduction (D2).

Logistic considerations (L)

L1) How many infestations[A] are there?

>3 = 6
2–3 = 3
1 = 0

L2) What is the general accessibility of infestations?

Low (most sites difficult to access)[B] = 6
Medium (most sites readily accessible) = 3
High (all sites readily accessible) = 0

Weed detectability (D)

D1) Is the species conspicuous within the matrix of invaded vegetation?[C]

Yes: Conspicuous stage lasting for:
<1 month = 6
1–3 months = 3
>3 months = 0
No, i.e. always inconspicuous = 12

D2) For plants that reproduce by propagules, how detectable is the species prior to reproduction?

Difficult to detect (non-emergent from vegetation and with no distinctive features) = 6
Moderately easy to detect (either emergent or with distinctive features) = 3
Very easy to detect (emergent and with distinctive features) = 0

Weed biological characteristics (B)

B1) Can the species reproduce through vegetative fragmentation?

Yes = 3
No = 0

B2) For species that reproduce by seeds or vegetative propagules, what is the minimum length of the pre-reproductive period?

<1 month = 6
1–12 months = 4
1–2 years = 2
>2 years = 0

B3) What is the maximum longevity of seeds or vegetative propagules?

>10 years = 6
5–10 years = 4
2–5 years = 2
<2 years = 0
Default in absence of information = 4 for seed-producing species; 0 for those producing vegetative propagules

Control effectiveness (C)

C1) How many treatments are required to control the largest plants?[D]

Number of treatments = *n*

C2) Does more than 10% of the total infestation occur in situations that require control procedures that are more expensive than standard methods?[E]

Yes = 3
No = 0

C3) Potential for managing propagule dispersal

Dispersal primarily abiotic (e.g. wind and/or water) or biotic but not involving humans = 6
Dispersal occurs through a balanced mixture of human- and non human-mediated modes = 3
Dispersal primarily human-mediated (includes stock) = 0

[A] Infestations must be independently searched and controlled, i.e. geographically distinct.
[B] Seasonal difficulties (e.g. flooding) in gaining access to infestations should be considered.
[C] Score for the type of vegetation in which the weed would be expected to be least visible. 'Vegetative propagules' include bulbs, bulbils and corms, but exclude rhizomes and stolons.
[D] 'Largest plants' may be clones in vegetatively reproducing species.
[E] For example, proximity to watercourses may limit use of herbicides.

Figure 2. A prospective scoring system for evaluating eradication impedance (I). Simple scales are provided to guide the scorer.

The existence of a dormant, seed phase poses particular problems for detection since seeds are, for all intents and purposes, undetectable. Species that develop persistent seed banks require repeated visits, at a frequency that allows control of new recruits before they become reproductive (see next section).

Weed biological characteristics (B)

Species that are capable of reproducing through vegetative fragmentation (B1) (e.g. *Tradescantia* spp. and *Opuntia* spp.), pose a particular challenge, since individuals may develop this capacity at a young age. For species that reproduce by seed, two biological characteristics are considered to be critical to the amount of effort that would be required to achieve eradication. The length of the pre-reproductive period (B2) provides a measure of how soon after germination and establishment a plant must be controlled if it is to be prevented from reproducing. This attribute varies from a matter of weeks for some annual species to a number of years for some of the larger woody perennials. In practical terms, reproduction *in situ* may often have occurred by the time that an infestation is found, since it is generally unlikely that single, colonizing plants would be detected. The length of the pre-reproductive period has also been considered by some ecologists as a major factor in conferring invasiveness to plants (Rejmánek and Richardson 1996, Reichard and Hamilton 1997).

The required duration of an eradication effort at a given site will be related to the length of time over which new plants continue to arise from propagules. This is determined by both the production of propagules by plants that escape control and maximum propagule longevity (B3). Persistent seed banks have been identified in species from many plant families; it is not exceptional for seeds to persist for decades under field conditions (Baskin and Baskin 1998). A recent study on the survival of gorse (*Ulex europaeus* L.) seeds in New Zealand reported that it might take in the order of 200 years for seed banks to decline to 1% of initial levels at one site, although a similar decline was expected to occur within 10–30 years elsewhere (Hill *et al.* 2001). As critical as this type of information is to the assessment of eradication impedance, usually little is known about seed longevity and the acquisition of such information is, by nature, very time consuming.

