Geometric insights into managing breaches of containment and eradication of invasive plants

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Summary Although containment is frequently advocated as a fall-back option for eradication, analysis shows that it is not necessarily more economic or effective. While containment has one major advantage over eradication, in that a smaller area is managed, this must be balanced against its disadvantage; that it must continue indefinitely. Moreover, both containment and eradication programs are at risk of breaches of the management unit, and each management strategy incurs different additional costs if they experience a breach. Here, we use graphical illustrations of the net present costs of management to provide some simple geometric insights into managing breaches of containment and eradication of populations of invasive plants.

Keywords Containment, eradication, breach.

INTRODUCTION

Practical on-ground management programs often explicitly or implicitly specify containment as the default fall-back option for failed eradication programs or as an alternative when eradication is deemed infeasible. In Australia, for instance, following reviews in 2012, all the National Plans for twenty Weeds of National Significance now contain the term 'containment' (Thorp and Lynch 2000, AWC 2012a, AWC 2012b), although many of them do not provide sufficient guidance as to how it might be achieved in practice.

This perspective on containment seems to persist despite the fact that many theoretical studies have shown that eradication is likely to outperform containment when infestations are smaller than a certain threshold size, and that above a threshold size, neither containment nor eradication are likely to provide an economic option for management (e.g. gypsy moth (*Lymantria dispar* L.) (Sharov and Liebhold 1998); Scotch broom (*Cytisus scoparius*, L.) (Cacho *et al.* 2008)).

Clearly, many of the simple insights into containment from the modelling literature have not achieved common acceptance within management circles. To help address misalignments between practice and the limited research literature, Grice *et al.* (2012) proposed the simple notion of a containment unit that consists of a zone occupied by the invasive species and a buffer zone into which propagules are dispersed. They also defined three types of breach of such a containment unit (Grice *et al.* 2010).

Here, we revisit and expand Grice *et al.*'s breaches of containment, and apply them to both eradication and containment programs using a simple graphical representation to explore the validity of containment as a fallback for a failed eradication program.

MATERIALS AND METHODS

A conceptual model of containment Grice *et al.* (2012) proposed that containment is 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'*. By this definition management actions must continue indefinitely because the occupied zone population is not reduced**.** This spatial categorisation can be represented graphically (Figure 1, shaded zones). Moreover, we can use the same zone structure to define an eradication program as a: '*deliberate action taken to prevent establishment of a species beyond the "occupied and buffer zones" until the soil seed bank is depleted*'.

Breaches of containment and eradication In their 2010 paper, Grice *et al.* defined three modes of containment breach: *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. Here, we expand this to six breaches to encompass breaches of both eradication and containment programs and refine it based on the ecological and management processes driving the breach (Figure 1, icons).

We define a new breach, Type 0 (not shown), which involves failure to remove an individual before its propagules are dispersed from within the occupied zone. A breach of this type affects only eradication programs because propagules are expected to disperse from the occupied zone in a containment strategy. As in Grice *et al.* (2010), in a Type I breach plants reproduce somewhere in the buffer zone. We split a Type II breach, in which propagules are dispersed beyond the buffer zone but are removed before reproduction, into two mathematically distinct subcategories based on the cause of the breach: Type IIa – a further breach as a result of a Type I breach; and Type IIb – as a result of an originally mis-specified dispersal distance. 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 reproduction event from the original infestation: Type IIIa – a 'close' breach, which we assume is outside the buffer zone but within another maximum dispersal distance of the original infestation; and a Type IIIb – a 'distant' breach, which we assume is so far from the original infestation that it can be treated as requiring an entirely separate eradication effort.

