Feasibility of eradicating the large white butterfly *(Pieris brassicae)* from New Zealand: data gathering to inform decisions about the feasibility of eradication

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Abstract *Pieris brassicae*, large white butterfly, was first found in New Zealand in Nelson in May 2010. The Ministry for Primary Industries (MPI) responded with a monitoring programme until November 2012 when the Department of Conservation (DOC) commenced an eradication programme. DOC was highly motivated to eradicate *P. brassicae* by the risk it posed to New Zealand endemic cress species, some of which are already nearly extinct. DOC eliminated the butterfly from Nelson in less than four years at a cost of ca. NZ$5 million. This is the first time globally that a butterfly has been purposefully eradicated. Variation in estimates of benefits, costs, the efficacy of detection and control tools, and the probability of eradication success all contributed to uncertainty about the feasibility. Cost benefit analyses can contribute to assessing feasibility but are prone to inaccurate assumptions when data are limited, and other feasibility questions are equally important in considering the best course of action. Uncertainty does not equate to risk and reducing uncertainty through data gathering can inform feasibility and decision making while increasing the probability of eradication success.

Keywords: biodiversity, cost-benefit analysis, eradication success, extinction risk, invasive species, non-native species

INTRODUCTION

Biological invasions by insects, including Lepidoptera, are increasing worldwide (Liebhold, et al., 2016; Suckling, et al., 2017). Insect invaders can cause significant biodiversity, economic, social and health impacts, which makes eradication an attractive management strategy (Liebhold, et al., 2016). Expanding international trade and travel have increased the numbers of exotic organisms entering New Zealand (Biosecurity Council, 2003; MPI, 2016).

Pieris brassicae (Lepidoptera: Pieridae), a Northern Hemisphere species native to Eurasia, was first found in the wild in New Zealand in Nelson (41°27′S, 173°28′E), a coastal city at the north of the South Island, in May 2010 (Toft, et al., 2012). An Unwanted Organism under the Biosecurity Act 1993, and a known pest of cultivated brassicas, it was referred to locally as 'great white butterfly' (GWB), or 'great white cabbage butterfly' (GWCB'). In this paper we use the scientific name *Pieris brassicae*.

Pieris brassicae can migrate hundreds of kilometres to new locations within a season (Spieth & Cordes, 2012). Together with the species' cold tolerance, its dispersal ability would put most New Zealand endemic brassica populations at risk (Kean & Phillips, 2013). However, the rate of *P. brassicae* spread in Nelson was uncertain. It was found at eight sites spread over 10–12 km in urban Nelson five months after the initial detection, but its distribution appeared not to have changed significantly after a further two years (Phillips, et al., 2016). This suggested unexpectedly slow dispersal for this species, perhaps impeded by parasitic wasps, predation or other factors.

DOC considered that *P. brassicae* had potential to cause extinctions of New Zealand endemic cresses, many of which occur in isolated, small populations; this makes them vulnerable to a wide range of threats and expensive to protect. New Zealand has 79 native cress species within the Brassicaceae family, most of them endemic and two already presumed extinct. Fifty-five species are currently threatened by extinction: 18 listed as nationally critical (the closest ranking to extinction), four nationally endangered, five nationally vulnerable, one declining, eight naturally uncommon, and 19 threatened though not yet ranked (Townsend, et al., 2008; de Lange, et al., 2013; S. Courtney, DOC, pers. comm.).

After mating, a *P. brassicae* female lays a cluster of 50–150 eggs on a host plant, and can lay a total of ca. 500 eggs (Gardiner, 1963; Spieth & Schwarzer, 2001). After hatching, larvae feed together and can wander up to 350 m in search of food plants. *Pieris brassicae* develop through five larval stages, usually defoliating several host plants in the process. Larvae at the fifth stage crawl away from their host plants to form pupae. The time required for *P. brassicae* to complete its lifecycle depends both on temperature and day length. It had two to three generations per year in Nelson (Kean & Phillips, 2013).

