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Eradication versus containment strategies for invasive species management

Helen T. Murphy, Cameron S. Fletcher, Tony Grice,
John Clarkson and David A. Westcott

Australian Government
Department of the Environment

Reef & Rainforest RESEARCH CENTRE

Eradication versus containment strategies for invasive species management

Helen T. Murphy[1], Cameron S. Fletcher[1], Tony Grice[2], John Clarkson[3] and David A. Westcott[1]

[1] CSIRO Land and Water Flagship, Tropical Forest Research Centre, Atherton, Queensland

[2] CSIRO Land and Water Flagship, ATSIP, Townsville, Queensland

[3] Queensland Department of National Parks, Recreation, Sport and Racing, Mareeba, Queensland

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Acronyms Used In This Report

NERP .... National Environmental Research Program

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Introduction

The terms 'prevention', 'eradication', 'containment' and 'asset protection' (Grice 2009) are commonly applied to describe strategic options for managing weeds and they are usually linked to the traditional 'invasion curve' which describes the state of an invasion along axes of time and area of invasion or abundance (Figure 1). Prevention is prescribed for the pre-introduction phase when a species is absent from a targeted region. Eradication is usually deemed a prospect in the immediate post-introduction phase, when there are only a small number of localised populations. Once a species has spread beyond a limited number of sites or when there is a rapid increase in distribution and abundance, the hope of eradication is usually abandoned and containment is considered the next most feasible option. Finally, once the species is abundant and widespread, 'asset protection' is generally advocated, focusing efforts on specific locations where particular assets are under threat from the invader (Grice et al. 2013).

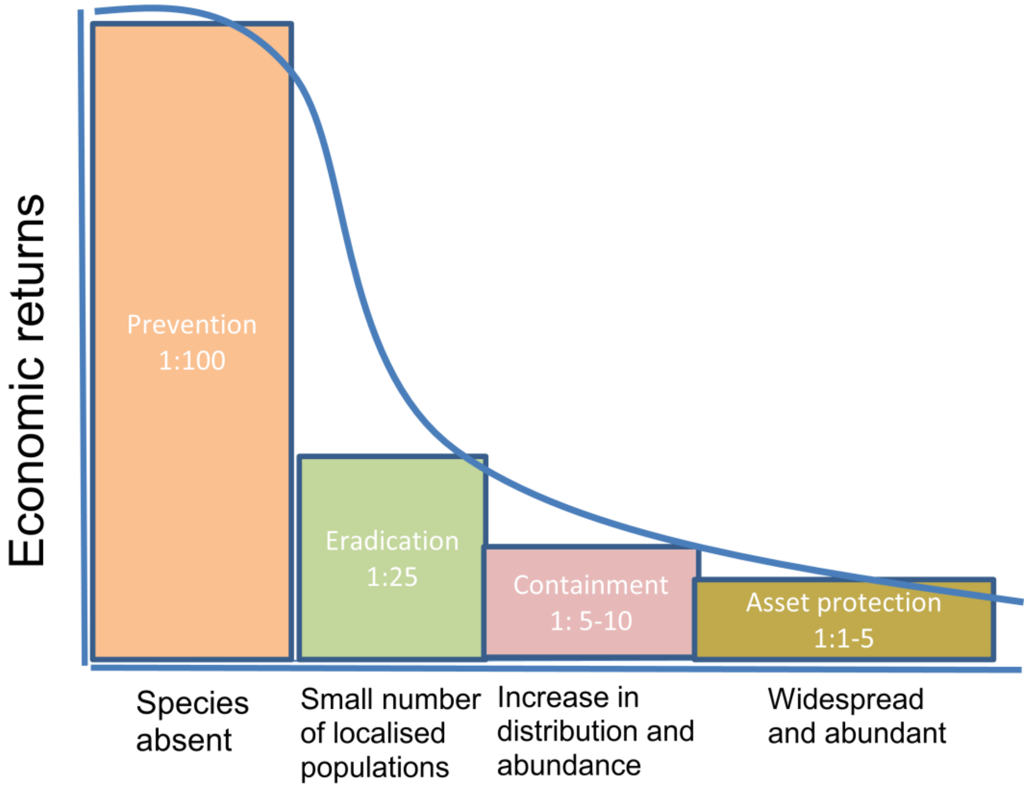


Figure 1: The invasion curve (adapted from DEPI, 2013)

This report focuses on the transition between eradication and containment as management strategies for invasive plants. CSIRO Tropical Ecosystems Hub researchers in collaboration with QPWS (Project 7.2 Invasive species risks and responses) have been using modelling approaches to understand where, why and when land managers might shift their management focus from eradication to containment. We have undertaken a net present value analysis of the costs of eradication and containment, then extended it to estimate the costs of adapting both strategies in response to six types of breach. We derived rules to guide land managers in determining the circumstances under which a containment strategy is likely to be more effective or efficient than an eradication strategy, the effect of a breach of the management unit on each type of management strategy, and the situations in which containment would form a valid fall-back strategy for a breach in an eradication program.

Eradication

Eradication is relatively simple to define and measure; it can be defined as 'a deliberate action taken to eliminate a plant from a predefined area', and it is successful when all individuals have been eliminated and the soil seed bank has been exhausted. The science and practice of eradication has a long history, although, despite many successful campaigns, there is widespread pessimism about the prospects of eradicating invasive species (Simberloff 2009). There has been considerable research on the feasibility of eradication and the factors that affect it with the general conclusion that eradication is likely to be feasible only when the total population is small, there are few infestations and the total area occupied by the invader is limited (Panetta 2007).

Weeds can be particularly difficult targets for eradication for several reasons. They may have a persistent seedbank extending over many years or decades and therefore eradication programs require long-term funding and agency commitment (Panetta and Lawes 2005). Furthermore, the mode and distance of dispersal events can be very difficult to determine for weed species and without a good understanding of dispersal it becomes very difficult to understand or predict weed spread to structure management actions (Fletcher and Westcott 2013), or delimit infestations and to detect new infestations. Detection of weed species is often difficult and this is particularly true for weeds of rainforest habitats where the number of co-occurring native species is relatively high.

Containment defined

Containment is a frequently advocated strategic objective for countering plant invasions in Australia. For example, of the original National Plans for twenty Weeds of National Significance released in 2000 (Thorp and Lynch 2000), the management plans of only two, athel pine *Tamarix aphylla* (ARMCANZ and ANZECCFM 2000a) and salvinia, *Salvinia molesta* (ARMCANZ and ANZECCFM 2000b) did not employ the term 'containment'. Both of those species had a reference to containment added during review in 2012 (AWC 2012a, b).

