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Managing breaches of containment and eradication of invasive plant populations

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Summary

1. Containment can be a viable strategy for managing invasive plants, but it is not always cheaper than eradication. In many cases, converting a failed eradication programme to a containment programme is not economically justified. Despite this, many contemporary invasive plant management strategies invoke containment as a fallback for failed eradication, often without detailing how containment would be implemented.

2. We demonstrate a generalized analysis of the costs of eradication and containment, applicable to any plant invasion for which infestation size, dispersal distance, seed bank lifetime and the economic discount rate are specified. We estimate the costs of adapting eradication and containment in response to six types of breach and calculate under what conditions containment may provide a valid fallback to a breached eradication programme.

3. We provide simple, general formulae and plots that can be applied to any invasion and show that containment will be cheaper than eradication only when the size of the occupied zone exceeds a multiple of the dispersal distance determined by seed bank longevity and the discount rate. Containment becomes proportionally cheaper than eradication for invaders with smaller dispersal distances, longer lived seed banks, or for larger discount rates.

4. Both containment and eradication programmes are at risk of breach. Containment is less exposed to risk from reproduction in the 'occupied zone' and three types of breach that lead to a larger 'occupied zone', but more exposed to one type of breach that leads to a larger 'buffer zone'.

5. For a well-specified eradication programme, only the three types of breach leading to reproduction in or just outside the buffer zone can justify falling back to containment, and only if the expected costs of eradication and containment were comparable before the breach.

6. *Synthesis and applications*. Weed management plans must apply a consistent definition of containment and provide sufficient implementation detail to assess its feasibility. If the infestation extent, dispersal capacity, seed bank longevity and economic discount rate are specified, the general results presented here can be used to assess whether containment can outperform eradication, and under what conditions it would provide a valid fallback to a breached eradication programme.

Key-words: biological invasions, breach, containment, eradication, management strategy, net present value, weeds

Introduction

The invasion of unwanted plants and animals into natural and agricultural systems costs billions of dollars across the globe every year. For example, the total loss of environmental welfare to the Hawaiian state from the invasion of *Miconia calvescens* D.C. has been estimated at several billion dollars over a one-hundred-year period (Kaiser 2006). Production losses to agriculture due to weeds were estimated at $2·2 billion in Australia in 2001–2002 (Sinden *et al*. 2004; Sinden & Griffith 2007), and at over $24 billion in the United States in 2000 (Pimentel *et al*. 2000; Pimentel, Zuniga & Morrison 2005). In response to these costs, farmers invested $1·5 billion

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managing weeds in Australia in 2001–2002 (Sinden *et al.* 2004), and over \$8 billion in the United States in 2000 (Pimentel *et al.* 2000; Pimentel, Zuniga & Morrison 2005). Driven by these significant impacts and investments, programmes to manage invasive plants aim to prevent the introduction of problematic species (Hulme 2006), eradicate infestations before they become established (Simberloff 2003; Panetta 2007) or contain spread if eradication fails (Hulme 2006; Panetta 2009; Radosevich *et al.* 2009; Panetta & Cacho 2012).

From a theoretical perspective, 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. Sharov & Liebhold (1998a) illustrated that the economically optimal strategy for managing the spread of gypsy moth *Lymantria dispar* L. in the United States changed from 'eradication' to 'slowing the spread' via a barrier zone, and eventually to 'doing nothing' as the area occupied by the infestation increased. Cacho *et al.* (2008) extended this bioeconomic approach to identify 'critical decision points' at which eradication, containment or no management were the most economically rational strategy for isotropically spreading scotch broom *Cytisus scoparius* L. in Australia. Carrasco *et al.* (2010) extended Sharov and Liebhold's formulation to show that in many cases, the optimal choice between applying an eradication strategy or a strategy designed to slow the rate of spread applied even when parameter estimates were uncertain. Panetta & Cacho (2012) found that because containment was susceptible to breaches by rare long-distance dispersal events, surveillance and fecundity control were likely to be important components of an effective management strategy. They recently extended this work and found that the use of barrier zones was unlikely to be successful for weeds exhibiting fat-tailed dispersal with high median dispersal distances (Panetta & Cacho 2014).

However, despite well-founded theoretical recognition of the limitations of containment as a management strategy, practical on-ground management programmes have continued to view containment as a default fallback option for failed eradication programmes. In Australia, for instance, of the original national plans for twenty Weeds of National Significance released in 2000 (Thorp & Lynch 2000), the management plans of only two, Athel pine *Tamarix aphylla* (ARMCANZ & ANZECCFM 2000a) and salvinia *Salvinia molesta* (ARMCANZ & 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). Clearly, many of the simple insights into containment from the modelling literature have not achieved common acceptance within management circles.

