Estimating the benefit of early control of all newly naturalised plants

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Cover: Control of a small *Pinus contorta* tree on Mount Ruapehu by a youth volunteer, 2002.
Photo: J.R. Keys, Department of Conservation.

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CONTENTS

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ABSTRACT

Early eradication of weeds is preferable to attempting to control them when they are well-established, and becoming a problem. But when a plant is newly naturalised, we often do not know if it will eventually become a weed. In this study, we compare the cost effectiveness of removing all newly naturalised plants early or delaying action until they prove to be weeds. We obtained data from 58 Department of Conservation weed control projects around New Zealand and used these data to compare the typical cost for controlling a weed infestation at two stages of invasion: early stage small infestation, and late stage large infestation. We also modelled weed spread using different scenarios of plant growth rate and dispersal plus typical time estimates for weed infestations to spread. We then analysed the control costs at 5, 10, 20 and 40 years from establishment, to predict the cost implications of delaying weed control. Our data suggest that, early on, while an infestation is small (only a few plants or plants covering an area up to 400 m^2), all individuals can be easily removed for a minimal cost—an average of $1090. By contrast, if control is postponed until a later stage (when the infestation is widespread or dense) it is, on average, 40 times more expensive than early removal. Furthermore, it is shown that if a plant's weed potential is unknown, its early removal will still be beneficial if removal can be achieved for less than $7000. Once a weed disperses from its initial establishment point, the costs of control increase dramatically, largely because of the burgeoning cost of searching for individual plants.

Keywords: control, benefit analysis, early intervention, environmental weeds, weed control costs

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1. Introduction

The New Zealand Department of Conservation's (DOC's) Surveillance Plan aims to facilitate the detection of new plant species early in their naturalisation in an area (Braithwaite 2000). The Plan recommends prompt control of new weeds, soon after they are found (recognising there will always be a delay between the weed arriving and its being found). This advice is based on Harris et al.'s (2001) analysis of different logistic plant growth functions, which showed that early detection and control is highly advantageous for weeds with a moderate to fast growth rate and spread. There is less benefit to be had from early detection or control of species that spread slowly, because any increase in control costs over time is offset by the change in the value of money over time (discount rate). However, all weeds of conservation concern considered in that study had a growth and spread rate well above the threshold[1] that delivered a dividend from early control.

It follows, therefore, that when a new naturalised plant species is found, the next step should be to decide whether or not to get rid of the infestation immediately. This involves considering three questions:

1. Is elimination of the infestation feasible?
2. Is eradication of the species from a wider area feasible?
3. Is elimination or eradication worthwhile?

Elimination refers to removing just the known infestation from a site. By contrast, eradication means permanent removal of a species from large (e.g. catchment-sized areas). To achieve eradication, a wide area must be searched for the weed and all individuals removed, and re-invasion must be very unlikely. Therefore, in contrast to elimination, eradication is only feasible under rare circumstances—when effective control methods are available, when re-invasion is unlikely to occur and when appropriate social conditions prevail to facilitate the necessary work. The biology of the weed and its detectability, plus the logistics and effectiveness of the control technique, can make eradication impossible (Panetta & Timmins 2004). When eradication is not possible, because the weed keeps re-invading, the goal may become zero-density, i.e. the area is kept free of that weed by ongoing searching and management. It is always difficult to detect any species that is present in low numbers (McArdle 1990), but this is even more difficult for plants, because seeds are not detectable until they germinate and they may survive in the soil for a long time (Cacho et al. 2006). Further, the larger the extent of the weed, the less likely it is that eradication will be feasible (Rejmanek & Pitcairn 2002). For these reasons, eradication is often prescribed but seldom achieved (Hester et al. 2004).

Further evidence that eradication is difficult to achieve comes from a review of DOC's weed-led programmes to 2005/06 (T. Belton and C. Howell, DOC, unpubl. data). Of the 134 weed-led programmes with the stated aim of eradication, only six had been successful (defined as no active control sites within the control area). Most were still active (128) and eight programmes had been discontinued.

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[1] Expressed in Harris et al. (2001) as a logistic growth function (r) greater than 0.3.