In these and other weed management strategies, the term containment has been used to refer to a number of objectives: (i) management strategies that aim to either prevent spread of invasive species from an invaded region; (ii) exclude species from an uninvaded region; (iii) 'slow-the-spread' of an invasive species; (iv) provide an interim response during which decisions are made regarding the costs and benefits of eradication, control or no management; or (v) prevent commercially useful species from spreading outside areas where they are intentionally cultivated (Grice et al. submitted). In a recent paper (Grice et al. submitted) we suggested that a consistent definition for containment was necessary to improve the prospect of effective, science-based management strategies and to facilitate a reliable evaluation of progress against those strategies. Thus, we propose that containment be defined as a ***deliberate action taken to prevent establishment and reproduction of a species beyond a predefined area, or "containment unit", consisting of an "occupied zone" occupied by established, reproductive plants and surrounded by a "buffer zone" that is free from established plants but that does receive propagules from the occupied zone***. (see also Grice et al. submitted) (Figure 2).

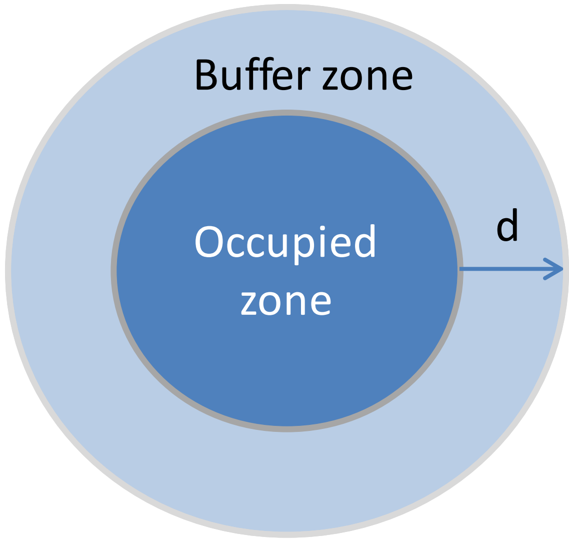


Figure 2: A simple model of invasion

The model is defined by a 'containment unit', consisting of an "occupied zone" around the current extent of reproductive individuals (dark shading), and a buffer zone of width d related to the dispersal capacity of the invader, into which individuals may be dispersed. Eradication requires management of both the occupied and buffer zones until the seed bank is completely depleted. Containment requires management of only the buffer zone, but that management must continue indefinitely.

In practice, containment involves some combination of reducing (i) reproduction of the source population; (ii) dispersal from the source population; and (iii) establishment and reproduction away from the source population. Although dispersal is the critical ecological process, our definition focuses on establishment and reproduction because it is difficult to manage many dispersal processes and pathways (Grice et al. 2012).

Although containment is widely proposed as a weed management objective and there is a growing body of scientific literature that addresses the topic, the links between scientific understanding and practical application are still rather weak. Our research has aimed to strengthen the scientific understanding of containment in a way that allows managers to make a more reliable assessment of the feasibility and costs of containment in particular circumstances.

Choosing between eradication and containment.

Containment generally aims to restrict where a species grows by focusing on removal of individuals in the buffer zone only, whereas in an eradication strategy all individuals must be removed from both the occupied and buffer zones (Figure 3a). By definition then, a manager must be able to effectively eradicate a species in some parts of the containment unit for containment to be successful. Therefore, if eradication is very difficult because of, for example, detection or surveillance difficulties, limited control options, difficult access, unknown dispersal pathways or insufficient funding over a long-enough period, then containment is likely to be similarly difficult for the same reasons To be effective, the spatial scale of management must be no smaller than the scales set by the ecological drivers of spread and establishment and must also incorporate temporal scales set by seed bank longevity and the particular life history of the species. Thus eradication strategies must continue for a least as long as the seed bank longevity plus one year, whereas in theory containment strategies continue indefinitely (Figure 3b).