Worse yet, many strategies that identify containment as an option give insufficient guidance as to how it might be achieved in practice. This prevents the management objective being linked to the biology of the invader, its environment or the capacity of managers on the ground. To begin addressing these concerns, Grice *et al.* (2012) proposed a simple definition of a containment unit consisting of an occupied zone inhabited by the invasive species and a buffer zone into which propagules are dispersed (Fig. 1). In Grice *et al.*'s formulation, the width of the buffer zone is related to the 'maximum dispersal capacity' of the invader but, because long-distance dispersal does not exhibit a hard maximum limit, the possibility of a containment breach must be recognized (Panetta & Cacho 2012). In an earlier publication, Grice *et al.* (2010) identified three types of breach that could affect a containment programme. Similar criteria can also be applied to an eradication programme (Fletcher *et al.* 2014), and here we extend and generalize Grice *et al.* (2010) types of breach to consider the relative impacts of a breach on eradication and containment programmes.

We frame Grice *et al.* (2012) proposal in a simplification of the form pioneered by Sharov & Liebhold (1998a) and Cacho *et al.* (2008) to derive 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 and the situations in which containment would form a valid fallback strategy for a breach in an eradication programme. We focus our analysis on well-specified systems in which eradication and containment are expected to perform comparably, and ask under what conditions a single unexpected breach or change in system specification would change the choice of management strategy.

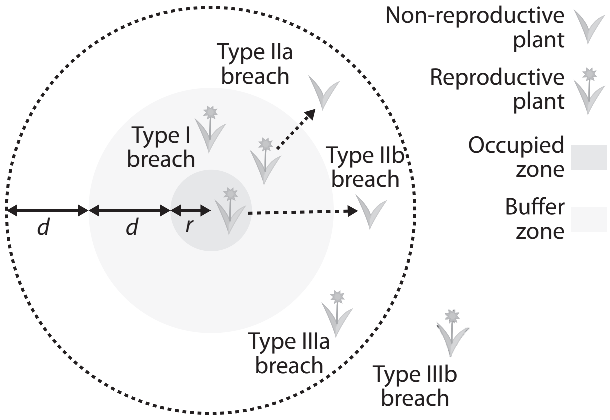

Fig. 1. A simple model of invasion, consisting of an 'occupied zone' (dark shading) of radius r around the current extent of reproductive individuals, and a 'buffer zone' (light shading) of width d related to the effective dispersal capacity of the invader, into which non-reproductive individuals may be dispersed. The types of breach are summarized in Table 1. 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.

Materials and methods

A CONCEPTUAL MODEL OF CONTAINMENT

Grice *et al.* (2010, 2012) propose that containment is a 'deliberate action taken to prevent establishment and reproduction of a species beyond a predefined area'. This definition leads to the idea of a 'containment unit', consisting of an 'occupied zone' containing reproductive plants surrounded by a 'buffer zone' that is free from reproductive plants but does receive propagules (Fig. 1). To contain an infestation every new individual that germinates in a buffer the width of the 'expected' maximum dispersal distance (d) around the occupied zone (r) must be removed before it becomes reproductive. Management does not eliminate reproductive individuals from the occupied zone, so the infestation continues to disperse propagules into the buffer zone and containment actions must continue unless the management goal changes. These zones can also be used to represent an eradication strategy, in which case every established individual within the occupied zone plus any that arise from seeds that are dispersed to the buffer region must be removed before it reproduces along with every new individual that germinates from the seed bank, until that seed bank is depleted.

This definition of containment is intended as a starting point and intentionally avoids more complicated refinements, such as management of the occupied zone to gradually reduce propagule pressure (Lockwood, Cassey & Blackburn 2005) or 'partial containment' aiming to slow the rate of spread (Cacho 2004). We refine the definition Grice *et al.* (2012) to refer to the 'effective' dispersal distance implicitly determined by the spatial distribution of management effort. It is well known that management strategies should structure the distribution of effort in response to the scales of the ecological processes determining dispersal (Fletcher & Westcott 2013). However, estimating or even defining the maximum dispersal distance of an invasive plant is a notoriously difficult problem (Nathan 2006), because in many species, (i) a tiny proportion of seeds experience rare long-distance dispersal events (Nathan 2006), and (ii) the potential exists for completely different modes of dispersal, for example human-mediated spread, to transport small numbers of seeds vast distances (Higgins, Nathan & Cain 2003; Nathan 2006). In practical studies, long-distance dispersal is generally defined as either a proportional threshold (e.g. 1% of the number of dispersal events) or an absolute threshold (e.g. 500 m from the parent plant) (Panetta & Cacho 2012). For this analysis, we use the second definition and assume that the 'effective' dispersal distance is being determined by managers. Assuming the same approach is used across eradication and containment strategies, the manner in which they determine this distance does not affect the results or conclusions of our analysis.