The Ministry for Primary Industries (MPI) is New Zealand's lead biosecurity agency with responsibilities to protect New Zealand's environment, economy, health and socio-cultural values under the Biosecurity Act 1993. MPI responded quickly to the 2010 detection of *P. brassicae* in Nelson by alerting the public and establishing a monitoring and surveillance programme. However, they terminated their response in November 2012 based on the results of the final of several cost benefit analyses (CBA) (Dustow, 2010; Dustow & van Eyndhoven, 2012; Manning, 2012). MPI predicted costs would outweigh benefits and that the probability of success was low (Manning, 2012).

The Department of Conservation (DOC) has a responsibility to protect native biodiversity under the Conservation Act 1987. DOC has a strong track record of pest management and successful eradication of (mostly) vertebrate pests from islands (Diamond, 1990; Simberloff, 2002; Howald, et al., 2007). On 19 November 2012, DOC initiated an eradication attempt to eliminate the risk that *P. brassicae* posed to New Zealand endemic cresses, primarily using systematic ground-based searching (Phillips, et al., 2016). The attempt succeeded: the last *P. brassicae* was captured near central Nelson on 16 December 2014, and the eradication programme closed on 4 June 2016. MPI and DOC declared *P. brassicae* eradicated from New Zealand on 23 November 2016, at a cost of NZ$4.97 million (€3.22 million).

DOC and MPI both had very pressing competing priorities and were acutely aware that spending money on an eradication attempt would take resources from other high priority work. To spend limited taxpayer dollars wisely, MPI responds to incursions according to carefully

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considered priorities using CBA to prioritise management responses. When considering eradication, MPI calculates a Benefit Cost Ratio (BCR) by estimating: the pest's impact over 20 years, the predicted cost of the eradication attempt, and the probability of eradication success. A BCR over 3:1 is required for MPI to initiate an eradication attempt.

Unfortunately, elements of a CBA can be difficult to quantify. Accurately predicting the impacts of invasive species can be difficult (Andersen, et al., 2004; Paterson, et al., 2015; Simberloff, et al., 2013; Simberloff, 2015). There is no universally accepted way of quantifying the benefit of conserving biodiversity in dollar terms (Spash, 2008; Parks & Gowdy, 2013; Barkowski, et al., 2015). Predicting eradication costs (Donlan & Wilcox, 2007; Holmes, et al., 2015) and the probability of eradication success also pose challenges, especially when there are few precedents and limited field data (Pluess, et al., 2012; Brown & Brown, 2015; Phillips, et al., this publication).

A feasibility study that considers eradication costs and benefits is a routinely used decision support tool in DOC (Broome, et al., 2005). Before starting the *P. brassicae* eradication attempt, DOC also considered costs, benefits and probability of success, though in a proposed eradication strategy rather than a CBA (Toft, et al., 2012). After commencing it, DOC revised costings, procured an independent CBA (East, 2013a) and developed additional feasibility criteria (Phillips, et al., this publication)

In this paper we explore uncertainties in the feasibility and economics of eradicating *P. brassicae* and suggest ways of reducing them to help inform future decision-making.

METHODS

We examined the question of when to attempt or abandon eradication when faced with high uncertainty and discuss ways to assist future decisions in such circumstances.

Cost Benefit Analysis

Four CBAs were developed, three by MPI and one by the University of New England for DOC. CBA is a systematic process for calculating and comparing the costs and benefits of a decision. Written as a formula it would read: (discounted benefits × probability of success)/ discounted costs. Costs and benefits were discounted at a rate of 8% for 20 years based on New Zealand Treasury advice (NZ Treasury, 2005).

The costs of aerial and ground-based eradication were predicted using known or estimated costs of service providers. Predictions also drew on experience with previous eradication operations regarding the activities required and their likely timeframes. Costs were included for active surveillance, passive surveillance (media, public), organism management (insecticide spraying, etc.), vegetation (host plant) movement controls, host plant removal and science support (developing a lure, augmenting natural enemy populations by releasing parasitic wasps, developing the sterile insect technique, data analysis, genetics and modelling).

The benefits of eradication are the avoided impacts. The impacts on brassica seed production, vegetable growing, and livestock forage production were calculated based on the cost of applying additional insecticide to control *P. brassicae*. These purely monetary impacts were estimated using several assumed rates of *P. brassicae* dispersal that were based on previous observations of *P. brassicae* spread in Chile (400 km in seven years), South Africa (350 km in two years) and Japan (400 km in five years or less) (Manning, 2012).