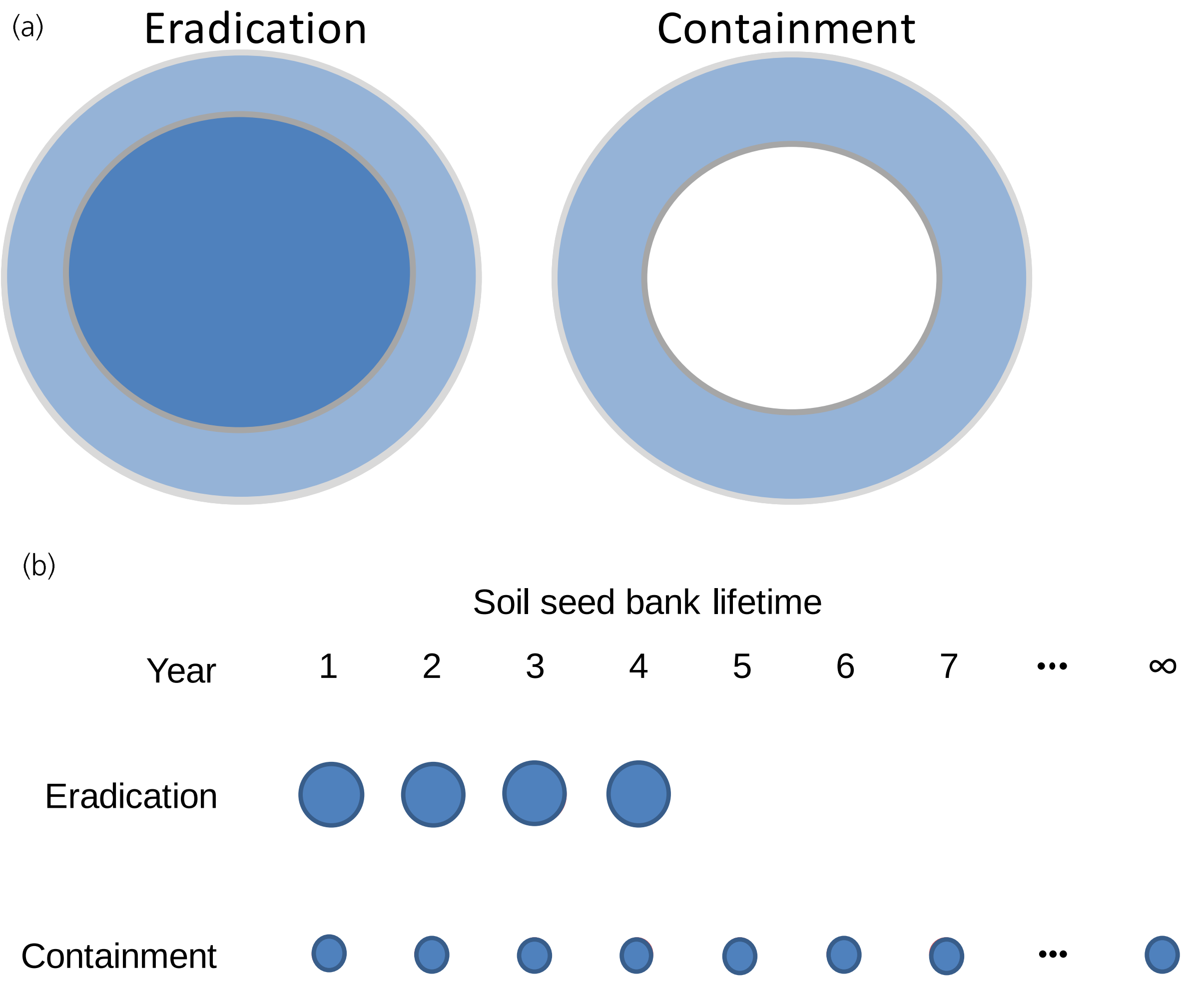


Figure 3: The (a) spatial and (b) temporal distribution of effort in eradication and containment strategies for a species with a seed bank longevity of 4 years

(a) Containment strategies aim to prevent establishment of a species beyond a predefined area – management primarily occurs in the buffer zone of an infestation which is defined by the dispersal distance. Eradication aims to eliminate all plants from a predefined area – management occurs in both the occupied zone and buffer zone of an infestation. (b) Eradication is successful when all individuals have been eliminated and the seed bank is exhausted - in a species with a seed bank of 4 years, and assuming perfect delimitation, detection and control, eradication can be achieved after 4 years. If the area of the containment zone is illustrated as an equivalent-area circle we see that the area to be managed is smaller than eradication, but containment continues indefinitely.

Despite increasing recognition of the limitations of containment as a management strategy, practical on-ground management programs have continued to view containment as a default fallback option for failed eradication programs. However, the ecological drivers that determine containment success are the same as those that limit successful eradication. Particularly important drivers of the feasibility of eradication or containment thus are:

1. The size of the infestation when management commences;
2. The dispersal capacity of a species and the shape of the dispersal kernel (Figure 4); and
3. Seed bank longevity

The minimal target of a containment strategy is the current extent of reproductive individuals, assuming that the current extent has been delimited. The minimum width of the buffer zone is defined by the distance over which seeds from the occupied zone are dispersed, assuming there is a maximum limit to a dispersal kernel. Although infestations can't always be reliably delimited, and it is virtually impossible to know with complete certainty that all individuals have been located (Panetta and Lawes 2005), the extent of an infestation can generally be estimated to within a reasonable range.

Estimating or even defining the maximum dispersal distance of any plant species is a notoriously difficult problem (Fletcher and Westcott 2013), because in many species: 1) a tiny proportion of seeds experience rare long-distance dispersal events (Nathan 2006); and 2) the potential exists for completely different modes of dispersal, e.g. human-mediated spread, to transport small numbers of seeds vast distances (Higgins et al. 2003, Nathan 2006). Research has shown that the shape of the dispersal kernel is of enormous importance in determining the rate of spread. In particular, species with 'fat-tailed' dispersal kernels, where a relatively large proportion of seeds is dispersed over long distances, are capable of very rapid spread and may be particularly difficult to eradicate or contain (Panetta and Cacho 2012) (Figure 4).

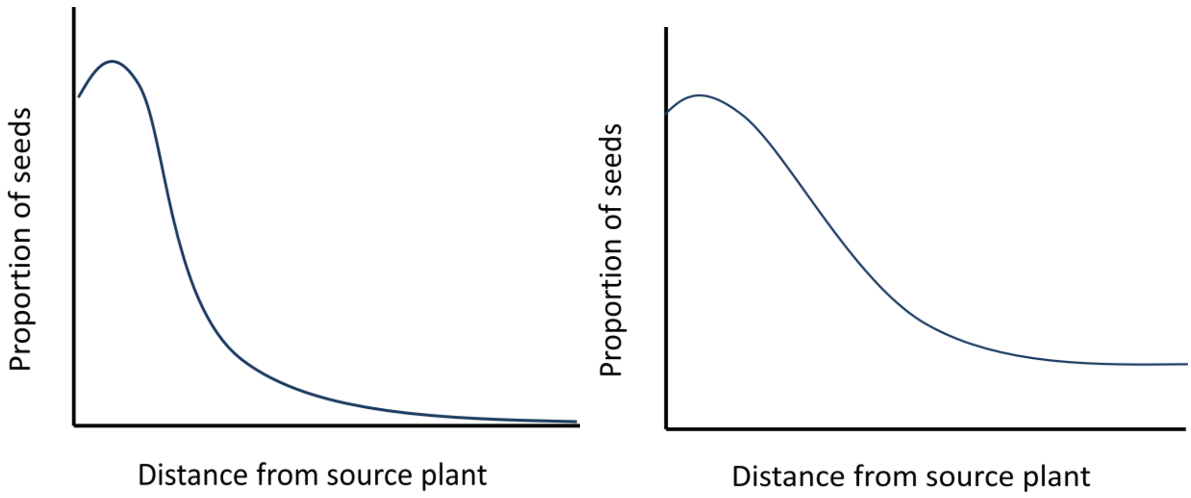


Figure 4: A dispersal kernel

Left – typical dispersal kernel with the vast majority of seeds dispersed close to the source plant and a very small proportion of seeds dispersed over longer distances. Right – a 'fat-tailed' dispersal kernel with a larger proportion of seeds dispersed over longer-distances.

Seed bank longevity is very important when choosing between containment and eradication. Eradication programs must continue for at least until the seed-bank is exhausted and as soon as a new reproductive event is recorded the count-down resets. Therefore, it makes sense that eradication programs become more expensive with increasing seed bank longevity. Of course, this is not so much of an issue for containment programs which in theory are required to run indefinitely anyway. Seed bank longevity is not always known but can usually be estimated relatively well with experimental and field studies.