Grice *et al.* (2010) define three modes of containment breach as follows: *Type I* – plants reproduce within the buffer zone; *Type II* – propagules are dispersed beyond the buffer zone; and *Type III* – plants reproduce beyond the buffer zone (Fig. 1). Because the maximum length of very rare long-distance dispersal events is not absolutely bounded, a containment strategy is likely to eventually experience a breach given the indefinite time frames that containment requires (Panetta & Cacho 2012). In contrast, an eradication programme can, theoretically, remove all individuals before a breach is experienced. In practice, however, both strategies are at risk of a breach due to rare events, poor parameter estimation or imperfect detection (Carrasco *et al.* 2010).

THE COSTS OF CONTAINMENT AND ERADICATION

To model the relative performance of containment and eradication strategies under this framework, we assume a circular infestation of radius r (m), a buffer zone related to the effective dispersal distance, d (m), and seed bank longevity, s (years). Total 'costs' in net present values are the cost of searching for and removing individuals, c (\$ m^{-2}) multiplied by the area searched every year, A (m^2), with future costs converted to net present values via an appropriate discount rate, δ This assumes that the cost of searching and removing individuals remains the same independent of how many individuals are found. Eqn 1 shows how the cost, C (\$), of either strategy is determined by the area to be searched every year (A) and by how long management must continue ($y_{\max}$):

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

An eradication programme 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

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

In contrast, a containment programme that does not aim to control the occupied zone needs to 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

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

For a given weed, d and s are defined. The costs of searching for 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.

The relative performance of the two strategies may be compared by finding the point at which their costs are equal, r_* (m), an approach similar to Cacho's 'critical decision points' (Cacho *et al.* 2008). The analytic expression is shown in eqn 4. It allows us to separate 'management space' into two regions separated by the line defined by these solutions. To one side of this line, eradication is the cheaper option, and to the other, containment.

$$r_* = d\left(\frac{1}{(1+\delta)^{s/2} - 1}\right) \qquad \text{eqn 4}$$

For a given infestation, the difference in cost between eradication and containment programmes 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.

BREACHES OF CONTAINMENT AND ERADICATION

We extend the breach modes identified by Grice *et al.* (2010) (Table 1) to capture the relative performance of eradication and

Table 1. The six breaches of containment and eradication programmes, extended from Grice *et al.* (2010)

Grice	New	Description
N/A	0	Plants reproduce within the occupied zone
I	I	Plants reproduce in the buffer zone
II	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 (estimate of *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 (estimate of *d* incorrect)
III	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

containment strategies and summarize the costs of each type of breach in Table 2. We define a new mode: Type 0 – failure to remove an individual before its propagules are dispersed from within the occupied zone. A breach of this type only affects eradication programmes because the occupied zone is not managed by a containment strategy. A Type 0 breach 'resets the clock' on eradication in terms of seed bank longevity.

In a Type I breach, plants reproduce somewhere in the buffer zone. The worst case scenario is when this occurs close to the outer edge of the buffer zone because both eradication and containment programmes must respond by expanding their occupied zone radius by the effective dispersal distance. An eradication programme must also reset its seed bank clock, while a containment programme will continue indefinitely, as before the breach.

We split a Type II breach, in which propagules are dispersed beyond the buffer zone but removed before reproduction, into two mathematically distinct subcategories based on the cause of the breach: Type IIa – a further breach as a result of an undetected Type I breach; and Type IIb – as a result of an originally misspecified dispersal distance. A Type IIa breach implies no further costs over and above a Type I breach. A Type IIb breach, on the other hand, affects both eradication and containment in a manner distinct from a Type I breach. Because the plant derived from 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.

We further split a Type III breach, in which reproduction occurs outside the buffer zone, into two subcategories based on the distance of the individual reproductive event from the original infestation: Type IIIa – a 'close' breach, which we assume is outside the buffer zone by less than the effective dispersal distance; and a Type IIIb – a 'distant' breach, which we assume is so far from the original infestation that it can be treated as an entirely separate eradication programme.

A Type IIIa breach is functionally similar to an extreme example of a Type I breach, in which the occupied zone is expanded by twice the effective dispersal distance. A Type IIIb breach requires that an entire secondary eradication programme 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.

CONTAINMENT AS A FALLBACK FOR FAILED ERADICATION

Finally, we consider the merit of switching from an eradication programme to a containment programme following a breach of each type. The question is whether a system that is initially well specified as an eradication programme, 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.

