Criteria to help evaluate and guide attempts to eradicate terrestrial arthropod pests

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Abstract Attempts to eradicate invasive terrestrial arthropods are often regarded as gambles. They offer the possibility of long term freedom from a pest but are usually confronted with substantial uncertainty and come with a range of technical, economic, environmental, social and political risks. Few guidelines are available for evaluating eradication attempts against terrestrial arthropods. Here, we build on scientific literature, including six criteria previously developed to evaluate the feasibility of vertebrate eradications, and our own experiences to define nine criteria that are intended to both assist experts to evaluate proposed arthropod eradication attempts and guide attempts that are underway. The criteria are straight forward and easily interpreted, though evaluating them for a particular programme relies on expert group assessment that will often benefit from rigorous supporting statistical and/or modelling analyses.

Keywords: area wide management, decision support, eradication attempt, eradication campaign, eradication feasibility, invasive species, pest control

INTRODUCTION

Invasive species eradications make substantial contributions to conservation (Keitt, et al., 2015; Hoffmann, et al., 2016), agriculture (Vreysen, et al., 2007b; Suckling, et al., 2014a) and human health (Kay & Russell, 2013; Monteiro, et al., 2014). They offer perpetual benefits over long-term pest damage and associated control costs, but are usually expensive, can be disruptive both socially and ecologically, require whole-hearted long-term commitment from those involved, and success is far from guaranteed (Myers, et al., 2000; Myers, 2003; Tobin, et al., 2014; Liebhold, et al., 2016). Thus, eradication attempts invoke a range of technical, economic, environmental, social and political risks. Weighing up information about the potential benefits, costs, risks and probabilities of success of eradication attempts can be fraught with uncertainty (Brown, et al., 2019; Cannon, et al., 1999) and demands that diverse technical issues and societal perspectives be considered (Simberloff, et al., 2013).

Bomford & O'Brien (1995) defined six criteria to help evaluate the feasibility of eradicating vertebrate pests. They drew from lessons learnt in eradicating feral goats from islands, coypus in England, and infectious human diseases in various countries. These criteria have become widely adopted (Brown & Sherley, 2002; Burbidge & Morris, 2002; Clout & Veitch, 2002; Simberloff, 2003a), and have been used in New Zealand by the Department of Conservation (DOC) and Ministry for Primary Industries to help assess the feasibility of eradicating various vertebrate and arthropod pests (Cromarty, et al., 2002; Ashcroft, et al., 2010). We were members of a Technical Advisory Group convened by DOC to assist it with its eventually successful attempt to eradicate a non-native butterfly, *Pieris brassicae* (Lepidoptera: Pieridae), from New Zealand (Phillips, et al., 2016; Brown, et al., 2019). This Palearctic butterfly was regarded as a major risk to New Zealand's 79 native (mostly endemic) Brassicaceae species, many of which were already at risk (Hasenbank, et al., 2011; de Lange, et al., 2013), and also to cultivated exotic brassicas. We began using Bomford & O'Brien's (1995) criteria while evaluating the *P. brassicae* eradication programme and found them useful, though not entirely appropriate for arthropods. Moreover, we were cognisant of valuable insights about arthropod eradications that had been described in the literature since Bomford & O'Brien (1995). Thus, we refined and added to their criteria near the outset of the *P. brassicae* eradication attempt, then used these modified criteria throughout the programme to help both evaluate if the campaign should continue and identify the improvements required to maximise its chance of succeeding.

We present our refined set of criteria here with the aim of assisting others with expertise in pest eradication and arthropod ecology to evaluate and guide further arthropod eradication attempts. Other authors have summarised the elements and processes needed to mount an effective eradication campaign (Cromarty, et al., 2002; Hosking, 2002a; Hosking, 2002b; Vreysen, et al., 2007b; Pacific Invasives Initiative, 2013). However, to our knowledge, criteria developed specifically to help evaluate attempts to eradicate terrestrial arthropods have not previously been documented. Information about previous eradication programmes has recently been compiled in an on-line database (Kean, et al., 2018), yet much valuable information about eradication attempts remains either as grey literature or unrecorded, which impedes improvements in eradication methods (Myers, 2003; Hoffmann, et al., 2011). Thus, we endeavour to document some of our own lessons here.