All but one of the six successful programmes had only one infestation site of 1 ha or less (the exception was a 3-ha site). Five of six successful eradication programmes were initiated within 2 years of the first discovery of the weed in the DOC Area Office area. In reality, many of these programmes were probably not true eradication programmes in the first place; rather, they were zero-density programmes. It is also acknowledged that a few of them were doomed to failure due to inadequate budget for the programme (K. Briden, DOC, pers. comm.).

When considering the third question—is elimination or eradication worthwhile—it might seem reasonable to also consider whether the plant in question may become a problem. A method for assessing the potential invasiveness of plants of conservation concern was developed by Williams & Newfield (2002) and tested by Williams et al. (2005). However, when a plant is at an early stage of invasion, often we do not know its potential for damage in the new area. This may explain why eradication is rarely even contemplated at an early stage, despite recommendations for prompt action (such as in DOC's surveillance plan) and regular finds of new naturalised plants. For example, 38 species were recorded as wild in New Zealand for the first time in 2003, but a year later none had been considered for eradication (C. Howell, DOC, pers. comm.).

As well as focussing on the weed species itself, Williams (1997) drew our attention to the future: what changes in the vegetation cover at the site could be expected in 5, 10 or 30 years if nothing was done? Does the impact of the weed on the conservation values of the site differ in each of these time frames? If weed control is conducted and is successful, what plants will replace the weed—native(s) or other weed species (e.g. Zavaleta et al. 2001)?

Making a decision in the absence of knowledge means that some decisions will, in hindsight, be proved wrong—some newly naturalised plants would never have become problems (type I and type II errors). We could delay control until we are certain; but by this time, if a species proves to be a problem, it will probably be too late for effective action.

Given the high costs of ongoing control and the damage large weed infestations cause to conservation values, it may be worthwhile to remove more newly naturalised plants than is strictly necessary to make sure we prevent the few that will become problems from becoming established. The question is, how many innocuous naturalised plant species is it worth removing for the sake of preventing one bad weed from getting away?

This report explores whether the removal of all newly naturalised plants at sites of conservation interest is worthwhile, regardless of their known or potential weed status.

2. Methods

We used two approaches to answer the research question. First, we used actual cost data for a range of weed control programmes to estimate the typical costs of managing a weed. Second, we used a matrix model to estimate weed spread under different scenarios. For cost calculations, the site includes both formally protected areas such as reserves, and adjacent land of any tenure that could provide a source of weed propagules to the conservation site.

2.1 COST DATA APPROACH

We collected data on 58 actual or proposed DOC weed control projects from five Area Offices. We interviewed staff from those offices and analysed their project budgets and accounting reports for 2003/2004. The cost data can be updated to reflect current costs by using the consumer price index inflation calculator on the Reserve Bank website (www.rbnz.govt.nz/statistics/0135595.html; viewed 28 November 2008). For example, between 2004 and 2008, the change in the value of money was 12.5%. Despite the change in the value of money, we expect the broad relativities between the costs to be sufficiently similar that conclusions drawn in this study will continue to be valid in the future.

Most projects involved control of a single weed species under a weed-led programme. Although many of these projects were (nominally) attempting eradication of the species; in reality, most were just removing it from a site or sites, as none of the weed-led projects included the cost of getting rid of cultivated plants in the vicinity—a prerequisite for eradication. In addition, a few site-led projects were included, where control was confined to a single weed or where control costs were documented for a single weed. These projects aimed only to remove the infestation from the site of interest and, perhaps, maintain zero-density of the weed there.

The dataset included projects at both extremes—the early removal of tiny infestations and large-scale weed control programmes. The latter represented infestations of weeds that were originally left uncontrolled, but later turned out to need controlling. The costs of these projects were compared, to determine the cost difference between early and late control.

Using historical data had the advantage that our study was based on real weeds and real invasions and thus included the vagaries of different types of invasion—such as rapid invasions (when conditions are ideal), and slower invasions. It also included examples where weeds had been established for some time before they were even detected.

2.1.1 Data limitations

There were some shortcomings in the actual data collected.

Some project budgets covered several weed species. As we could not separate out the costs for just one species, we omitted these projects from the analysis.

Some projects were under-costed. Materials or vehicles were drawn from a central pool, so their costs were not attributed to the project itself. Project overheads were also under-costed in some instances. For example, DOC uses staff time to calculate overheads, but many weed control projects used temporary staff with only a small amount of supervision, and often this supervision was not recorded against the project.