THE PROBABILITY OF BREACH, AND FECUNDITY REDUCTION IN THE OCCUPIED ZONE

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 Types 0, I and IIa

Table 2. The costs of a breach. Costs are represented for a breach occurring in year *t* in terms of the cost functions for eradication and containment specified in equations 2 and 3. The notation EC[*r*, *d*, 1, *s*] should be interpreted as the Eradication cost for a system with an occupied zone of radius r and a buffer zone of width d with management beginning in year 1 and ending in year *s*

	Eradication costs			Containment costs		
Breach	Pre-breach ($y \le t$)		Post-breach ($y > t$)	Pre-breach ($y \le t$)		Post-breach ($y > t$)
None	EC[r, d, 1, s]*			CC[r, d, 1, ∞]*		
0	EC[r, d, 1, $s + t$]*			CC[r, d, 1, ∞]*		
I	EC[r, d, 1, t]	+	EC[$r + d$, d, $t + 1$, $t + s$]	CC[r, d, 1, t]	+	CC[$r + d$, d, $t + 1$, ∞]
IIa	EC[r, d, 1, t]	+	EC[$r + d$, d, $t + 1$, $t + s$]	CC[r, d, 1, t]	+	CC[$r + d$, d, $t + 1$, ∞]
IIb	EC[r, d, 1, t]	+	EC[r, $d + d$, $t + 1$, s]	CC[r, d, 1, t]	+	CC[r, $d + d$, $t + 1$, ∞]
IIIa	EC[r, d, 1, t]	+	EC[$r + 2d$, d, $t + 1$, $t + s$]	CC[r, d, 1, t]	+	CC[$r + 2d$, d, $t + 1$, ∞]
IIIb	EC[r, d, 1, s]*	+	EC[0, d, $t + 1$, $t + s$]	CC[r, d, 1, ∞]*	+	EC[0, d, $t + 1$, $t + s$]

*Note that these costs extend across the pre-breach/post-breach threshold at *t* years.

represent a failure of detection, and Types IIb, IIIa and IIIb a failure of system specification in terms of dispersal distance. The probability of breach does not enter our current analysis because we focus on the economic cost following a single unexpected breach in an otherwise well-specified management programme, rather than the long-term average expected cost based on breach probability. Some recent studies have begun to assess the importance of the probability of breaches in containment and eradication programmes (Panetta & Cacho 2014), and in the Discussion we consider how such insights might extend our approach.

Results

THE COSTS OF CONTAINMENT AND ERADICATION

We plot eqns 2 and 3 to illustrate how the four parameters differentially affect the costs of eradication and containment (Fig. 2). As the radius of the occupied zone increases, the costs of both eradication and containment increase, but the proportional costs of eradication increase faster. As the width of the buffer zone increases, the costs of both strategies increase, but the proportional costs of containment increase faster. Increases in seed bank longevity do not affect containment costs, but increase eradication costs. Finally, increases in the discount rate affect both eradication and containment, but decrease the proportional costs of containment faster.

For a given invasive species being managed at a given discount rate, the parameters d, s and δ are defined and eradication will tend to cost less than containment for infestations that are 'small' relative to the critical decision radius, r_*, and more for 'large' infestations (Fig. 2a). The costs of both strategies are equal when the occupied zone is of radius r_*, which can be expressed as a multiple of the effective dispersal distance (eqn 4). Plotting these relationships 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 (Fig. 3). Invaders with larger effective dispersal capacities require a larger buffer zone, and the critical radius at which containment outperforms eradication increases. Invaders with long-lived seed banks require long eradication programmes, and so the critical radius at which containment outperforms eradication decreases. An increasing discount rate decreases the future value of money and the future costs of running a long-term containment programme, decreasing the critical radius at which containment outperforms eradication. These relationships can be summarized for all possible invasions in a dimensionless form by scaling the radius of the occupied zone against the buffer width (r/d), and plotting against the seed bank longevity and the log of the discount rate ($s \ln(1 + \delta)$). Each possible infestation and management strategy is represented by a single point within this dimensionless space, and its location determines whether it is most economically managed via an eradication or containment programme.

BREACHES OF CONTAINMENT AND ERADICATION

The performance of containment and eradication under the six types of breach differs markedly (Table 3). A Type 0 breach affects only eradication and acts functionally as an increase in seed bank longevity. Type I, Type IIa and Type IIIa breaches affect both eradication and containment, but for a system at the critical radius before the breach, the extra costs are lower for a containment programme than an eradication programme (Table 3). In contrast, a Type IIb breach necessitates an increase in the size of the buffer zone, so always incurs more costs for a containment programme at the critical radius than the equivalent eradication programme. A Type IIIb breach requires an entire secondary eradication, for both eradication and containment, so incurs the same extra management costs.