We do not: review any eradication programmes (Vreysen, et al., 2007b; Hoffmann, et al., 2011; Suckling, et al., 2014a); discuss the growing ecological knowledge and developing technologies that are steadily increasing the potential for eradication attempts to succeed (Vreysen, et al., 2007b; Liebhold, et al., 2016; Alphey & Bonsall, 2017; Scott, et al., 2017); or discuss the enormous benefit of protecting countries or regions from invasions by new pests and diseases (Leung, et al., 2002; Hoffmann, et al., 2011; Lovett, et al., 2016). Nor do we attempt to provide a list of criteria that must be irrefutably met before choosing to initiate – or persevere with – an eradication attempt. Rather, we aim to list some readily interpretable, easily used criteria to assist constructive discussion, decision making and planning within the broader context of what is at stake if the pest is allowed to persist and spread, the pest's priority relative to other problems, and the availability of the resources, expertise and personnel required to mount an effective campaign. Evaluating the criteria will often benefit from expert group assessment and rigorous supporting statistical and/or modelling analyses. Eradication attempts usually involve many uncertainties,

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and the criteria should help to identify those that are most important to resolve as programmes proceed. Certainly, we will have missed our goal if the criteria impede prompt, effective action (Simberloff, 2003a; Simberloff, 2003b; Martin, et al., 2012; Sims & Finnoff, 2013).

METHODS

We adapted the six criteria of Bomford & O'Brien (1995) to make them clearer and more directly applicable to arthropod eradications. We reviewed science literature about factors that influence the success of eradication attempts, and used the insights gained from the science publications to further refine the six criteria. Based both on the literature and our own experiences of eradication attempts, we also developed three additional criteria.

RESULTS

The nine criteria are listed below, each with clarifying comments and, where available, supporting evidence from the literature. The list begins with criteria that deal mainly with details of the species being considered, the tools available to suppress it, and the physical environment in which it occurs, and ends with those that relate more to the societal and organisational context of the eradication attempt. Criteria 1–3, 5, 7 and 8 are based on the six criteria of Bomford & O'Brien (1995), though we modified them to make them clearer and more directly applicable to terrestrial arthropod eradications. Criterion 6 is from Pacific Invasives Initiative (2013), and we added criteria 4 and 9 based both on recent research (Pluess, et al., 2012a; Pluess, et al., 2012b; Tobin, et al., 2014; Buddenhagen & Tye, 2015) and our own experiences (Cromarty, et al., 2002; Brown & Brown, 2015; Keitt, et al., 2015; Phillips, et al., 2016; Brown, et al., 2019).

1. The pest population can be forced to decline from one generation to the next, irrespective of its density.

This is a re-wording of criterion 1 of Bomford & O'Brien (1995): *Rate of removal exceeds rate of increase at all population densities.* Myers, et al. (2000), in a review that covered eradications of species from several phyla including arthropods, also emphasised that the pest must be susceptible to control. Our changes recognise that terrestrial arthropods typically have several life stages per generation, which will likely have differing susceptibilities to control. Thus, it may be acceptable for particular life stages to numerically increase (e.g., egg-stage offspring may outnumber their adult parents) provided the overall effect of control measures is to cause inter-generational declines. Moreover, the availability of tools to suppress the pest population both at very high and at very low population densities should be considered. The eradication attempt must be capable of driving the population to extinction once it has been suppressed to very low densities and becomes more difficult to detect. Some commonly used pest control methods, such as host plant removal, biological control, and insecticide applications, do not require direct detection of pest individuals, and have potential to be effective across a range of population densities. Some species suffer Allee effects at low population densities, which can drive them to extinction once they have been suppressed to below critical density thresholds (Blackwood, et al., 2012; Liebhold, et al., 2016).