To accommodate these discrepancies, we derived a standard costing regime, based on the Area Offices involved in the study. We used a suite of their weed projects (Appendix 1), including each Area's core weeds project, to determine the average relationship between staff time and other expenses, and thus determine a standard cost for all items. So, where an item was omitted from the original project budget, but where the nature of the operation suggested that such a cost was likely to have been incurred, we used the standard cost as an estimate. For example, we allowed for annual surveillance (3 hours per site visit) for 10 years after weed control and added this to the total costs (where needed), and we used a standard estimate of overheads of 58% of staff salary time—an average based on the budgets used in the study. Overall, this gave us a more complete and accurate budget for each of the weed projects. For the purposes of using the standard costing, contractor and wage costs were treated interchangeably.

Another data difficulty was that future costs could only be (at best), informed guesses because of uncertainty about the effectiveness of control. However, since we know that searching for plants throughout the potentially affected area is often a big part of the future cost, these guesses may be quite adequate. Note that we took the search area to be just the vicinity of the weed infestation. This is current DOC practice for checking if an infestation at a site is eliminated, rather than the more extensive searching (e.g. across a whole catchment) that is required if eradication is the goal.

2.2 MODELLING APPROACH

In the approach above, which used actual cost data, we made the assumption that the same conditions that exist now will apply in the future. To allow for any change in conditions, we modelled weed spread under different scenarios of growth rate and dispersal, using a matrix model—a more sophisticated approach than used previously (Harris et al. 2001). The model assumed that a new infestation had established alongside a site of interest—perhaps a reserve or an area in the vicinity of a high-value site. The model infestation then spread in a semi-circular pattern from its establishment site.

The matrix model was set up with adjacent cells equal to dispersal distance. The model was based on a woody weed that spreads to adjacent cells within 3 years, i.e. a typical weed of conservation concern (an environmental weed; Howell 2008). The model started with a small (10 m^2) initial infestation[2] and spread to adjacent cells. The model did not explicitly allow for any subsequent invasions,

[2] In the real dataset, some infestations were much smaller than 10 m^2 and others much larger at the time of first discovery. Thus, 10 m^2 seemed a sensible size for an initial small infestation. As it happens, the size of the initial infestation proved to be less crucial than other factors in the ultimate cost of control.

but it was assumed that any similar small-scale invasion that established in the surveillance zone would be detected and controlled[3]. The model allowed for 10 years of surveillance after the initial invasion.

Plant density increased in each cell according to a theta (θ) logistic curve, where exponential growth is constrained by maximum density according to the formula:

$N_t = N_{(t-1)} + (N_{(t-1)} * r * (1 - (N_{(t-1)}/K)^{\theta})$

where N_t is the population size in year t, r is the population growth rate, θ is a shape parameter (set to 1) and K is the maximum population size, which we set at 0.4 (i.e. we assumed that the weed might occupy up to 40% of the area—the upper threshold of probable weed density). The maximum area that could be infested was set at 1000 ha.

The model did not allow for the establishment of separate foci of infestation and assumed semi-circular spread. Both these assumptions are simplistic, but do ensure that model results will be conservative.

We ran the model under different permutations of weed growth rate and dispersal distance. A previous study that used focus groups to estimate growth rates (*r* values) for environmental weeds obtained rates that ranged from moderate (0.4; e.g. willow *Salix* spp. in wetland) to fast (0.65; e.g. wandering Jew *Tradescantia fluminensis*), or even very fast (0.9; e.g. old man's beard *Clematis vitalba* in disturbed forest) (Harris et al. 2001). We assumed three different maximum dispersal distances for propagules: 20 m, 100 m and 500 m. Many bird- and wind-dispersed seeds fall within 100 m of the source or even within 20 m (Burrow 1994; Williams & Karl 1996, 2002; Bray et al. 1999; Stansbury 2001), and most propagules of any weed species, regardless of its dispersal mechanism, fall near the parent plant, within 4 m (P.A. Williams, Landcare Research, pers. comm.). Despite this, we did not allow for a dispersal distance less than 20 m, because the extra costs of control for even a 20-m dispersal event are already small. We recognise that a dispersal event of 100 m or 500 m may have a low probability (a 'fat-tailed dispersal kernal'; Shigesada & Kawasaki 1997), but the maximum dispersal distance is a measure of how far afield we might need to search for the weed. It is known that bird-dispersed Darwin's barberry (*Berberris darwinii*) has a maximum dispersal distance of 100 m from a parent plant (Allen & Lee 2001) and wind-dispersed lodgepole pine (*Pinus contorta*) can be dispersed up to 20 km (although more usually 1.2 km). Once such an event has occurred, the costs of searching escalate. Thus, the cost estimates are for the worst case scenario, giving us a precautionary result.