Control effectiveness (C)

The primary consideration relating to management tactics is how readily the target species can be killed. The number of treatments required to kill the largest individuals (C1) is a simple measure of this. Another consideration is whether very small plants are exposed to the treatment. However, the contribution to eradication impedance of such escapes is similar to that of plants arising from the seed bank following treatment (i.e. captured in B2 and B3). In some cases the most effective control measure may be unsuited to the particular situation in which the infestation occurs, for example in a riparian habitat where restrictions upon the use of certain herbicides may apply. A less effective or more expensive control option (C2) may be required in such cases, which would increase the amount of resources needed to achieve the objective.

Failure to prevent reproduction can lead to further spread. The potential effectiveness of intervention in preventing or reducing such spread depends largely upon the vector(s) of dispersal. Where grazing animals are primarily responsible for spreading weeds, restrictions upon their movements before and after transport may markedly reduce the potential for further invasion. A capacity for human-mediated dispersal (C3) signals a potential for the development of distant foci of infestation, but also an opportunity for limiting dispersal through management actions that are supported by public education (Panetta and Scanlan 1995). The action of other vectors of dispersal is essentially unmanageable.

Synthesis and application of the scoring system

We earlier referred to the effort required to achieve eradication as a function of infestation area (A) and eradication impedance (I). I is a function of: logistic considerations (L), weed detectability (D), weed biological characteristics (B) and control effectiveness (C), as detailed in Figure 2:

$$I = \sum L + \sum D + \sum B + \sum C$$

We calculate the eradication effort score (E) as the product of A and I:

$$E = A \times I$$

We re-emphasize that the appropriate measure of A is gross, i.e. includes the area that must be searched, as well as the generally much smaller area that requires treatment. Therefore costs associated with E include surveillance as well as control components, all expressed per hectare.

In order to illustrate the use of the scoring system, it has been applied to several eradication programs that have targeted weeds of agriculture (Table 2). The two species for which eradication has been confirmed (*Eupatorium serotinum* Michx. and *Helenium amarum* (Rafin) H.L.) comprised relatively small infestations, at 0.1 ha and 50 ha respectively. For a third species (*Bassia scoparia* (L.) A.J. Scott), virtually complete eradication (from 98% of the properties on which it is known to occur) from Western Australia has been achieved. This appears to be a striking exception to the '1000 ha rule'. The emerging success of this eradication program is attributed to several factors. First, it began within 12 months of the intentional introduction of this species for reclamation of salt-affected land. All the sites of introduction were known, thus reducing the need for surveillance over large areas. Most of the introductions were fenced off, limiting dispersal by both excluding stock and trapping the wind-blown plants or 'tumbleweeds'. Further, *B. scoparia* has a vegetative period of several months, is generally highly detectable and has relatively short-lived seeds (Dodd and Randall 2002). Other major factors predisposing this program to success were an adequate level of funding (c. $A 500 000), shared between the Federal and State governments, and a very high degree of cooperation from local landholders. While the current eradication effort against *Orobanche ramosa* L. also has a high level of funding and landholder support (Jupp *et al.* 2002), the higher I value (25 v. 16 for *B. scoparia*), in conjunction with a larger area of infestation (4850 v. 2480 ha), suggest that eradication may be much less feasible for this species.

It is obviously not possible to demonstrate a full range of values for I by employing such a small number of examples.

Table 2. Application of the scoring system to some Australian eradication programs targeting weeds of agriculture.

Species	Program status	Impedance sub-criterion										I	A	E
		L1	L2	D1	D2	B1	B2	B3	C1	C2	C3			
Bassia scoparia	Nearly completed	6	0	0	0	0	4	2	1	0	3	16	2480	39680
Eupatorium serotinum	Completed	3	0	3	3	0	2	4	1	0	3	19	0.5	9.5
Helenium amarum	Completed	3	0	3	6	0	4	4	1	0	3	24	50	1200
Orobanche ramosa	Ongoing	6	0	3	3	0	6	6	1	0	0	25	4850	121250

Because the examples that we have used comprise solely weeds of agriculture, a land use in which accessibility to infestations is generally high, the potential influence of variations in accessibility on I has not been captured. We will return to this point later.