A simple model comparison of eradication and containment

We developed a simple model of the relative performance of containment and eradication strategies to derive some basic rules for choosing between the two strategies with the need for minimal data. The model assumes a circular infestation of radius *r* (in metres) and a buffer zone related to the dispersal distance *d* (in metres, as per Figure 2), and requires an estimation of seed bank longevity *s* (in years). Total 'costs' in net present values are the cost of searching for and removing individuals, *c* ($ per square metre) multiplied by the area searched every year, *A* (m^2), with future costs converted to net present values via an appropriate discount rate, δ (%/100).

For a given weed, *d* and *s* can be estimated as outlined in the section above. The costs of searching and removing individuals depend on the species being managed, the structure of the invasion and the cost of labour and materials in the infested region. The discount rate, δ, reflects the fact that a dollar invested in weed management at some point in the future could be funded by something less than a dollar of today's money invested and earning interest at the discount rate. For a given species in a given region, the only undetermined variable is the radius of current extent, *r*.

For a given infestation, the difference in cost between eradication and containment programs is determined by the current extent of the infestation relative to the dispersal capacity of the invader, scaled by the decreasing value of money over the seed bank lifetime. The relative performance of the two strategies may be compared by finding the point at which their costs are equal r_*.

For further details of the equations used in the model see Box 1 and Fletcher et al. (2014b).

Box 1

Equation 1 shows how the cost of either strategy, C ($), is determined by the area to be searched every year (A) and by how long management must continue (y_{max}):

$$C(A, y_{max}) = \sum_{y=1}^{y_{max}} c A (1+\delta)^{-y} \qquad \text{(Equation 1)}$$

An eradication program must manage both the occupied and buffer zones ($A = \pi(r+d)^2$) until the seed bank is completely depleted ($y_{max} = s$). The total net present cost of such a strategy is:

$$EC = \sum_{y=1}^{s} c\,\pi(r+d)^2(1+\delta)^{-y} \qquad \text{(Equation 2)}$$

In contrast, a containment program that does not aim to control the occupied zone need manage only the buffer zone ($A = \pi(r+d)^2 - \pi r^2$), but it must do so indefinitely ($y_{max} = \infty$). The net present cost is:

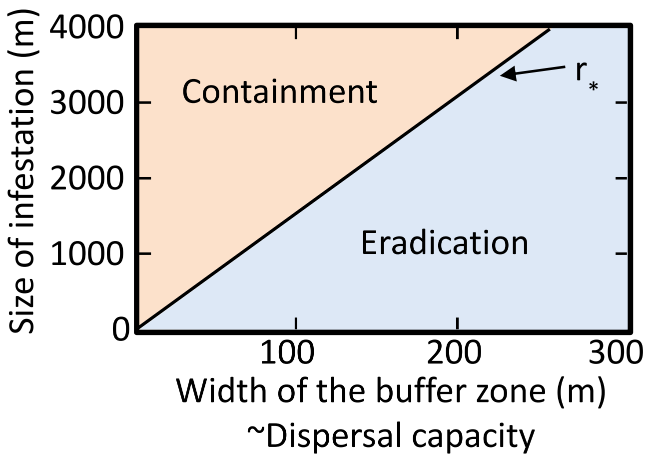
$$CC = \sum_{y=1}^{\infty} c\left(\pi(r+d)^2 - \pi r^2\right)(1+\delta)^{-y} \qquad \text{(Equation 3)}$$

The relative performance of the two strategies may be compared by finding the infestation size for which their costs are equal, r_* (m):

$$r_* = d\left(\frac{1}{\sqrt{(1+\delta)^{s}}-1}\right) \qquad \text{(Equation 4)}$$

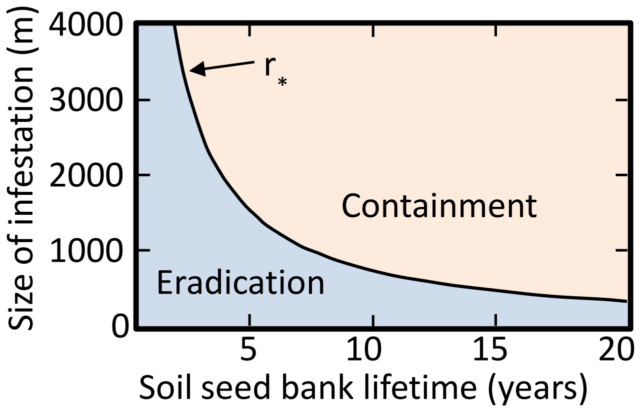
Under what circumstances is containment more efficient than eradication?

Figure 5 allows us to understand how the critical decision point between containment and eradication depends on effective dispersal distance, seed bank longevity and the discount rate. For example, for Figure 5 below, the costs of both strategies are equal when the occupied zone is of radius r_* (metres), which can be expressed as a multiple of the effective dispersal distance. Plotting r_* allows us to separate 'management space' into two regions. To one side of the r_* line, eradication is the cheaper option; on the other side containment is cheaper.

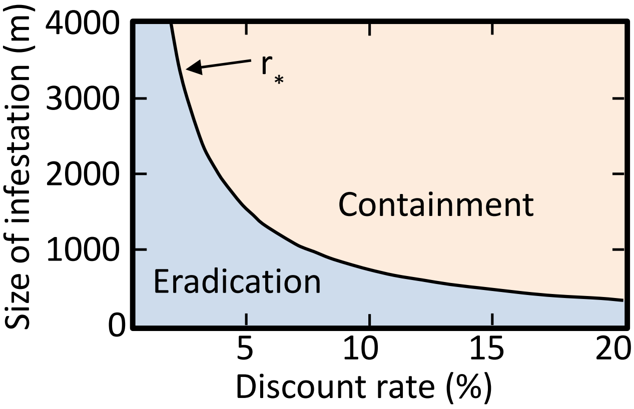


(a) Invaders with larger effective dispersal capacities require a larger buffer zone, and the critical radius at which containment outperforms eradication increases.

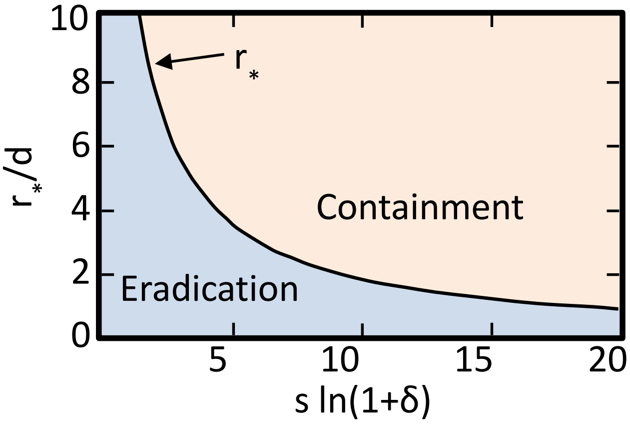
The longer an infestation has been established and the further it has spread, the more likely it is that a containment strategy will be a cheaper option than eradication.