The biodiversity impacts (i.e. the cost of applying insecticide to endemic cresses to control *P. brassicae*) were considered by two CBAs (Dustow & van Eyndhoven, 2012; East, 2013a). In both analyses, 'willingness to pay' – a non-market valuation method which is based on a New Zealand community's willingness to avoid local extinction of a native plant – was also used to estimate biodiversity impacts (Dustow & van Eyndhoven, 2012; East, 2013a: East, 2013b). However, neither Dustow (2010) nor Manning (2012) used the cost of applying insecticide to endemic cresses for controlling *P. brassicae* in their 'willingness to pay' calculations.

Criteria used to evaluate eradication feasibility

Feasibility analysis aims to scope the size of the project, decide if eradication is possible and identify issues that require resolution to maximise the chance of eradication success (Pacific Invasives Initiative, 2013) and thereby estimate the probability of eradication success. MPI estimated the probability of success of ground-based eradication at approximately 30% based on overseas examples and expert opinion (Manning, 2012). The feasibility criteria used by MPI when considering eradication probability are based on Bomford & O'Brien (1995). They are:

- Rate of removal exceeds rate of increase at all population densities
- Immigration is zero
- All reproductive pests must be at risk
- Target pest can be detected at low densities
- Cost benefit analysis must favour eradication
- Suitable socio-political environment.

DOC assembled a Technical Advisory Group (TAG) to support the eradication attempt. The TAG developed a modified set of nine criteria, which built on the six criteria above, to evaluate feasibility (including the probability of success) and guide the eradication attempt (Phillips, et al., this publication). The criteria used by MPI are discussed below.

Technical advice and decision making

Both MPI and DOC used in-house and external expertise to inform decision making. DOC's TAG comprised three senior animal pest technical advisors from DOC including an entomologist, three senior scientists from two government research institutes (AgResearch and Plant and Food Research), and a private insect ecology consultancy (Entecol Ltd). DOC's TAG had considerable experience in ground-based eradication having advised or been directly involved in multiple animal and weed pest eradications nationally and worldwide. MPI consulted in-house technical staff, some of whom had been involved in previous insect eradication programmes, and also held a day-long meeting to consult with an external group of insect ecologists and industry stakeholders about the feasibility of eradicating *P. brassicae*. An MPI Governance Group reviewed the evidence provided by technical staff and decided not to attempt eradication in September 2012. DOC senior managers decided in November 2012 to attempt eradication based on the technical advice they received (Toft, et al., 2012).

RESULTS

The greatest variation between the four CBAs is in the predicted costs of eradication and discounted benefits (Table 1). The former due to differences in method and labour unit cost, and the latter due to the presence or absence of biodiversity benefit. Probability of success estimates were relatively similar, although the Manning CBA, which MPI ultimately used in their decision to abandon eradication, was somewhat less optimistic.

Eradication feasibility and cost benefit uncertainty

There was uncertainty about *P. brassicae*'s New Zealand distribution, reproductive rate, seasonality, rate of emigration, and host plant range. Similarly, it was difficult to predict the response of the public to control measures, efficacy of control measures, efficacy of detection methods, ability to monitor progress towards eradication, eradication costs, eradication benefits and probability of success.

Technical assessment of eradication feasibility criteria

Rate of removal exceeds rate of increase at all population densities

This was unknown at the outset given the potentially high reproductive capacity. No pheromones or other chemical attractants were available for *P. brassicae*, therefore trapping could not be used as a control tool, nor as a surveillance tool to monitor changes in population density. Aerial insecticide application was considered a potential method of maximising *P. brassicae* mortality at all population densities but was not pursued due to its likely unacceptability to Nelson residents (see criterion 6) and some uncertainty over just how vulnerable eggs and larvae would be to aerial spraying of large-leaved host plants. The large, conspicuous larvae feeding in groups on the same host plant did, however, suggest ground-based searching may be effective if the scale of operation could match the scale of infestation. Also, most *P. brassicae* host plants were likely to be low-growing, which would facilitate ground-based searching.