Discussion

Feasibility of eradication must always be viewed in the context of the amount of effort that can be mustered towards the objective (Rainbolt and Coblenz 1997). It is notable that Rejmánek and Pitcairn (2002) qualified their generalization that eradication of infestations >1000 ha was unlikely, by relating it to the availability of a 'realistic' amount of resources. Presumably the upper boundary of eradication feasibility, given unlimited levels of resourcing, is set by the required effort at which eradication is no longer the most cost-effective management option. Thus, the assessment of eradication feasibility cannot be divorced from the hazard posed by the incursion, with more effort justified by greater threats.

Feasibility may also be considered in terms of the probability of achieving success. We assume that there is an inverse relationship between probability of success and the effort required for eradication, since effort increases with the size of the problem, while the probability of achieving success can be expected to decrease. It is by no means clear how to quantify the increase in effort that would be necessary to manage the risk of failure, but we suggest that this risk may be managed most effectively by increasing the level of surveillance. As our eradication effort score is a product of infestation area and impedance, it also unclear whether different combinations of A and I that give the same value of E (e.g. A = 100 ha and I = 20 v. A = 50 ha and I = 40) are associated with similar probabilities of success. The fact that some successful weed eradication programs have taken decades to complete (e.g. 18 years for *E. serotinum* and 39 years for *H. amarum* (Tomley and Panetta 2002)) indicates, nevertheless, that the risk of failure will remain high without mechanisms in place to ensure long-term continuity of both funding and staffing.

Impedance criteria and sub-criteria can influence eradication programs in a variety of ways (Table 3). The development of a readily employable system necessarily involves a compromise between the inclusion of sub-criteria and the ease with which relevant information can be acquired. However, some sub-criteria are so crucial to the assessment of feasibility that they must be included, despite the fact that the necessary information is often lacking. One such problematic subcriterion is maximum propagule longevity (B3). We have dealt with the uncertainty inherent in this criterion by including a default option (Figure 2) that corresponds to long persistence (up to 10 years). Another is dispersal distance; this will affect ease of containment as well as the area over which surveillance must be conducted (Table 3). Data on distance of dispersal are very rarely available, meaning that scoring systems that include this criterion must rely upon 'educated guesswork' (or worse!) on the part of the user. In our system, the potential for intervention to curb dispersal (C3) is used as a proxy for the spread that might occur from known infestations during the course of an eradication program. Other criteria (e.g. breeding system, as a surrogate for the colonization potential of individual plants) could be added to the system, but gains to the effectiveness of the system may be slight relative to the increase in information requirements.

A number of the criteria relate to the potential duration of the eradication program. Clearly, it will not be possible to derive an accurate estimate of the amount of the resources needed without knowing for how long the effort must be maintained. For pest animals, Bomford and O'Brien (1995) stated that eradication programs should be time-limited, '…because an eradication campaign without a specified end point is *de facto* continuing control.' Where there is uncertainty in relation to the length of the eradication program, estimates of required effort (and hence total resources) are bound to be imprecise. Moreover, cost-benefit analyses of eradication programs are affected by biases that tend to underestimate costs and overestimate benefits (Dahlsten *et al.* 1989, Myers *et al*. 1998). Difficulties in estimating benefits arise from the uncertainties involved in prediction of the potential impact of the weed, whereas underestimates of the costs are related to both imperfect knowledge of the extent of the problem and the timeframe required for dealing with it. Simberloff (2003) has suggested that such cost-benefit analyses are likely to have extremely wide confidence limits for the foreseeable future. For these reasons, our scoring system may be most applicable to choices between alternative targets for eradication, with reference to a defined amount of resources.

Apart from the selection of criteria, the largest issue with scoring systems is the determination of weightings for individual criteria and sub-criteria. With regard to scoring for I, detectability is the *sine qua non* of weed eradication — it is only possible to control a weed if it can be found. Our scoring system reflects this, in that detectability can potentially have the highest score (18) of any of the impedance criteria. The best way to determine the appropriate weightings for criteria would be to analyse the effort expended in a number of successful and fully documented eradication case histories, substantially more than are currently available. A solid empirical basis will also be required to establish the relationship between E and the amount of resources involved.