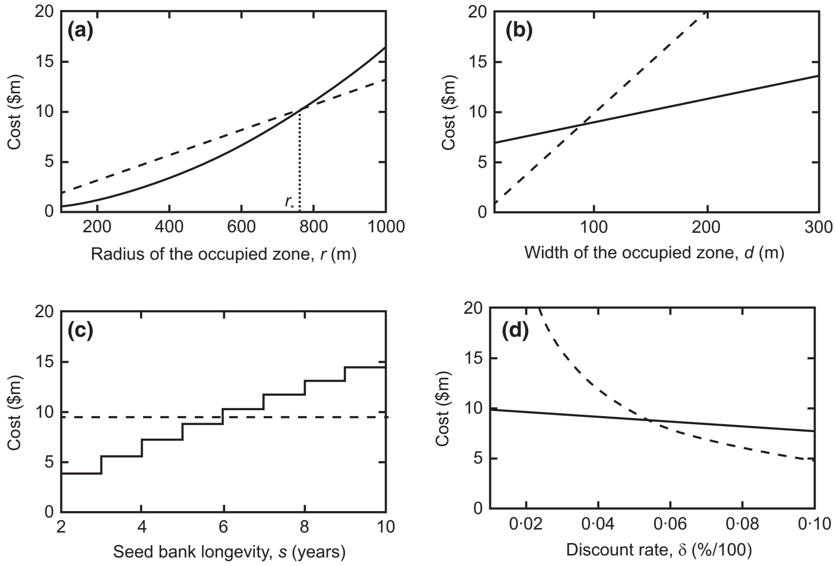

Fig. 2. The differential impact on the costs of eradication (solid) and containment (dashed) programmes. Default parameter values are $r = 700$ m, $d = 100$ m, $s = 5$ years and $\delta = 0{\cdot}05$ (5%). For a given species, the values of d, s and δ are defined, and the size of the occupied zone at which the curves intersect (marked in a) represents the infestation for which containment and eradication are expected to cost the same amount.

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CONTAINMENT AS A FALLBACK FOR BREACHED ERADICATION

Finally, we consider the merit of switching from an eradication programme to a containment programme following a breach of each type (Table 4). Before a breach, a well-specified eradication programme will involve an occupied zone equal to or smaller than the critical radius ($r \leq r_*$). An eradication breach of Types I, IIa or IIIa will increase the size of the occupied zone. If it becomes larger than the critical decision point ($r > r_*$), containment will become a more attractive 'fallback' strategy than eradication following the breach. In contrast, eradication breaches of Types 0, IIb and IIIb do not change the size of the occupied zone, and so would not be expected to improve the performance of a containment programme relative to an eradication programme following a breach.

We can use these insights to update Fig. 3a for the case of a breach of each type in an eradication programme at r_* (Fig. 4). For breaches of Types I, IIa and IIIa, a new intermediate region is added within the eradication zone in which, if a breach is experienced, containment would become a valid fallback strategy. For a breach of Type IIb, a new region is added to the containment zone in which, if an eradication breach is experienced, further eradication is recommended even though a first assessment would have recommended containment. For breaches of Type 0 and Type IIIb, an eradication breach does not change the optimal strategy.

Table 3. Change in performance following each breach type, at the critical radius

Breach	Relative costs with breach for system at r_*	Favours
None	CC = EC	
0	$CC_{E:0} = EC_{E:0}$	Containment
I	$CC_{E:I} < EC_{E:I}$	Containment
IIa	$CC_{E:IIa} < EC_{E:IIa}$	Containment
IIb	$CC_{E:IIb} > EC_{E:IIb}$	Eradication
IIIa	$CC_{E:IIIa} < EC_{E:IIIa}$	Containment
IIIb	$CC_{E:IIIb} = EC_{E:IIIb}$	Neither

The notation $CC_{C:I}$ should be interpreted as the containment cost following a Type I breach of a containment strategy. Alternatively, $EC_{E:IIa}$ is the eradication cost following a Type IIa breach of an eradication strategy.

Discussion

Although theoretical studies have shown that containment is not always cheaper than eradication (Sharov & Liebhold 1998b; Cacho *et al.* 2008; Panetta & Cacho 2014), management plans currently in place still invoke containment as a fallback for failed eradication (Thorp & Lynch 2000), often without describing exactly what containment would require. To begin addressing this issue, Grice *et al.* (2012) developed a simple concept of a containment unit that managers could use to ensure that they clearly defined how containment would be implemented. Here, we have built on this concept to provide a simple but general analysis of the relative economic performance of eradication and containment, including the consequences of breaches and the merit of viewing containment as a fallback for a breached eradication programme. The general nature of our analysis means that managers can apply the results generated to any invasion for which the infestation size, dispersal capacity, seed bank longevity and discount rate can be estimated.