2. Every pest individual must be at risk of control at some stage of its development.

This is a re-wording of criterion 3 of Bomford & O'Brien (1995): *All reproductive animals must be at risk.* Our changes recognise that terrestrial arthropods typically have several life stages per generation, and these will likely have differing susceptibilities to control. A combination of control techniques targetting different life stages could increase the likelihood the pest will be successfully eradicated (Blackwood, et al., 2012; Suckling, et al., 2014b; Hoffmann, et al., 2016). Control methods might include augmenting natural enemies that already occur in or near the treated area to increase predation or parasitism of the pest (Montoya, et al., 2007; Hogg, et al., 2013; Richards, et al., 2016).

3. Pest individuals can be detected at low population densities.

This is a minor re-wording of criterion 4 of Bomford & O'Brien (1995): *Animals can be detected at low densities.* It is supported by many studies (Myers, et al., 2000; Simberloff, 2003a; Tobin, et al., 2014). The latter study analysed factors that influenced the outcomes of 672 arthropod eradication programs and found that high detectability contributed to success rates. Population declines must be measurable and, assuming the pest population is eventually suppressed, management tools should be adequate to confirm it has been eradicated. Are effective lures, attractants or traps available, or can they be developed in a timely fashion? When such tools are unavailable and eradication attempts depend on visual searches, they are more successful when targeting easily-observed foliage-feeding species, rather than species that occupy more cryptic niches such as roots, fruit or stems (Tobin et al., 2014). Moreover, programmes without sensitive detection tools that capitalise on citizen reports of sightings have higher probabilities of success than those that do not (Tobin et al., 2014). Thus, detection will be more likely when: effective attractants are available; the pest and its feeding damage are conspicuous and easily recognised; the pest's host plants are low growing, easily searched and of interest to gardeners, commercial growers and/or citizen ecologists; and citizen surveillance is supported by effective outreach programmes. Some control methods may impede detection. For example, using pheromones to disrupt mating will reduce their efficacy as lures for detection (Suckling, et al., 2014b).

4. Success is favoured by small spatial extent of the population.

Bomford & O'Brien (1995) acknowledged pest population spatial extent as important under 'Other factors'. The meta-analysis of Tobin, et al. (2014) considered 672 arthropod eradication programs that involved pest infestations ranging in area from about 0.1 km^2 to about 100,000 km^2. Overall, there was a base rate of 59% success, and the spatial extent of the targeted population was the most important factor explaining variation around this rate (Tobin, et al., 2014). Population spatial extent was also recognised as a critically important factor in the outcomes of 136 eradication programs against invertebrates, plants and plant pathogens (Pluess, et al., 2012a). When infested areas are small, eradication attempts are less expensive and more likely to be successful (Myers, et al., 2000; Simberloff, 2003a; Brockerhoff, et al., 2010; Pluess, et al., 2012a; Tobin, et al., 2014). This is why "wait and see" responses to detections of new pests are seldom justifiable even when uncertainty is high (Sims & Finnoff, 2013).

5. Immigration and emigration can be prevented.

Here, we added 'and emigration' to criterion 2 of Bomford & O'Brien (1995) (*Immigration prevented*) because an attempt to eradicate a localised arthropod population will fail if individuals disperse from the eradication zone and establish new undetected populations nearby. Myers, et al. (2000) and Hoffmann, et al. (2016) emphasised that immigration (reinvasion) must be prevented, and Bomford & O'Brien (1995) acknowledged pest dispersal rates as important under 'Other factors'. Attempts to eradicate isolated localised populations (e.g. on islands or other geographically isolated areas) might benefit from low likelihoods of natural pest dispersal in or out of the eradication zone (Myers, et al., 2000), though an analysis of 173 eradication programmes found no evidence that eradication attempts were more successful on islands (Pluess, et al., 2012b). The likelihood the pest will be transported in or out of the infested area in association with humans must also be considered, as should the extent to which this risk can be mitigated (e.g. by implementing regulatory controls on host plant movements). Pluess, et al. (2012b) found that implementing sanitary measures to restrict pest emigration made an important contribution to eradication success rates. A further consideration is the capability of the programme to identify when immigration or emigration is occurring, and to respond effectively to such processes. Recognising that immigration is occurring may be challenging, though genetically characterising the population within the eradication zone could help to identify new immigrants if they differ genetically from the initially targeted population (Barr, et al., 2014; Hiszczynska-Sawicka & Phillips, 2014; Piertney, et al., 2016). Detecting emigrants will depend on the extent, intensity and efficacy of active and passive surveillance outside the known infested area.