Having run the model, we calculated the weed control costs associated with the different permutations. We derived these costs using estimates for typical times taken for a weed infestation of known size to spread.

We were only able to use a subset of our dataset (ten projects) for this purpose because only the cases in the subset had accurate data on different combinations of weed density and areal extent of control, as well as the cost of the control. Where we had a range of costs, we used the most conservative estimate. We analysed the change in control costs at 5, 10, 20 and 40 years from establishment to predict the cost implications of delaying weed control, i.e. the wait-and-see approach.

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[3] Repeated arrival of a weed is likely if the plant species is widely cultivated in the vicinity.

3. Results

3.1 COST DATA

3.1.1 Cost components of weed control

Table 1 gives the average breakdown of costs for the weed control projects included in this study. While the value of money may change over time, we believe that the figures obtained clearly illustrate the relative importance of the cost components.

TABLE 1. AVERAGE COST BREAKDOWN FOR THE 28 DOC WEED CONTROL OPERATIONS LISTED IN APPENDIX 1.

ITEM	% OF TOTAL
Wages	36
Contractor	22
Salary	14
Herbicide and materials	12
Overheads	8
Machinery	4
Vehicle	2
Administration	2
Total	100

Labour was the biggest cost component—in the order of 65%–70% of total costs (assuming contractor costs were largely for labour)—because it included searching for the weed as well as direct weed control.

Materials—herbicide, protective equipment, disposables, and a variety of other operational materials—comprised (on average) just 12% of the total budget (although this proportion was significantly higher in some operations). Machinery costs were only 4% of the total budget. In part, this reflects the fact that few of the operations included in this study used helicopters. Vehicle costs, where itemised, were also low.

Overheads and administration averaged 10% of the total project costs. However, since temporary waged staff or contractors are often used to do the actual control work, this may be an underestimate.

3.1.2 Influences on the cost of control

We might assume that the number of sites a weed has invaded will strongly affect the cost of control. Where a weed has invaded several widely spaced locations, getting workers and equipment to each place will be expensive, particularly if sites are inaccessible and repeat visits are needed. Although our dataset did not include any examples of this sort of multi-location invasion, it did include projects where weeds were controlled in widely distributed, low-density patches (e.g. Russell lupins *Lupinus polyphyllus* in the Mackenzie Basin). In this instance, driving to small patches could take 30 minutes, with the actual control work taking just 2 hours, making travel time a significant proportion of total cost. However, it was more usual for control at a site to take one or more days. In this situation, the additional cost of driving to a new location was low, because workers tended to drive from base to the work site each day anyway. The same applied to helicopter costs, where costs were based largely on helicopter travel time from base to the control site. Consequently, the additional cost of controlling extra sites was small and not significant in the total cost of the operation.

Based on our data, the most important determinant of the total cost of control appeared to be the extent of the area to be searched for the weed, rather than the number of infestations to be controlled. (Note that although the DOC Surveillance Plan calls for wide searching—such as across a whole catchment—in practice, active searching is usually limited to the vicinity of the infestation or the area of interest—in places where the weed is most likely to be present.)

3.1.3 Costs of controlling small and large infestations

Within our entire dataset there were 11 projects dealing with tiny infestations—those which comprised just a few plants or covered small areas (up to 400 m^2). Control costs for these small weed infestations ranged from $750 to $1800, and averaged $1090 at net present value (NPV)[4]. Based on this (admittedly small) sample, early removal can apparently be achieved for a very low cost. These estimates could have been lower still had the weed been removed during surveillance.

From our dataset, we selected 35 projects to use for estimating the average cost of late weed control (listed in Appendix 2). The average cost for these in their first year was $23 000. The average total cost, at net present value of when control commenced, was $142 000 (Appendix 2).