(b) Invaders with long-lived seed banks require long eradication programs, and so the critical radius at which containment outperforms eradication decreases.



(c) An increasing discount rate decreases the future value of money and the future costs of running a long-term containment program, decreasing the critical radius at which containment outperforms eradication.



(d) These relationships can be summarised for all possible invasions in a dimensionless form by scaling the critical radius against the buffer width (r_*/d), and plotting against the seed bank longevity and the log of the discount rate ($s \ln(1+\delta)$). As the seed bank longevity or the discount rate increase, the ratio of the infestation size to the dispersal distance at which containment outperforms eradication becomes smaller. Each possible infestation and management strategy represents a single point within this dimensionless space, and its location determines whether it is most economically managed via an eradication or containment program.

Figure 5: Eradication versus containment

The first three figures show how large the occupied zone must be before containment out-performs eradication as a function of (a) maximum dispersal distance, (b) seed bank longevity, and (c) the discount rate. Figure d) shows how the slope of this critical decision point between the two strategies depends on the dimensionless combination of the discount rate and the seed bank longevity, s ln(1+δ). As the seed bank longevity or the discount rate increase, the ratio of the infestation size to the dispersal distance at which containment outperforms eradication becomes smaller.

The relative cost of containment versus eradication – an example

Figure 6 illustrates the relative costs of an eradication and containment program for a specific case (see also Fletcher et al. 2014a for further details). In this example the radius of the core area is twice the dispersal distance, the soil seed bank lifetime is 4 years, the discount rate is 20% per annum (this is much higher than a typical discount rate but it works better visually – it is only the relative difference in cost we are concerned about in Figure 6). The bottom two rows of the figure illustrate that although a containment program must run forever, the area to be managed is smaller (in this case half the area) than the area managed in an analogous eradication program. The top two rows show how the decreasing value of money over time makes the per-annum cost of running a long-term containment program fall off the further into the future we project.

The size of the final circle in the top row answers the question: *how much money would we have to put in a savings account today to fund the entire management program*? Although a simplification, the idea is loosely that if we put enough money in the account, annual containment actions could be funded forever from the compound interest alone. Because an eradication program is relatively short-lived, this is a small effect, but for a containment program that continues to run indefinitely, this significant effect means that a finite amount of today's money could fund containment operations indefinitely into the future.

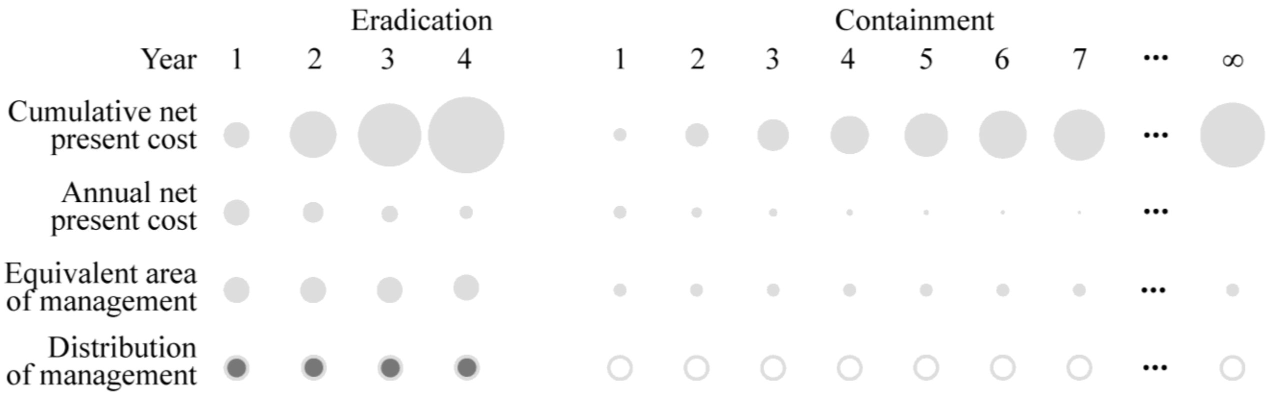


Figure 6: The relative costs of containment and eradication.

The system illustrated has an occupied zone radius twice the size of the buffer width (r = 2d), a soil seed bank lifetime of 4 years, and a discount rate of 20%. The second bottom row shows the area of the management distribution as a simple circle, enabling comparison between the two strategies. The second top row shows the cost in today's dollars of management each year, assuming fixed costs per unit area. The top row shows the cumulative costs in today's dollars, and the size of the last circle in this row represents the total cost of each strategy (Fletcher et al. 2014a).

This figure graphically demonstrates that while containment has one major advantage over eradication, in that a smaller area can be managed, this must be balanced against its disadvantage; that it must continue indefinitely. For the specific parameters illustrated above, the total Net Present Costs of containment are lower than those of eradication, as illustrated by the size of the final circles in the top row for each strategy.

In summary: Containment or eradication?

Different invasions will be more effectively managed by either eradication or containment based on the soil seed longevity, the discount rate, and most importantly, the size of the infestation relative to the width of the buffer zone. Crucially, there is a threshold invasion size below which it will better to eradicate than contain, and above which the opposite is true. If the infestation size, dispersal capacity, soil seed bank lifetime and discount rate of an infestation can be estimated for a given infestation, then a single coordinate can be identified on Figure 5d, and the optimal strategy immediately identified. However, the potential that neither eradication nor containment is affordable should be considered (Panetta and Cacho 2014).

In terms of general relationships, containment becomes more attractive than eradication for invaders with smaller dispersal distances or long lived seed banks, or for larger discount rates. These parameters are generally fixed outside of managers' control, determined by either the biology of the plant or the economic system, but they can change over time if, for example, further study improves estimates of seed bank longevity. Similarly, parameters may vary between individual isolated sites, such as the limited dispersal capacity of a wind dispersed species established in a sheltered site.

When is it logical to switch from eradication to containment?

Both containment and eradication programs are at risk of a breach due to rare events (Cacho et al. 2008). For example, there is always a small probability of dispersal over much greater distances than is typical. It is vital that any management strategy explicitly recognizes the potential for breaches of containment units or eradication targets and the need to place the effect of the breach in a broader management context, possibly involving transitions to other strategic objectives (Fletcher et al. 2014b).