We have utilized agricultural weeds for our (admittedly) limited application of the scoring system because the '1000 ha rule' was derived primarily from examples drawn from the agricultural sphere (Rejmánek and Pitcairn 2002). For weeds of natural ecosystems, we predict that high

Table 3. Possible influences of impedance criteria and sub-criteria on eradication programs.

Detectability (D)	Length of pre-reproductive period (B2)	Propagule longevity (B3)	Mode of propagule dispersal (C3)
• Search effort required to: – determine scale of operation – locate new infestations – locate and control plants in known infestations before they can reproduce – detect target at low density • Risk that program will be prolonged or fail because of undetected reproductive plants or additional, undetected infestations	• Frequency of visits to infested sites required to ensure new plants are found before they reproduce • Risk that program will be prolonged or fail because of undetected reproductive plants	• Duration of program required to ensure that weed is locally extinct • Risk that the program will fail owing to premature termination	• Potential to prevent the further spread of the weed • Details of systematic surveillance strategies, including the patterns of surveillance required • Risk that program will be prolonged or fail because of additional, undetected infestations

impedances to eradication arising from limitations in both accessibility and detectability will often constrain eradication potential to considerably smaller incursions, possibly an order of magnitude less than 1000 ha. At present we are unable to incorporate weightings in the scoring system that might reflect such limitations, owing to the rarity of documented examples of weed eradication from natural ecosystems. It is our hope that this paper will stimulate interest in the determination of eradication feasibility for weeds, supported by appropriate documentation of eradication programs.

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References

Baskin, C.C. and Baskin, J.M. (1998). 'Seeds. Ecology, biogeography, and evolution of dormancy and germination'. (Academic Press, San Diego).

Bomford, M. and O'Brien, P. (1995). Eradication or control for vertebrate pests? *Wildlife Society Bulletin* 23, 249-55.

Daehler, C.C. and Carino, D.A. (2000). Predicting invasive plants: prospects for a general screening system based on current regional models. *Biological Invasions* 2, 93-102.

Dahlsten, D.L., Garcia, R. and Lorraine, H. (1989). Eradication as a pest management tool: concepts and contexts. *In* 'Eradication of exotic pests. Analysis with case histories', eds D.L. Dahlsten, R. Garcia and H. Lorraine, pp. 3-15. (Yale University Press, New Haven).

Dodd, J. and Randall, R.P. (2002). Eradication of kochia (*Bassia scoparia* (L.) A.J. Scott, Chenopodiaceae) in Western Australia. Proceedings of the 13th Australian weeds conference, Perth, eds H. Spafford Jacob, J. Dodd and J.H. Moore, pp. 300-3. (Plant Protection Society of Western Australia, Perth).

Grice, A.C. and Ainsworth, N. (2003). Sleeper weeds – a useful concept? *Plant Protection Quarterly* 18, 35-9.

Groves, R.H. and Panetta, F.D. (2002). Some general principles for eradication programs. Proceedings of the 13th Australian weeds conference, Perth, eds H. Spafford Jacob, J. Dodd and J.H. Moore, pp. 307-10. (Plant Protection Society of Western Australia, Perth).

Harris, S., Brown, J. and Timmins, S. (2001). Weed surveillance – how often to search? *Science for Conservation 175*, Department of Conservation, Wellington, New Zealand.

Hill, R.L., Gourlay, A.H. and Barker, R.J. (2001). Survival of *Ulex europaeus* seeds in the soil at three sites in New Zealand. *New Zealand Journal of Botany* 39, 235-44.

Hobbs, R.J. and Humphries, S.E. (1995). An integrated approach to the ecology and management of plant invasions. *Conservation Biology* 9, 761-70.

Jupp, P., Warren, P. and Secomb, N. (2002). The branched broomrape eradication program: methodologies, problems encountered and lessons learnt. Proceedings of the 13th Australian weeds conference, Perth, eds H. Spafford Jacob, J. Dodd and J.H. Moore, pp. 270-3. (Plant Protection Society of Western Australia, Perth).