Using the 35 late weed control projects and their time delay, we also calculated what the total control costs would have been in the dollar values at the time of discovery (Appendix 2). These data suggest that (on average) control would have cost $47 000 (expressed in the dollar value of the time when the infestation was first found). In other words, if a recently discovered plant is left, but later turns out to be a weed and is eventually controlled, the average cost of that control is equivalent to $47 000 in the dollar value of the time of first discovery.

Thus, eliminating a weed infestation at an early stage costs, on average, $1090 NPV, while delayed control costs $47 000 NPV. This means that if an infestation is a known weed that will need to be controlled at some stage, and the operation can be done now for less than $47 000, then the most economical choice is to get on with the control without delay. However, if we do not know whether the new plant is likely to be benign or a potential problem, we need to determine whether we should undertake control anyway. To date, nearly 15% of the plants naturalised in New Zealand have become environmental weeds (Table 2; Howell 2008). Therefore, if a plant is newly found in an area and we do not know whether it will be benign or a problem, we could assume there is at least a 15% probability that it will eventually prove to be a weed of conservation concern. Using our estimate that delayed control costs (on average) $47 000 NPV, if the new infestation can be removed now for less than $7000 (i.e. 15% of $47 000), there will be a net benefit from doing this.

[4] Net present value (NPV) compares the value of a dollar today to the value of that same dollar in the future, taking inflation and returns into account.

3.2 MODELLING

The cost of controlling a weed infestation will be influenced by the weed's growth rate and its dispersal ability. Table 3 gives the control costs modelled for different combinations of growth rate and dispersal. Our data suggest that a weed's ability to disperse is the more important of the two factors (growth rate and dispersal ability). If a weed is capable of distant dispersal, then the control costs will increase exponentially over time, even if the species has only a moderate growth rate, because searching a much larger area for new weed seedlings is expensive (see section 3.1.2). This cost will be even greater where searching is difficult, e.g. when the vegetation is dense or the weed is cryptic. The control costs in Table 3 were converted to estimated NPV using the ratios of ongoing control to initial control derived earlier (Appendix 2). The pattern of change in control costs over the first 20 years of invasion clearly illustrates that a weed's ability to disperse strongly affects the cost of its control (Fig. 1).

TABLE 2. NEW ZEALAND EXOTIC PLANT STATISTICS.

Number of introduced (Williams et al. 2002) and naturalised (Howell & Sawyer 2006) plant species, and number of environmental weeds (Howell 2008).

CATEGORY	NUMBER	PROPORTION INTRODUCED (%)	PROPORTION NATURALISED (%)
Introduced species	24 700		
Naturalised species	2390	10	
Environmental weeds	328	1	c. 15

TABLE 3. CONTROL COSTS ($, NET PRESENT VALUE) FOR MODEL WEEDS, ALL BEGINNING WITH AN INITIAL INFESTATION OF 10 m^2, BUT WITH DIFFERENT GROWTH RATES (r) AND DISPERSAL DISTANCES (m).

Time delay is the number of years between discovery and control commencing. Weed growth rates (r) are categorised as 0.1 = slow growing, 0.4 = a moderate rate of increase in biomass, 0.65 = a moderate to high growth rate, and 0.9 = rapid coverage of a new site. Dispersal distance is the maximum distance propagules could reasonably be expected to get to in a dispersal event. Control costs are given for the first year that control commences and includes the cost of both intensive grid searching to detect the weed and actual control.

TIME DELAY (years)	GROWTH RATE (r)	CONTROL COSTS FOR THREE MAXIMUM DISPERSAL DISTANCES (m)		
		20 m	100 m	500 m
3	0.4	$100	$1000	$28 000
	0.65	$100	$1000	$28 000
	0.9	$100	$1000	$28 000
6	0.4	$200	$2000	$95 000
	0.65	$200	$2000	$98 000
	0.9	$200	$4000	$100 000
10	0.4	$200	$8000	$200 000
	0.65	$200	$10 000	$240 000
	0.9	$300	$13 000	$316 000
20	0.4	$2000	$45 000	$1 021 000
	0.65	$9000	$205 000	$4 957 000
	0.9	$21 000	$500 000	$12 262 000