Even without parameterizing the model for a specific invasion, we can see that while containment has one major advantage over eradication - that a smaller area can be managed - this must be balanced against its disadvantage - that a containment strategy does not aim to reduce the population in the occupied zone and must therefore continue to run as long as managers wish to limit the extent of the invasion. Moreover, the two

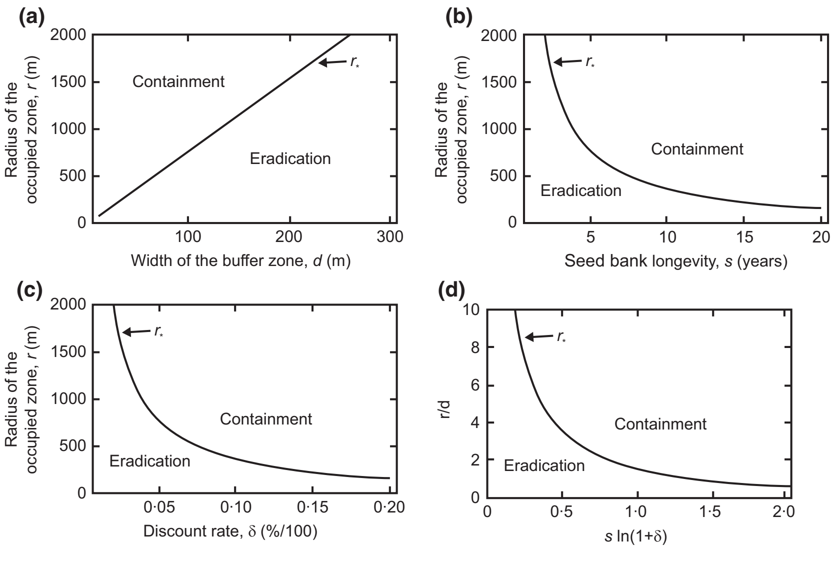

Fig. 3. Zones of optimal management in terms of the radius of the occupied zone as a function of (a) maximum dispersal distance; (b) seed bank longevity; and (c) the discount rate. (d) shows the optimum management strategy for any infestation. Each weed (defined by its dispersal capacity and seed bank longevity), infestation (defined by the radius of the occupied zone) and discount rate is represented by a single coordinate in this plot, which falls either in the zone where the costs of eradication are lower than containment, the zone where the costs of containment are lower than eradication, or on the line in between where the costs of eradication and containment are equal.

Table 4. Change in performance of containment following a breach in an eradication programme

Breach	Containment costs following an eradication breach at r_*	Valid fallback?
None	CC = EC	
0	$CC_{E:0} = EC_{E:0}$	No
I	$CC_{E:I} < EC_{E:I}$	Yes
IIa	$CC_{E:IIa} < EC_{E:IIa}$	Yes
IIb	$CC_{E:IIb} > EC_{E:IIb}$	No
IIIa	$CC_{E:IIIa} < EC_{E:IIIa}$	Yes
IIIb	$CC_{E:IIIb} = EC_{E:IIIb}$	No

The notation $CC_{E:0}$ should be interpreted as the containment cost following a Type 0 breach of an eradication strategy.

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 programme following a breach are higher than the costs of a containment programme for only three of the six types of breach examined, suggesting that containment is not a good default fallback for a breached eradication programme.

CONTAIN OR ERADICATE?

Figure 2 and eqn 4 suggest that containment would be cheaper than eradication only when the size of the occupied zone exceeds a multiple of the dispersal distance determined by seed bank longevity and the discount rate. This threshold is similar to Cacho *et al.*'s 'critical decision points' (Cacho *et al.* 2008). Biologically, this means that containment is less likely to be viable for species exhibiting large effective dispersal distances via fat-tailed distributions, as found by Panetta & Cacho (2014). 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. This is a similar result to that reached by Sharov & Liebhold (1998a) for gypsy moth in the United States. Of course, the possibility that neither eradication nor containment is economically viable should also be explicitly considered (Cacho *et al.* 2008). Some studies have suggested that when funds are limited, optimal outcomes may involve partial containment coupled with fecundity reduction actions in the occupied zone (Panetta & Cacho 2012).

Containment becomes proportionally 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 the 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. In either of these scenarios, if contain-