In some cases weed managers may conclude that eradication is no longer feasible or cost-effective if certain types of breach occur and that management should fall-back to containment. In this section we use the model described in the section above to consider the merit of switching from an eradication program to a containment program following a range of breach types (Fletcher et al. 2014b). The question is whether a system that is initially well-specified as an eradication program (i.e. dispersal distances and seed bank longevity are well understood and the infestation extent has been delimited), with an occupied zone smaller than the critical radius for containment, changes its optimal management strategy from eradication to containment as a result of the breach. We assume that the decision to change from eradication to containment is being made as soon as the breach is discovered, and only costs from that point on are considered. This reduces the problem to an analysis of the costs of containment and eradication for the newly specified system.

Breaches of containment and eradication programs

We categorise breaches of management strategies as shown in Figure 7. Different types of breach are driven by different ecological and management processes, and will therefore be more or less likely in a given system. Broadly speaking, breaches of type 0, I, and IIa represent a failure of detection, and types IIb, IIIa and IIIb an incorrect understanding of the system in terms of dispersal distance.

Breach	Description
0	Plants reproduce within the occupied zone
I	Plants reproduce in the buffer zone
IIa	Propagules disperse beyond the buffer zone as a result of a seeding event in the buffer zone but resulting plants are located and removed before seeding (*d* correct, breach due to failure to locate and remove plants from the buffer zone))
IIb	Propagules disperse beyond the buffer zone as a result of an incorrectly estimated dispersal distance but resulting plants are located and removed before seeding (*d* wrong)
IIIa	Propagules disperse and produce reproductive plants beyond the buffer zone but less than one maximum dispersal distance beyond the original occupied zone – a 'close' breach
IIIb	Propagules disperse and produce reproductive plants beyond the buffer zone and greater than one maximum dispersal distance from the original occupied zone – a 'distant' breach

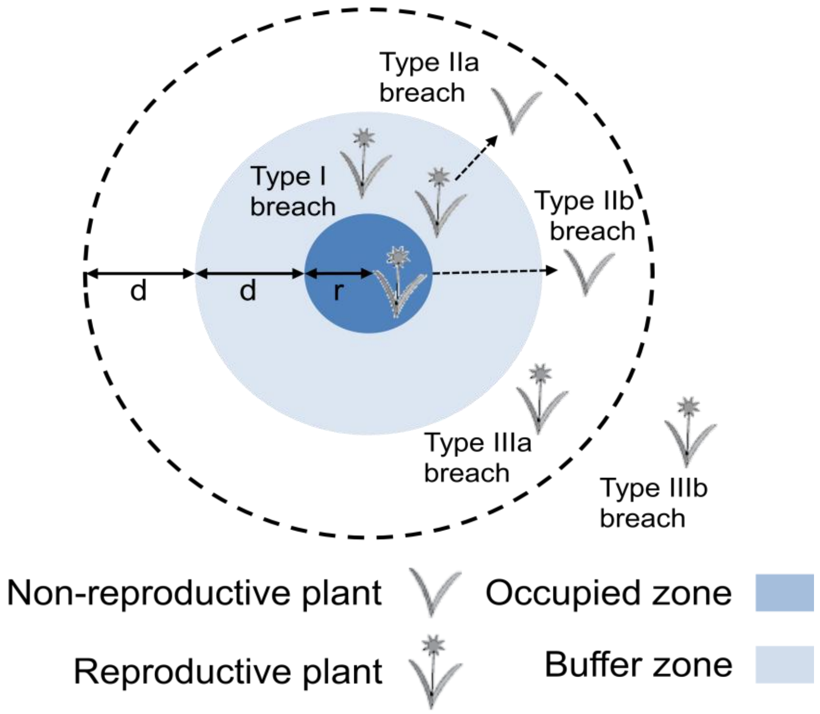


Figure 7: A simple model of weed management and possible breaches of containment.

The radius of the occupied zone, r, is comparable to the size of the invasion. The width of the buffer zone, d, should be related to dispersal processes of the invader (Fletcher et al. 2014b).

When is containment a valid fall-back option to eradication?

Figure 8 and Table 1 outline the result of each type of breach on a containment or eradication strategy. Type I, Type IIa, and Type IIIa breaches affect both eradication and containment but for a system with an occupied zone at the critical radius, $r = r_*$, the cost of the breach will be lower for a containment program than an eradication program. This perhaps supports the use of a containment strategy in borderline cases where eradication and containment are expected to be comparably expensive. In a system currently being managed for eradication each of these types of breach effectively increases the size of the occupied zone, while maintaining the size of the buffer zone. This increases the r/d ratio of the system, and in cases that were borderline before the breach, the system will move into the region where containment is expected to outperform eradication (Table 1). This suggests that containment may become a valid fallback strategy for a borderline eradication program that suffers a Type I, Type IIa or Type IIIa breach.