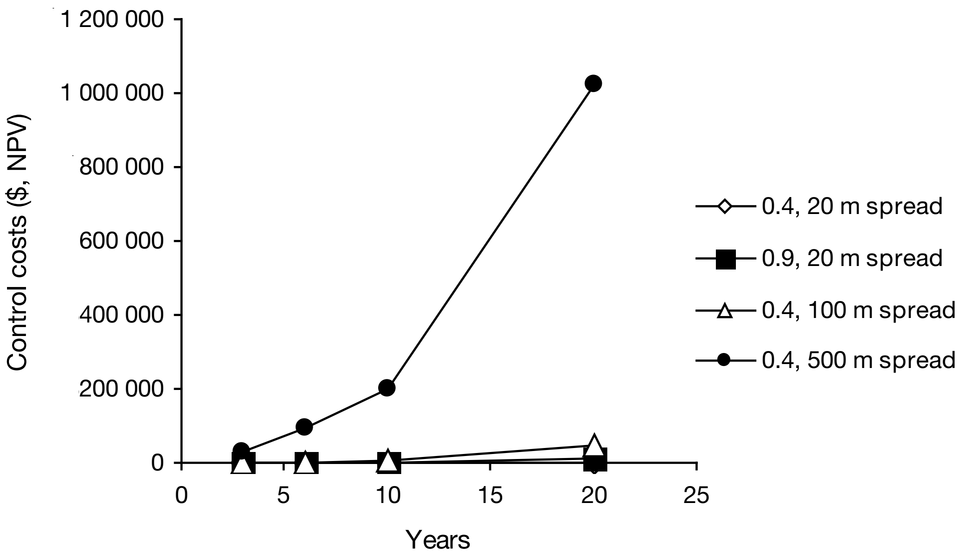

Figure 1. Changes in control costs ($, NPV) as a shrub infestation in short vegetation expands from a small (10 m^2) initial infestation at year 0. Expansion is projected for four combinations of growth rate (r = 0.4 or 0.9) and dispersal distance (20 m, 100 m or 500 m). Species with an r of 0.4 have a moderate growth rate and those with an r value of 0.9 have a rapid growth rate. To date, all weeds of conservation concern have r values of 0.4 or greater. Dispersal distance is the maximum distance propagules could reasonably be expected to travel in a dispersal event. *Note*: the plot of the first combination (r = 4, 20 m spread) is hidden behind the plots of the second and third combinations.

4. Discussion

The most important determinant of total control cost is the extent of the area to be searched for the weed, rather than the weed density or the number of infestations to be controlled. Thus, in long-running projects, control costs tend not to diminish much over time: there may be fewer weeds to kill (hopefully), but the whole area still has to be searched—a labour-intensive (and thus expensive) business. Similarly, if we decide not to remove an infestation, but to instead check the area regularly to see if the infestation is spreading, that searching can end up costing, over time, as much as it would have cost to remove the infestation in the first place. Using search theory, Cacho et al. (2006) also showed that increasing search effort reduces the duration of a weed control programme and improves the likelihood of its success.

Control costs for small weed infestations averaged $1090 at net present value. Based on our (admittedly small) sample, early removal (while the infestation is small) can apparently be achieved for a very low cost. These estimates could have been lower still had the weed been removed during surveillance. In contrast, delaying control inevitably means that the infestation will be larger and more costly to eliminate. We found that late control was (on average) 40 times more expensive than early control. Similarly, Harris et al. (2001) found that early elimination was preferable for any weed with an exponential growth function, i.e. with an r value of greater than 0.3 (and all of the environmental weeds assessed in their study had an r value greater than 0.4). Both of these studies provide quantitative support for a weed strategy which promotes early detection and elimination of new weeds through regular surveillance (e.g. Braithwaite 2000; Brown et al. 2004). This is the most cost-effective approach. Similarly, Morfe & Weiss (2007) demonstrated that controlling new and emerging weed species in a region gives a better return on government investment than control of weeds that already have a widespread distribution. Naylor (2000) also showed that broad prevention is cheaper than targeted cure; illustrating that, while delaying control of a species until its invasiveness is known may be cheaper in the short term, in the longer term it is far more costly than preventing the spread of a much larger number of species, even though many may never become problem weeds.