6. Environmental impacts of the programme are acceptable.

Most methods used to manage pests will have non-target impacts (Bomford & O'Brien, 1995; Pacific Invasives Initiative, 2013). These include host plant removal, biological control, synthetic pesticides, biopesticides and traps (e.g. due to by-catch). Eradicating a pest from an ecosystem could release other non-native species from competition, predation or parasitism, thus solving one problem while exacerbating another (Myers, et al., 2000). Decision makers must consider if such impacts will be reversible and/or socially and environmentally acceptable, and if they will be substantially less than those likely to be sustained if the pest became permanently established and more widely distributed. If the infested area being treated is small and the expected term of the programme is short, then environmental impacts might be ephemeral because those non-target species negatively impacted by the eradication programme may be able to recover once the programme ends.

7. Benefit-cost analysis favours eradication over control.

This is a minor re-wording of criterion 5 of Bomford & O'Brien (1995): *Discounted benefit-cost analysis favours eradication over control*. It was also listed by Pacific Invasives Initiative (2013). We omitted the word 'discounted' from Bomford & O'Brien's (1995) criterion because discounting in benefit-cost analysis remains controversial (Gollier & Hammitt, 2014; Hockley, 2014). Myers, et al. (2000) acknowledged that evaluating the benefits and costs of eradication is difficult, and contended that the benefits of eradication are often over estimated and the costs of eradication under estimated. Nevertheless, many successful eradication programmes have been regarded as highly cost-effective (Brockerhoff, et al., 2010; Buddenhagen & Tye, 2015; Scott, et al., 2017). Benefit-cost analyses provide useful frameworks for aggregating information about an eradication attempt to support decision making. However, they must often include educated guesses about parameter values, struggle to quantify the value of biodiversity and ecosystem services, and seldom address uncertainty (Born, et al., 2005; Epanchin-Niell & Hastings, 2010; Simberloff, et al., 2013; Hockley, 2014; Brown, et al., 2019).

8. Suitable social, political, legal and institutional environment.

This is a minor re-wording of criterion 6 of Bomford & O'Brien (1995): *Suitable socio-political environment*. It was emphasised by Buddenhagen & Tye (2015) and similar criteria were listed by Pacific Invasives Initiative (2013) and Simberloff (2003a). Myers, et al. (2000) also stressed that funding must be sufficient and lines of authority clear. Our changes more clearly specify the need for eradication programmes to be supported by every facet of society that has an important role or stake in the programme. Those evaluating eradication attempts must ask questions like: Will property owners allow or support eradication activities on their land? Would those implementing the eradication programme have legal authority to implement control actions on private and public land? Will the programme be supported by stakeholders such as local and regional authorities, farmer organisations and environmental advocacy groups? Will all management levels of the institution(s) attempting the eradication remain fully committed – especially financially – to the programme for the long haul?

9. Programme is effectively managed, and its status is reliably monitored and accurately recorded.

Efficient, meticulous and effective planning and management are critical to eradication success (Cromarty, et al., 2002), as are clear lines of authority (Myers, et al., 2000; Simberloff, 2003a). These programme attributes must be supported by efficient and robust data collection and analysis to enable progress to be monitored, assumptions tested, weaknesses identified, and improvements devised and implemented (Vreysen, et al., 2007a). Brown & Brown (2015) suggested that systematic and persistent effort by individuals with a "completer-finisher" personality type (Belbin, 2010) or an "eradication attitude" can increase the likelihood of success. For arthropod eradications, it is clearly important to involve people with expertise in arthropod ecology and management.

DISCUSSION

We propose that the nine criteria can help to focus discussion and evaluate and guide attempts to eradicate terrestrial arthropods. We repeatedly scored the criteria throughout the *P. brassicae* eradication programme (Phillips, et al., 2016) and, although our individual assessments often differed, they always provided a valuable basis for discussion and planning. Moreover, our individual assessments all became progressively more optimistic as the programme proceeded and uncertainty declined (Phillips, et al., 2015). In fact, optimism grew even as the pest's known geographical distribution increased because we also gained confidence that the pest was detectable and controllable.