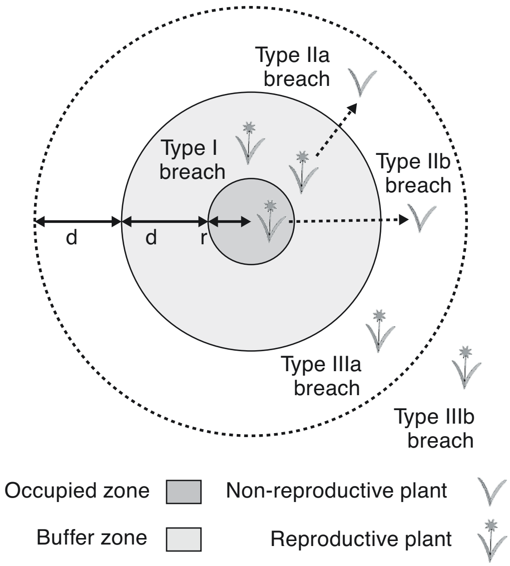

Figure 1. A simple model of weed management and possible breaches of containment. The radius of the occupied zone, r, is comparable to the size of the invasion. The width of the buffer zone, d, should be related to dispersal processes of the invader (Fletcher *et al.* 2013).

RESULTS

A graphical representation of management costs

Figure 2 represents the costs of non-breached eradication and containment programs. The example shows a system where the radius of the core area is twice the dispersal distance, the soil seed bank lifetime is four years, and the discount rate is an unrealistic but graphical 20% per year. 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 that managed in an analogous eradication program. The top two rows show how the decreasing value of money over time makes the per-annum net present cost of a containment program fall off the further into the future you project.

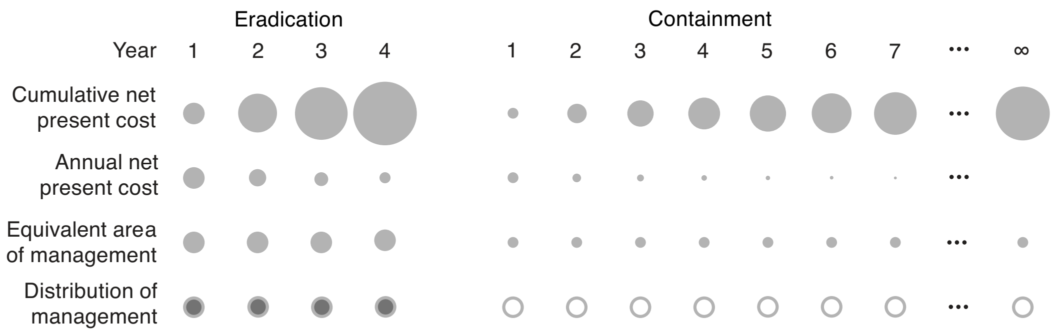

Figure 2. The costs of containment and eradication. The system illustrated has an occupied zone radius twice the size of the buffer width (r = 2d), a soil seed bank lifetime of four years, and a discount rate of 20%. The second bottom row shows the area of the management distribution as a simple circle, 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.

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 an imperfect 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. For the specific parameters illustrated in Figure 2, 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.

A graphical representation of the cost of breaches Figure 3 shows the effect of each type of breach on the area to be managed through time, in the same notation as the bottom row of Figure 2, where dark gray represents the occupied zone and light gray the buffer zone. In a Type I breach, plants reproduce somewhere in the buffer zone, and in the worst case, both eradication and containment programs must expand their occupied zone radius by the maximum dispersal distance. An eradication program must also reset its soil seed bank clock, while a containment program will continue indefinitely, as before the breach. A Type IIa breach implies no further costs above those of 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 propagule is removed before reproduction, the core zone does not increase, but from the time of its discovery the buffer zone must be increased appropriately for both management strategies. A type IIIa breach is functionally similar to an extreme example of a Type I breach, in which the core area is expanded by twice the maximum dispersal distance. A Type IIIb breach requires an entire secondary eradication, for both eradication and containment programs, run across a 0 m core region (the effective invasion diameter for a single plant) for the length of the soil seed bank lifetime, assuming the individual is found as soon as it reproduces.