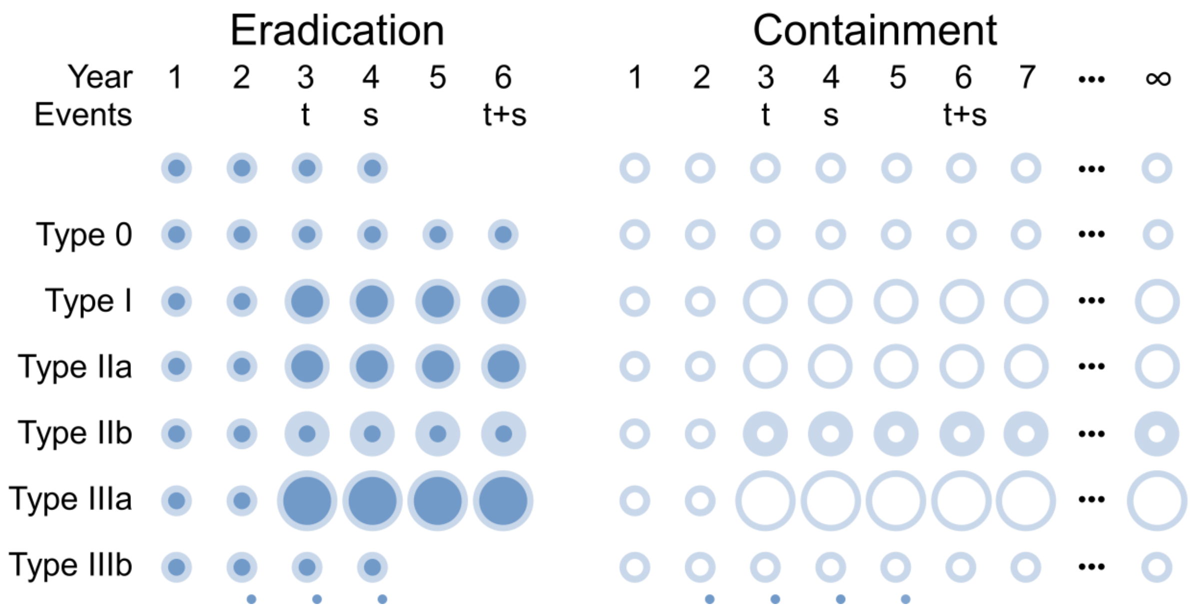


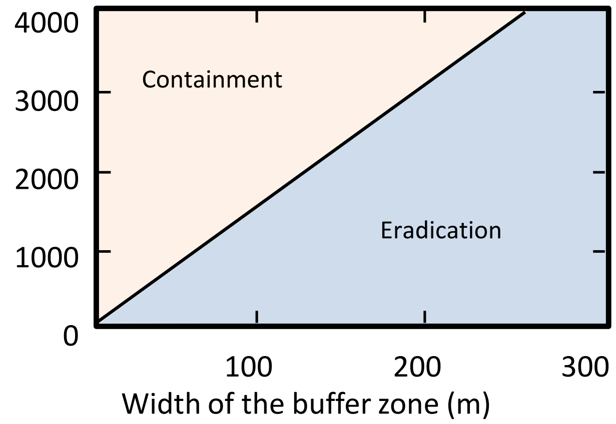
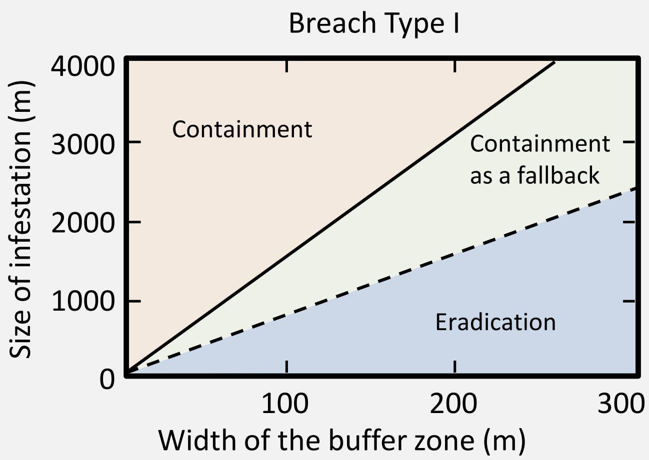
Figure 8: A graphical representation of the consequences of breaches of containment and eradication.

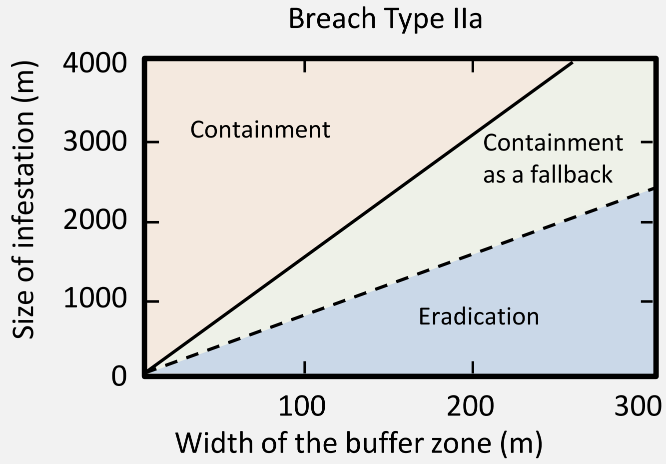
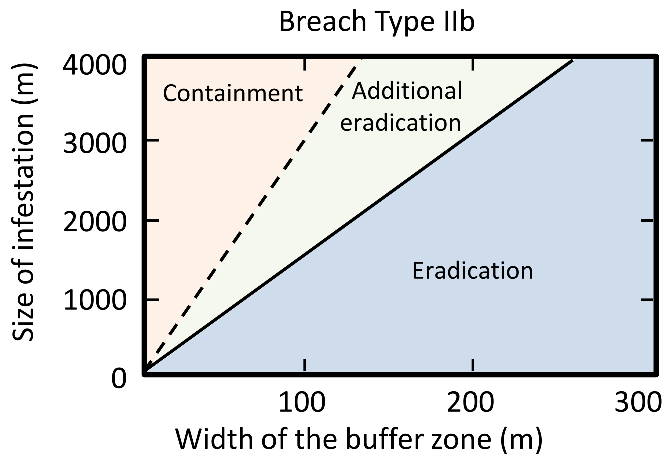
The size of the circle represents how the area to be managed changes in response to a breach**.** The breach is assumed to occur in year 3 (t), and the soil seed bank life time is s, 4 years.

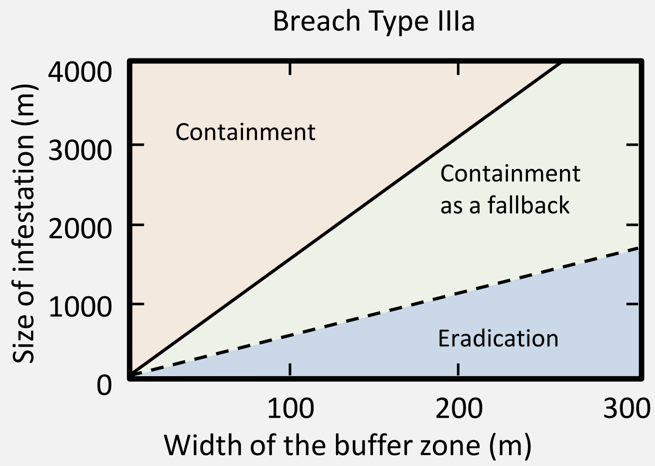
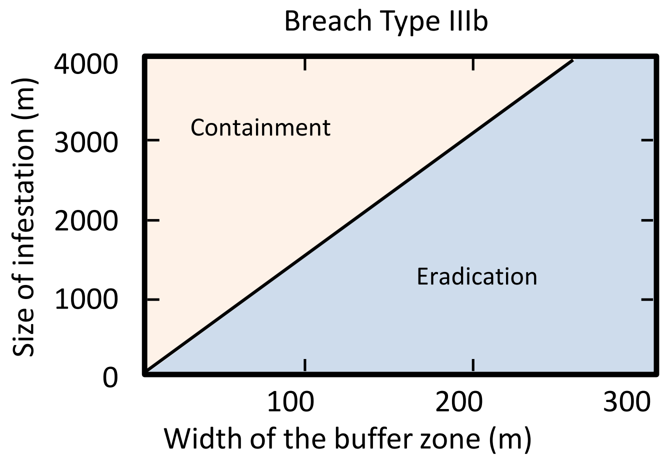
The two management strategies incur very different additional costs if they experience an unexpected breach. Of particular interest, the additional costs of adapting and continuing a well specified eradication program following a breach are higher than the costs of a containment program for only three of the six types of breach examined, suggesting that containment is not a good default fall-back for a breached eradication program.