We found it useful to classify each criterion as being either 'not met', 'marginally met' or 'substantially met'. These qualitative terms recognised that criteria can be met to varying degrees and using just three classes simplified the assessment process and eased interpretation. Criteria were classified as 'not met' if the eradication attempt was likely to fail unless improvements to that aspect of the programme were urgently made. Criteria were considered 'marginally met' if there was some evidence the criterion could be (or was being) met, but knowledge gaps caused uncertainty to be high and made assessing the criterion difficult. This classification also signalled a need for action because important knowledge gaps had to be addressed to ensure eradication feasibility. Criteria were scored as 'substantially met' when these elements of the eradication attempt appeared (likely to be) effective. Improvements to aspects of the eradication classified as 'not met' or 'marginally met' were regarded as critical and urgent, and improvements to those classified as 'substantially met' were regarded as desirable.

In the context of vertebrate eradications, Bomford & O'Brien (1995) considered criteria 1, 2 and 5 (numbers as used in the main text of the Results in this paper) as essential to success, and criteria 3, 7 and 8 as desirable, though they emphasised that negatives in the latter three criteria "will greatly reduce the feasibility and desirability of eradication". With our criteria for terrestrial arthropod eradications, we suggest that all of the criteria except numbers 4 (small spatial extent) and 7 (benefit-cost analysis) will need to be substantially met before eradication is eventually achieved. However, it may be reasonable to initiate an eradication attempt before many of the critical criteria are substantially met. This is because, with thoughtful management, new knowledge and tools will often be developed during the course of a programme (Vreysen, et al., 2007b; Scott, et al., 2017) that will rectify some or all of its deficiencies and/or enable the criteria to be scored with more confidence. Indeed, the criteria aim to highlight those aspects of programmes that most need improvement. In cases where few critical criteria are substantially met, it will be particularly important to specify conditions under which the attempt will cease (e.g. when a key programme deficiency is not rectified by a specified date) in order to minimise expenditure on programmes that are doomed to failure.

The capability to robustly evaluate programme progress and confidently reclassify criteria is especially dependent on criterion 9 (excellent management). It is also highly desirable that a (proposed) programme substantially meets criteria 4 (small spatial extent) and 7 (benefit-cost analysis). Yet, with criterion 4, there are examples of arthropod populations with very large spatial extents that have been successfully eradicated (Vreysen, et al., 2007b; Monteiro, et al., 2014; Scott, et al., 2017), thus scores of 'not met' or 'marginally met' may be acceptable in cases where the other criteria for achieving eradication can be substantially met and resources are available to work effectively across large geographical areas. For criterion 7, perceptions of the potential economic and/or environmental benefits of an eradication attempt will strongly influence the level of risk that is deemed acceptable when deciding whether to initiate or persist with the attempt. However, the previously mentioned limitations of benefit-cost analyses (Born, et al., 2005; Epanchin-Niell & Hastings, 2010; Simberloff, et al., 2013; Hockley, 2014; Brown, et al., 2019) combined with overwhelming evidence of negative impacts of many invaders suggests that the precautionary principle (Simberloff, et al., 2013) should be applied particularly to criterion 7, and scores of 'marginally met' may be adequate to justify action.

We intend the criteria to be used by people with expertise in pest eradication and arthropod ecology and management. During the *P. brassicae* eradication attempt, we found it productive to discuss programme performance against each criterion as a group because our individual perspectives often initially differed. Our evaluations of one or more criteria were frequently supported by statistical and/or modelling analyses of data being collected by the programme. Eventually we would reach a consensus that enabled us to provide better advice to the programme than any one of us could have alone. Thus, we advocate using the criteria in fora similar to the 'Technical Advisory Groups' that are often applied in New Zealand to support management decision making. We believe that using the criteria to help evaluate the feasibility of an eradication attempt and its progress towards success will help to improve decision making and increase programme success rates. However, the quality of decision making will of course also depend on the values and motivations of decision makers, the experience and problem-solving abilities of the expert group, the quality of data analysis, and the preparedness of all involved to fill knowledge gaps and take timely action.

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