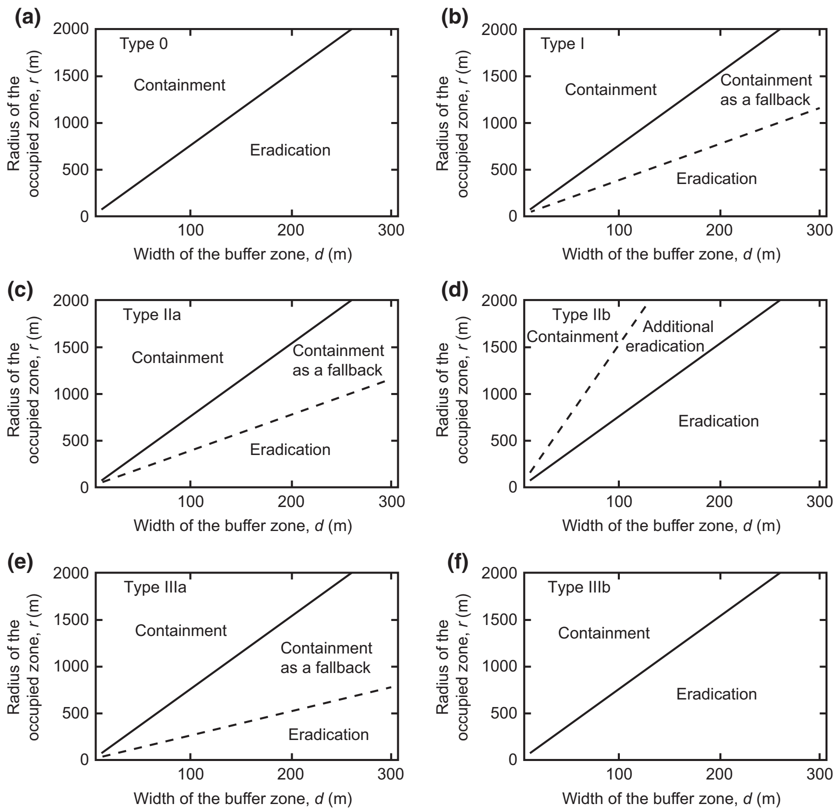

Fig. 4. Zones in which containment is a valid fallback for eradication. As in Fig. 3 (a), the solid line in each subfigure indicates how large the occupied zone must be for containment to be as economic as eradication in the absence of a breach. Above this line, containment will outperform eradication. In each subfigure, a dashed line is added to show how this relationship would change following each type of breach: Types 0 (a) and IIIb (f) do not change the size of occupied zone for which containment outperforms eradication; Types I (b), IIa (c) and IIIa (e) increase the effective size of the occupied zone, creating a region between the solid and dashed lines in which a system originally best managed with an eradication programme would be more effectively managed with a containment programme following the breach; Type IIb (d) increases the maximum dispersal distance, creating a region between the dashed and solid lines that would be better managed by an eradication programme, even though an assessment in the absence of a breach would have recommended containment.

ment has been initially ruled out, further consideration may recommend it as a viable option.

The first individual to arrive in a landscape may be easily missed, but as its seeds are dispersed and begin to germinate, the invasive population becomes much more visible. In the worst case scenario, if all the dispersed propagules of this individual become reproductive, the occupied zone will be as large as the maximum dispersal distance. Substituting ($r = d$) into eqn 4, we can specify reasonable discount rates to find 'threshold' seed bank longevities, above which containment would outperform eradication. For such an 'early infestation' and a discount rate of 5% ($\delta = 0.05$), the invader must have a seed bank longevity (s) greater than 29 years for containment to outperform eradication; a discount rate of 10% would yield 14 years. Longer established infestations would be expected to have larger occupied zones, and containment would outperform eradication for shorter seed bank longevities (e.g. $s > 8{\cdot}5$ years when $r = 2d$ and $\delta = 0.10$). There are many examples of invaders with seed bank longevities less than this (e.g. lion's tail *Leonotis nepetifolia* L. R.Br., gamba grass *Andropogon gayanus*, Kunth), but many others with greater seed bank longevities (e.g. siam weed *Chromolaena odorata*, L. King & H.E. Robins). This suggests that in some systems, the choice between containment and eradication is likely to be an important one. Indeed, for invaders with multiple infestations and seed bank longevities near the threshold, the best outcome might be achieved by attempting to eradicate some of the smaller sites while containing the larger ones. This was the approach recommended following review of a long-running programme targeting lion's tail on Rinyirru (Lakefield) National Park in Far North Queensland (Clarkson, Grice & Dollery 2012).

RECOVERY FOLLOWING A BREACH

Our analysis shows that containment and eradication programmes have distinctly different responses to different types of breach (Table 3). If there is a reason an infestation in a specific location might be expected to experience one type of breach disproportionately, this might recommend one management strategy over the other.

A Type 0 breach is caused by reproduction within the occupied zone and affects only eradication by extending the life of 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 programme does not change the relative benefit of switching to a containment strategy following the breach, unless such breaches are expected to recur.

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 programme than an eradication programme (Table 3). This perhaps supports the use of a containment strategy in borderline cases where eradication and containment are expected to be comparably expensive, although a full analysis would require a more advanced model capable of accounting for the differing probabilities of breach in eradication and containment programmes (Panetta & Cacho 2014). 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 (Fig. 4). This suggests that containment may be a valid fallback strategy for a borderline eradication programme that suffers a Type I, Type IIa or Type IIIa breach.