Immigration is zero

There was concern that the high dispersal potential of *P. brassicae* would make delimiting the population expensive and unreliable (given the unavailability of effective lures) and could result in undetected populations occurring outside the operational area that could reinvade. However, large commercial brassica crops on arable land near Nelson city were routinely monitored and by 2012 were still not showing evidence of *P. brassicae*.

All reproductive pests must be at risk

As described in more detail below, most potential control methods depended on visually detecting *P. brassicae*, but search efficacy was initially unknown. Thus, the possibility that some individuals would evade detection and avoid control was a major concern.

If *P. brassicae* populations occurred outside the operational area and remained undetected, those individuals would not be at risk, therefore violating criteria 2 and 3 above. *Pieris brassicae* adults are highly mobile and can cover long distances in search of larval food plants and nectar sources. Individuals are known to fly up to 5 km a day searching for host plants for egg-laying (Schutte, 1966, cited in Feltwell, 1982). Given the high dispersal potential of *P. brassicae* and the observed rapid spread of the closely related *P. rapae* when it appeared in New Zealand (at least 160–190 km within two years of detection) (Muggeridge, 1942), it was assumed *P. brassicae* would be widespread in Nelson and that undetected populations existed. It was considered that *P. brassicae* was capable of moving outside Nelson city's boundaries in the first season post-detection. There was also the risk that *P. brassicae* could escape Nelson in association with human transport, perhaps as larvae on infested vegetation or as pupae on inanimate objects including vehicles. However, despite the potential for rapid dispersal beyond Nelson, by 2012 there was still no evidence that it had occurred. Possibly dispersal was density-dependent (Toft, et al., 2012).

There was concern that wild brassicas and other food hosts in less accessible places would act as refugia if they could not be found and searched.

There was also concern that some life stages would not be susceptible to control. For example, eggs can occur under leaves making them difficult to see and less vulnerable to insecticide sprays. The cryptically coloured pupae can attach to man-made structures such as fences and it seemed they would often be difficult to find. However, every individual could be put at risk during one or more stages of its lifecycle through human search effort.

In addition, not all tools depended on people detecting *P. brassicae*. There was published evidence that eggs and larvae were vulnerable to storm events, and eggs, larvae and pupae would be susceptible to parasitism or predation by various species of parasitic wasps and paper wasps that were already present in New Zealand (Muggeridge, 1943; Bonnemaison, 1965; Gould & Jeanne, 1984; Richards, et al., 2016). Moreover, detection was not an essential prerequisite for applying control measures such as insecticides and destroying host plants (e.g. garden brassicas).

Target pest can be detected at low densities

There was concern that visually searching for *P. brassicae* without a lure would be costly, labour intensive and ineffective at detecting all individuals at low population densities. All previously successful eradications of Lepidoptera used pheromone lures (Tobin, et al., 2014). Pheromones can be used to detect and monitor populations, and also to disrupt mating, which can be a particularly effective control method at low pest densities. However, pheromones and other chemical attractants were unavailable for *P. brassicae*. Detection probabilities could be calculated but only through data gathering and analysis during an eradication attempt (Phillips, et al., 2014a).

Cost benefit analysis must favour eradication

Four separate CBAs were carried out, three before the eradication attempt commenced and one a year after the

Table 1 Eradication method, cost, benefit and probability of success.

Reference	Method	Discounted cost (NZ$ m)	Discounted benefit (NZ$ m)	Benefit: cost ratio	Probability of success (%)
Dustow (2010)	Aerial	25–73	21.7–60.9	0.3–2.44	50–75%
Dustow & van Eyndhoven (2012)	Aerial	25–73	21.7–123.2	0.3–4.93	50–65%
	Ground	13.3		1.64–9.28	
Manning (2012)	Ground	8.9	13.2–26.5	1.5–3	30–60%
East (2013a)	Ground	3.9	17.4–70.8	4.8–19.7	56–76%

eradication attempt started. All used different estimates of costs, benefits and probability of success and, therefore, all obtained different BCRs and reached different conclusions (Table 1).