Table 1: The six breaches of containment and eradication programs, the effect on each management strategy and the resulting performance of each strategy.

Rows in light grey shading indicate breach types where containment may become a valid fall-back option to eradication.

Breach	Description	Effect	Result	
0	Plants reproduce within the occupied zone	Affects only eradication by extending the seed bank.	Containment may offer benefits over eradication in a system prone to a Type 0 breach. However, the occurrence of a single Type 0 breach in a system currently being managed under an eradication program does not change the relative benefit of switching to a containment strategy following the breach, unless such breaches are expected to recur.	
I	Plants reproduce in the buffer zone	Both eradication and containment programs must extend their occupied zone radius by the effective dispersal distance. An eradication program must also reset its seed bank clock, while a containment program will continue as before the breach.	For a system with an occupied zone at the critical radius, $r = r_*$, the cost of the breach will be lower for a containment program than an eradication program. Containment may become a valid fallback strategy for a borderline eradication program that suffers this type of breach.	

Breach	Description	Effect	Result	
IIa	Propagules disperse beyond the buffer zone as a result of a Type 1 breach	No further costs over and above a Type 1 breach.	For a system with an occupied zone at the critical radius, $r = r_*$, the cost of the breach will be lower for a containment program than an eradication program. Containment may become a valid fallback strategy for a borderline eradication program that suffers this type of breach.	
IIb	Propagules disperse beyond the buffer zone as a result of an incorrectly estimated dispersal distance but resulting plants are located and removed before seeding	Because the propagule is removed before it matures and reproduces, the occupied zone does not increase, but from the time of its discovery the buffer zone must be increased appropriately for both management strategies.	Proportionally increases management costs of containment more than eradication, because it increases the size of the buffer zone An eradication program that suffers a Type IIb breach will not be served more effectively by “falling back” to a containment strategy after the breach	

Breach	Description	Effect	Result	
IIIa	Propagules disperse and produce reproductive plants beyond the buffer zone – a ‘close’ breach	Functionally similar to an extreme example of a Type I breach, in which the occupied zone is expanded by twice the effective dispersal distance. An eradication program must also reset its seed bank clock.	For a system with an occupied zone at the critical radius, $r = r_*$, the cost of the breach will be lower for a containment program than an eradication program. Containment may become a valid fallback strategy for a borderline eradication program that suffers this type of breach.	
IIIb	Propagules disperse and produce reproductive plants beyond the buffer zone – a ‘distant’ breach	Requires that an entire secondary eradication program be set up at the site of the breach and run for the duration of the seed bank longevity, assuming the individual is found as soon as it reproduces	Does not change the relative benefit of containment or eradication strategies, and switching from a well-specified eradication program to a containment program at the original infestation following this sort of breach will not improve the efficiency of management.	

Conclusion – Principles of Containment

Containment is increasingly advocated as a strategic objective for countering plant invasions. It is commonly perceived that it is the valid fall-back option when eradication has failed or is deemed impossible with the available resources. However, many infestations are likely to be no more amenable to containment than eradication, because the ecological drivers that determine containment success are the same as those that limit successful eradication, e.g. seed-bank persistence, dispersal mechanisms and capacity, and detectability. Moreover, both containment and eradication programs are at risk of 'breaches' (e.g. plants establishing or reproducing outside defined containment or eradication zones), and each management strategy incurs different additional costs if they experience a breach.

It is vital that sensible decisions are made about whether a species can be contained with the resources available, and whether containment is the best option for a species given characteristics of dispersal, seed longevity, the size of the infestation and the logistics of containment such as detection, accessibility etc. On the basis of our research to date we have distilled some general principles to help make decisions about containment strategies for invasive plants:

1. **Containment strategies should employ containment units that are scaled to suit the species dispersal capacity in the specific environment where it is growing.**

2. Containment presents many of the same challenges as eradication in terms of the ability to control, detection and delimitation. **Containment should not be assumed to be easier than eradication, cheaper than eradication or an achievable fall-back option when eradication is judged no longer feasible**.

3. Both eradication and containment programs will inevitably experience 'breaches' or failures. **Containment is not necessarily a valid fall-back option following a breach of an eradication strategy.**

4. A "one size fits all" approach to containment is not appropriate. Containment strategies should be devised to suit the demographic traits of target species and the environments in which they are growing. **Managers should assess the likely long-term costs of both eradication and containment for each particular species and invasion context.**

5. **Weed management plans must apply a consistent definition of containment** and provide sufficient implementation detail to assess its feasibility.

6. If the dispersal capacity or seed bank longevity of a species is not reasonably well understood, or if the infestation is not well delimited, it is likely that neither eradication nor containment will be successful. **It is critical to have a good understanding of the key components underpinning a successful containment strategy and to have the capacity to adapt quickly as better knowledge is gained.**

Future research priorities

In stark contrast to the importance given to containment in management strategies, and compared with the research literature addressing eradication, few research papers deal with containment of invasive species. We conducted a review of the scientific literature addressing containment and found that the majority of research papers don't make explicit the link between their research results and the feasibility, implementation or likely effectiveness of a containment strategy, limiting the ability of managers to apply research results.

Our research identified a need for a clear definition of containment (detailed in the section Containment defined) and containment terms, and for containment research that can help inform management strategies. For example, many containment strategy documents make reference to terms such as 'core' and 'non-core' which refer variously to infestations that may be more or less severe, more or less strategically important, or geographically central versus peripheral. The term "containment line(s)" is often used to delineate where in the distribution actions are to be taken to prevent spread. Other terms such as 'containment zone' and 'buffer zone' also appear to have different meanings across strategies. There is a clear need for research that explicitly addresses how these concepts best apply to designing effective containment strategies (see for example (Panetta and Cacho 2014).

Following on from the modelling work reported here, a more complete modelling analysis would consider the probability of each type of breach of a management program, including repeated breaches, and the expected costs over the long term. Future research should also focus on a better understanding of the optimal allocation of resources at the spatial and temporal scale of invasions to maximize the effectiveness and efficiency of containment or eradication strategies.

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