DISCUSSION

Contain or eradicate? Although containment is frequently advocated as a fall-back option for eradication (Thorp and Lynch 2000, AWC 2012a, AWC 2012b), analysis shows that it is not necessarily more economic or effective (Sharov and Liebhold 1998, Cacho *et al.* 2008). Here, we demonstrate graphically that while containment has one major advantage over eradication, in that a smaller area is managed, this must be balanced against its disadvantage; that it must continue indefinitely (Figure 2).

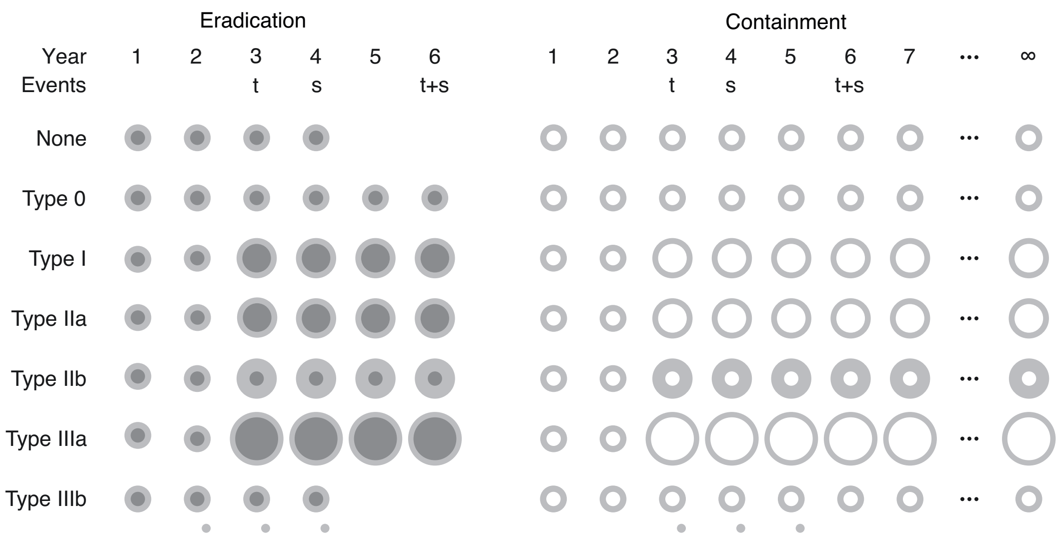

Figure 3. The consequences of breaches of containment and eradication. The breach is assumed to occur in year *t*, and the soil seed bank life time is *s*, four years.

Different invasions will be more effectively managed by either eradication or containment based on the soil seed longevity, the discount rate, and the size of the infestation, r, relative to the width of the buffer zone, d. Converting this graphical representation into a mathematical analysis lets us calculate these trade-offs (Fletcher *et. al.* 2014). When we do this, we find that invasive species with long soil seed bank lifetimes in economic systems with high discount rates will tend to be better managed with containment than eradication. Crucially, there is a threshold invasion size below which it will better to eradicate than contain, and above which the opposite is true. For very large invasions neither strategy may be economic (Cacho *et al.* 2008).

Breaches of management programs Both containment and eradication programs are at risk of breach due to rare events (Panetta and Cacho 2012, Fletcher *et al.* 2014). Each type of breach impacts eradication and containment differently. A breach of Type 0 affects only eradication, because in this simple conceptual model containment does not aim to eradicate individuals in the occupied zone. Breaches of Type I, IIa and IIIa affect the cost of an eradication program more than the comparable containment program because they increase the size of the occupied zone (Figure 3). A breach of type IIIb affects both eradication and containment identically. A breach of Type IIb affects containment more than a comparable eradication program because it increases the width of the buffer zone.

CONCLUSION

Considering the case of a well-specified eradication program that experiences a single isolated breach, we find that in the case of only three of the six breach types examined (I, IIa, and IIIa) would falling back to a containment program following the breach be more efficient than continuing a modified eradication program. Viewing containment as a default fall back when eradication fails, therefore, is not justified.

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