In contrast, a Type IIb breach proportionally increases management costs of containment more than those of eradication, because it increases the size of the buffer zone. This suggests that eradication may be a more effective strategy in systems where the maximum dispersal distance may have been underestimated (Higgins & Richardson 1999), perhaps because suitable habitat clustered near the infestation has constrained establishment (Jongejans, Skarpaas & Shea 2008). An eradication programme that suffers a Type IIb breach will not be served more effectively by 'falling back' to a containment strategy after the breach.

A Type IIIb breach affects both strategies equally, requiring an entire secondary eradication at the site of the failure. It does not change the relative benefit of containment or eradication strategies, and switching from a well-specified eradication programme to a containment programme at the original infestation following this sort of breach will not improve the efficiency of management. The potential for such a breach of both containment and eradication programmes highlights the importance of effective surveillance strategies (Panetta & Cacho 2012).

EXTENSIONS AND LIMITATIONS

Although the results presented here are based on circular infestations, Sharov & Liebhold (1998a) considered extensions to other geometries in the context of slowing the rate of spread of gypsy moth, and their insights hold here too. In particular, many invasions might be expected to begin near the edge of an area of suitable habitat (Cacho *et al.* 2008), and although the specific geometry would modify the numerical results presented, the qualitative conclusions would be similar.

In practice, it may be difficult to distinguish between different Types of breach in the field, especially between types IIa and IIb following the discovery of propagules or seedlings beyond the buffer zone. A combination of further studies, such as a coordinated search of the buffer zone for reproductive individuals driving a previously undetected

Type I breach, or an ecological reassessment of the dispersal distances assumed by the management programme, may elucidate the cause of the breach. Both of these drivers have been separately identified during breaches of eradication programmes for *Miconia calvescens* in the Wet Tropics of Australia, and insights used to modify the spatial scale and management effort of the programme (Murphy *et al*. 2008; Fletcher & Westcott 2013).

The simple model presented here does not consider the different probabilities of breach under containment and eradication strategies because it is focused on the question of the cost following a single unexpected breach in an otherwise well-specified management programme. A more complete analysis would consider the probability of each type of breach, including repeated breaches, and the expected costs over the long term. Although such an analysis is beyond the scope of the current study, others have recently begun making inroads into this subject (Panetta & Cacho 2014), and we can consider how these insights contribute to the choice between eradication and containment.

The probability of breach is proportional to the size of the population in the occupied zone. Containment programmes incorporating fecundity reduction can transfer some management resources from the buffer zone to reduce the population in occupied zone. This acts to decrease the probability of all types of breach, but at the same time the reduced management of the buffer zone acts to increase the chance of Types I and IIa breaches. Which effect predominates will be dependent on the characteristics of the species being managed and the cost and effectiveness of management. To date, two other studies have explicitly considered this scenario in the context of optimal strategies under resource constraints. Panetta & Cacho (2012) found that shifting resources to fecundity reduction in the occupied zone was a key parameter for optimal management when resources were limited. Taylor & Hastings (2004) found that the optimal choice of management for density-structured *Spartina alterniflora* populations prioritized high-density regions of the infestation when ample resources were available, but low-density regions when budgets were constrained.

None of these observations change the outcome of our analysis of the cost following a single unexpected breach in an otherwise well-specified management programme or the relative merit of containment as a fallback if eradication fails.

CONCLUSIONS AND IMPLICATIONS FOR MANAGEMENT

Containment can be a viable management strategy, but it is not guaranteed to be cheaper than eradication. Moreover, in many cases, converting a failed eradication programme to a containment program will prove neither more economic nor more effective. Despite this, many contemporary strategies for managing invasive plants invoke containment as a fallback if eradication proves infeasible, often without describing exactly what containment would require.

To begin addressing this issue, managers designing weed management strategies must: (i) apply a consistent minimum definition of containment; and (ii) provide sufficient implementation detail to assess its feasibility. The simple definition of a containment unit provided by Grice *et al*. (2012) provides a solid starting point.

With an explicit and sufficient definition of containment, a simple assessment of the sort outlined in this manuscript can quickly ascertain whether containment can outperform eradication, and under what conditions it could provide a valid fallback to a breached eradication programme. The infestation extent, dispersal capacity, seed bank longevity and economic discount rate specify a unique set of coordinates for any management strategy on Fig. 3d, illustrating whether containment is likely to be cheaper than eradication. If the system is far from the border between containment and eradication, this level of analysis may be sufficient.

Finally, our analysis shows that only a breach leading to reproduction in or just outside the buffer zone can justify falling back to containment from a breached eradication programme, and only if the expected costs of eradication and containment were comparable before the breach. If propagules are discovered outside the buffer zone of an eradication programme, a coordinated search of the buffer zone for reproductive individuals should be conducted, and the dispersal distances assumed by the management programme reassessed. If the breach is identified as Type I, IIa or IIIa, then the system should be assessed against Fig. 4 to see whether fallback to containment is justified.

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Data accessibility

This paper does not use data.

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