Clearly, it would be very useful if we could predict which newly naturalised plants are likely to become problem weeds. Although we have a weed risk assessment system for use in border control (e.g. Pheloung et al. 1999), predicting weeds of conservation concern can be difficult. Often, there is a long lag phase between a species naturalising and its recognition as a problem weed—this may be as much as 100 years for woody trees and shrubs (Kowarik 1995). This lag in a species behaving as a weed is often matched by a delay in people perceiving the species as a problem. This is compounded when species become weeds in New Zealand before they are known of as weeds elsewhere (e.g. Timmins & Reid 2000). Indeed, 20% of the exotic weedy species that have become naturalised in New Zealand since 1940 have no history of being weeds outside New Zealand (Williams et al. 2001). Many invaders flourish in high light, open environments in New Zealand, as they meet little competition from native plants, very few of which are early colonisers.

One of the most confounding factors in predicting the weed potential of naturalised plants is the role that people play. Human settlements, and the gardening behaviour of their residents (e.g. irresponsible dumping of garden waste; sharing of cuttings and seeds), increase the propagule pressure, and thereby the weed potential, of some plant species (Sullivan et al. 2004, 2005). Weed invasions stem from human decisions and risk perceptions (Perrings et al. 2002), meaning that the weed potential of particular species cannot be predicted solely on biological features (as used in classical weed risk assessments implemented as part of border control processes). Invasions are as much to do with chance and timing as some exotic species model (Kowarik 1995).

With this in mind, Williams & Newfield (2002) refined the border control model for use inside the border and, specifically, to assess the risk of a plant becoming an environmental weed. Their model took propagule pressure (gardening behaviour) into consideration. The model was tested using several weeds already invasive in New Zealand and proved to be a reasonable predictor of their weed potential (Williams et al. 2005). However, such predictions still rely on a good deal of information and technical expertise, which is often not available for a newly naturalised plant.

Our modelling suggests that if we leave a newly naturalised plant until we can assess its weed potential, we cannot rely on being able to catch it in time, i.e. before control costs have risen too dramatically (Fig. 1) to make control feasible. Also, just because a plant has not been a problem to date is no guarantee that it will continue to be well-behaved, especially if there is environmental change, e.g. as a result of fire, climatic events or human-induced disturbance. There are many examples of situations where quick action could have eliminated an invading plant, but where demands for more study before any action was taken meant that the plant went out of control (Simberloff 2003). Another aspect to this is public perception—government agencies are under pressure to do something about existing weed problems, never mind having to deal with new, as yet unrecognised, weeds (Morfe & Weiss 2007).

Even if only a few of the many plants which become naturalised eventually become weeds in areas of conservation interest, it is still be worth controlling all newly naturalised plants immediately (rather than waiting to see which ones spread) to ensure that we catch the bad few in time. In fact, even if the probability of a naturalised plant being a problem weed was as little as 2%, we could justify undertaking control without delay. This is because, once they get away, even moderately invasive weeds cost a lot of money to control.

However, we acknowledge that it can be all but impossible to detect a fast-growing weed early enough on difficult terrain. For example, moth plant (*Araujia sericifera*) was detected very early on Cuvier Island and an eradication programme started straight away. However, surveillance on the broken terrain is time-consuming—seven people working for 10 days can only comb about 10% of the island. Consequently, further mature moth plants have been found (and treated) every year for the past 5 years, and eradication has proved elusive. It is likely that this surveillance and control will have to occur indefinitely.

Some weed managers suggest that the best way to effect early removal is to practice 'armed surveillance'. This means that field staff are ready to remove any small infestation of a new exotic plant they encounter while searching (having first ensured that the species is an exotic plant, and not a threatened native plant). This approach improves the chances of newly naturalised species being found and controlled at an early stage of their spread. When a small infestation of a **known** weed is found, significant effort to remove the infestation is warranted, because to delay removal could cost $47 000 NPV or more. The figures from this study also suggest that control of larger infestations (where control may take up to several person days) is worthwhile, even when the plant's weed potential is unknown.

In calculating the cost effectiveness (cost threshold) for controlling newly naturalised plants of unknown weed potential, we used the probability of 15% for a naturalised plant becoming an environmental weed—equivalent to the whole of New Zealand figure. We recognise that there are several difficulties with this. First, this figure is likely to be a conservative estimate. To get a true estimate, we need to know the number of species that have **not** become problem weeds. We cannot know this before they become weeds, of course. We can only know the number of naturalised plants that have become problem weeds at any given time[5].