Dustow (2010) concluded that "the analysis strongly suggests that it is not economically beneficial to attempt to eradicate great white butterfly [using the aerial application of insecticide]". Dustow & van Eyndhoven (2012) concluded that "the CBA analysis indicates favourable benefit cost ratios for all but the most conservative ground-based eradication when biodiversity values are excluded", and "relatively low biodiversity values are required to generate favourable benefit cost ratios for many scenarios". Manning (2012) concluded that "given the level of uncertainty surrounding the development of effective control tools, low probabilities of successfully eradicating the GWCB, and the uncertainty surrounding biodiversity benefits, it is unlikely to be technically or economically feasible to eradicate the GWCB". Subsequently, East (2013a) concluded that "The high expected impacts of the GWB on New Zealand's native brassicas, the agricultural industry and home gardeners result in high net present values and benefit cost ratios [which suggests] that a GWB eradication programme in Nelson is warranted".

Manning (2012) stated that 'the ground-based eradication option is considered to have a probability of success of approximately 30% based on overseas examples and expert opinion". MPI used the probability of 30% when decision making. The probability of success value (mean 56%; range 50–60%) used in the fourth CBA (East 2013a) a year after eradication commenced was determined by DOC's TAG who had the benefit of some hard data on which to make their estimate.

Cost estimates varied greatly among the four CBAs (Table 1). Aerial spraying costs were based on previous experience of using this method against white tussock moth (*Orgyia leucostigma*) and painted apple moth (*Orgyia anartoides*) in Auckland (Ashcroft, et al., 2010) and assumed substantial social mitigation costs for affected residents of Nelson. Ground-based cost estimates were little more than guesses given uncertainty around method efficacy, delimitation boundaries and detection probabilities (which strongly influence the length of time ground crews must remain operational beyond the last detection to have confidence in declaring eradication success). MPI contractor costs were also estimated at three times higher than DOC staff costs. Again, East (2013a) had some actual data to work with and consequently her cost estimate came closer than the others to the final actual cost.

Suitable socio-political environment

An aerial application of the bio-pesticide bacterium Btk (*Bacillus thuringiensis kurstaki*) was thought likely to raise considerable public opposition as it did in Auckland for white tussock moth and painted apple moth (Ashcroft, et al., 2010). Ground-based control, on the other hand, was assumed likely to gain public and political support. This was evidenced shortly after the initial detection by positive public responses to official requests for reports of *P. brassicae* sightings.

DISCUSSION

When assessing the feasibility of eradication, three basic questions must be answered (Broome, et al., 2005): Why do it? Can it be done? What will it take to succeed?

Why attempt eradication?

It was impossible to precisely predict the impact of *P. brassicae* on New Zealand endemic brassicas (and predicting impacts on cultivated brassicas under different management regimes was also problematic). New Zealand's biodiversity has been geographically isolated for millions of years from Northern Hemisphere plants, herbivores, predators and parasitoids, which makes it hard to predict impacts. This is a generic issue for incursion response management in New Zealand. If the New Zealand native plants that a non-native herbivore will feed on cannot be immediately identified, then estimating impacts can only be achieved either through difficult, expensive and imperfect laboratory testing, or by watching them unfold in the wild. Laboratory testing of the suitability of threatened native cresses for herbivory by *P. brassicae* was impractical as most are not cultivated due either to the difficulty of obtaining seed, or to their complex cultivation requirements.

The risk of extinction to endemic cresses from herbivory by *P. brassicae* was considered significant even without multiple other threats. Other threats to endemic cresses include herbivory and disturbance by a range of pests, viral and fungus attack, weed competition, sea-level rise and the loss of seabird-driven ecosystem processes which all impact on different cresses. As Quammen (1996) pointed out, extinction often results from multiple causes and "to be rare is to have a lower threshold of collective catastrophe".

Preventing extinction of native biodiversity is a core function of DOC and is fundamental to the Department's legislative mandate (Conservation Act 1987). Given the multiple threats facing endemic cresses in addition to *P. brassicae*'s potential to access all endemic brassicas, dietary preference for brassicas, tendency to deposit large numbers of eggs on individual plants and voracious feeding on individual plants by clusters of caterpillars, DOC's senior botanists and entomologist concluded there was a high risk that *P. brassicae* would drive at least some New Zealand endemic cresses to extinction. Knowledge of this risk strongly motivated DOC to attempt eradication, despite the uncertainties, while using a 'learn by doing' approach.