Lonsdale, W.M. and Smith, C.S. (2001). Evaluating pest-screening systems – insights from epidemiology and ecology. *In* 'Weed risk assessment', eds R.H. Groves, F.D. Panetta and J.G. Virtue, pp. 52-60. (CSIRO Publishing, Melbourne).

Mack, R.N. (1996). Predicting the identity and fate of plant invaders: emergent and emerging approaches. *Biological Conservation* 78, 107-21.

Moody, M.E. and Mack, R.N. (1988). Controlling the spread of plant invasions: the importance of nascent foci. *Journal of Applied Ecology* 25, 1009-21.

Moore, R.M. (1975). An ecologist's concept of a noxious weed: plant outlaw? *Journal of the Australian Institute of Agricultural Science* 41, 119-21.

Myers, J.H., Savoie, A. and van Randen, E. (1998). Eradication and pest management. *Annual Review of Entomology* 43, 471-91.

Myers, J.H., Simberloff, D., Kuris, A.M. and Carey, J.R. (2000). Eradication revisited: dealing with exotic species. *Trends in Ecology and Evolution* 15, 316-20.

Panetta, F.D. and Scanlan, J.C. (1995). Human involvement in the spread of noxious weeds: what plants should be declared and when should control be enforced? *Plant Protection Quarterly* 10, 69-74.

Pheloung, P.C., Williams, P.A. and Halloy, S.R. (1999). A weed risk assessment model for use as a biosecurity tool evaluating plant introductions. *Journal of Environmental Management* 57, 239-51.

Pimental, D. (Ed.) (2002). 'Biological invasions: Economic and environmental costs of alien plant, animal, and microbe species'. (CRC Press, Boca Raton).

Rainbolt, R.E. and Coblenz, B.E. (1997). A different perspective on eradication of vertebrate pests. *Wildlife Society Bulletin* 25, 189-91.

Reichard, S.H. and Hamilton, C.W. (1997). Predicting invasions of woody plants introduced into North America. *Conservation Biology* 11, 193-203.

Rejmánek, M. and Pitcairn, M.J. (2002). When is eradication of exotic pest plants a realistic goal? *In* 'Turning the tide: The eradication of island invasives'. (eds C.R. Vietch and M.N. Clout), Occasional Paper of the IUCN Species Survival Commission No. 27, pp. 249-253. (IUCN- The World Conservation Union, Auckland, New Zealand).

Rejmánek, M. and Richardson, D.M. (1996). What attributes make some plant species more invasive? *Ecology* 77, 1655-61.

Rejmánek, M., Richardson, D.M., Higgins, S.I., Pitcairn, M. and Grotkopp, E. (in press). Plant invasion ecology: State of the art. *In* 'Invasive alien species: Searching for solutions', eds H.A. Mooney, J.A. McNeely, L. Neville, P.J. Schei and J. Waage. (Island Press, Washington, D.C.).

Richardson, D.M., Pysek, P., Rejmánek, M., Barbour, M.G., Panetta, F.D. and West, C.J. (2000). Naturalization and invasion of alien plants: concepts and definitions. *Diversity and Distributions* 6, 93-107.

Simberloff, D. (2003). Eradication – preventing invasions at the outset. *Weed Science* 51, 247-53.

Tomley, A.J. and Panetta, F.D. (2002). Eradication of the exotic weeds *Helenium amarum* (Rafin) H.L. and *Eupatorium serotinum* Michx. from south-eastern Queensland. Proceedings of the 13th Australian weeds conference, Perth, eds H. Spafford Jacob, J. Dodd and J.H. Moore, pp. 293-96. (Plant Protection Society of Western Australia, Perth).

Williams, P.A. (1997). Ecology and management of invasive weeds. Conservation Sciences Publication No. 7, Department of Conservation, Wellington, New Zealand.

Williamson, M. (2001). Can impacts of invasive species be predicted? *In* 'Weed risk assessment', eds R.H. Groves, F.D. Panetta and J.G. Virtue, pp. 20-33. (CSIRO Publishing, Melbourne).

Zavaleta, E.S., Hobbs, R.J. and Mooney, H.A. (2001). Viewing invasive species removal in a whole-ecosystem context. *Trends in Ecology and Evolution* 16, 454-9.