Can it be done?

The value attributed to the probability of success can significantly influence the benefit value obtained (i.e. benefit = discounted benefit × probability of success) and therefore the BCR. Estimating the probability of success is a subjective process based on evidence from previous eradication attempts and expert opinion. This becomes problematic when eradication of the taxon in question has not been attempted before, and where factors including the ecology, physiology and behaviour of the non-native species in the new environment are poorly understood. Accurately estimating the probability of eradication success is impossible without knowledge of the effectiveness of control tools, pest population rate of increase, pest distribution, and risk of immigration (Bomford & O'Brien, 1995; Tobin, et al., 2014; Phillips, et al., this publication). The challenge is to gather enough quality data quickly enough to inform decisions. Choosing a threshold of certainty – where there is enough information to make a decision – can be partly based on an assessment of the consequences of not deciding. As Harvey Cox (1968) puts it "not to decide is to decide".

If the pest can be killed at the same time as it is being surveyed for distribution and abundance, then eradication may gain a 'head start' while critical feasibility information is being collected. Pre-defined stopping rules can be used to trigger reassessments of feasibility, thus limiting the risk of over-investing in eradication attempts that cannot succeed. For example, the DOC TAG defined the following triggers for re-evaluating the *P. brassicae* eradication attempt (Phillips, et al., 2014b):

- If established *P. brassicae* populations are detected outside the residential Nelson operational area
- If the population has expanded outwards after 12 months of being subjected to control
- If *P. brassicae* has not been eradicated by 30 June 2015
- If no *P. brassicae* have been detected for two consecutive years.

Triggers clearly indicate when the objectives in the plan are or are not being achieved. The initial response gathered some information about *P. brassicae*'s distribution prior to commencing the eradication attempt, but not about its rate of increase or the efficacy of visual searching. Once the attempt was underway, however, distribution data and the effectiveness of control tools was gathered in a systematic way that was used to inform management decisions, reduce uncertainty, reassess feasibility through time, measure progress and eventually provide confidence that eradication had been achieved (Phillips, et al., 2016).

What will it take to succeed?

The 'learn by doing' approach informed the technical assessment of the probability of success (described above). It also allowed the level of resourcing and capability that was needed for the eradication to succeed to be accurately quantified and adjusted as the programme progressed. For example, in the early stages of the programme in 2012, the ground control team was limited to a team of four. However, by April 2013 it had become clear that, although the methods might be effective, more resources were needed to achieve success (Table 2). The field team size was increased to 10 (and up to 30 later in the programme) and the consequent increased costs were factored into the final CBA (East, 2013a). By constantly reassessing resource allocations to different aspects of the project, efficiencies were gained without jeopardising the probability of success. Crucial in this decision making was expert analyses of incoming data by DOC's TAG that supported the project.

CONCLUSIONS

Delays in attempting eradication can increase the programme's duration, cost and risk of failure.

Table 2 Sites searched, sites infested with *Pieris brassicae* and proportion infested by financial year (July to June).

Year	Sites searched	Sites infested	Proportion of sites infested
2009–10	3	3	1
2010–11	88	30	0.341
2011–12	76	71	0.934
2012–13	23,923	1,121	0.047
2013–14	80,263	1,490	0.019
2014–15	83,118	170	0.002
2015–16	76,507	0	0
Total	263,978	2,885	0.015

Quick, proactive responses can help to achieve eradication while simultaneously gathering data to inform decision making. Stopping rules can be used to assess if an eradication should cease to minimise the waste of resources.

In the absence of reliable information about costs, biodiversity benefits and probability of success, CBAs should not be relied on as the sole decision making tool.

A TAG can be a powerful tool for providing ongoing well-structured advice to assess feasibility and assist eradication decision making.

Close engagement with research agencies facilitates research support for eradication attempts, which can help to provide critical analyses, information and management tools.

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