Second, the 15% statistic refers to the proportion of plants that have naturalised in New Zealand and become a problem weed somewhere in New Zealand. Thus, we do not know what the ratio between naturalisation and weed status is at a regional level, let alone at site level. It is quite likely that the probability will be

[5] The best estimate of an unknown plant becoming a weed is given by 1 – (number of species known not to be weedy/total number of introduced plants). However, we cannot know in advance the number of species that will NOT be weedy, we can only know the number of weeds that have proven to be weeds so far.

higher than 15% in some ecosystems and locations, and less in others. It could be argued that in order to know that a newly discovered naturalised plant is, indeed, a new find for an area, we would need an accurate naturalised plant list for that part of the country. However, at the site level, 'first find' could refer to the first time someone has considered control of the species at this site—a fact more likely to be known. A further complication is that the date of discovery is usually taken as a surrogate for the naturalisation date, but there is actually a mean lag of about 5 years between naturalisation and discovery (based on the 2436 taxa naturalised in New Zealand; Howell & Sawyer 2006). (Note that our matrix model was based on time of establishment, but real control activity can only begin after the infestation is discovered.)

The cost differential between early and late control is orders of magnitude. This means that we should not dally while we ascertain whether a newly discovered naturalised plant is a problem weed or not. Since early control is relatively cheap, and the costs of delaying control are so high, it is better to remove any new plant that has a limited distribution, even when its weed potential is unknown.

That said, we acknowledge that if the site is re-invaded, the removal would have to be repeated. We have allowed for this on a small scale in the model by including 10 years of follow-up surveillance. However, if the cycle of invasion/removal occurs repeatedly, or the establishing infestations are substantially larger than 10 m^2, or there is an invasion in a second site, then a manager may need to re-assess whether it is appropriate to keep going with the removal approach. The first action would be to look more widely for other infestations. If multiple incursions are found, then the weed would no longer qualify as a new, early incursion.

We reported above that it is worthwhile to eliminate a new infestation of a plant of unknown weed potential from a site of conservation interest if it can be done for less than $7000. This could well be an underestimate of the cost threshold, because our data did not include the full spectrum of control projects. Most of the projects we used in our model were relatively small-scale, with just a few large control projects. We also necessarily omitted those projects that DOC does not attempt because they are beyond the DOC weed budget ($14 m per year in 2007; K. Briden, DOC, pers. comm.). In some instances, the infestation may be too large, widespread and costly for practical control; in others, the site may have some conservation value, but not enough to secure control funds. Finally, our analysis focused only on financial costs and ignored the damage weeds wreak on native ecosystems, specifically on biodiversity values, ecosystem services and economic activities (Naylor 2000). As Williams & Timmins (2002) concluded, the true economic cost of environmental weeds is enormous. This valuation of the full costs of weed invasions and their control was explored by Perrings et al. (2005). Had our analysis included these other costs, a much higher maximum cost than $7000 could be justified for removing plants of unknown weed potential.

5. Conclusions

Where it is feasible, early eradication is touted as the best weed management strategy. However, although it is widely believed that eradication is possible, the evidence suggests otherwise. In the past, and at present, most new naturalisations come from widely cultivated plants, and this is likely to continue into the future. The wide cultivation of many potential weeds makes eradication of a species from the wild unlikely, as the cultivated plants will provide an ongoing supply of new material.

Thus, this paper assessed the benefit of early removal of newly naturalised plants at conservation sites. For known problem weeds, we found the average cost of very early removal versus late control gives a benefit to cost ratio of 40 (i.e. late control is 40 times more expensive than early control). We also showed that, even when we do not know the weed potential of a newly naturalised plant, control is still worthwhile if it can be achieved for less than $7000 NPV, and success is more likely if the infestation is discovered early.

A wait-and-see approach—watching a new infestation to see if it turns out to be a problem weed—is a high-risk approach, even where excellent monitoring and follow-up systems are in place. This is because a single, distant dispersal event, even for a weed that is only moderately invasive, can significantly increase the costs of control, as searching for individual plants is usually labour intensive and, thus, expensive. Therefore, such an approach should only be considered where searching for outliers can be done inexpensively and reliably.

Where possible, the best approach is early removal of all newly naturalised plant infestations in areas of conservation interest. The benefits of catching bad weeds early compensates for also controlling a handful of plants that will never cause problems. Although we did not calculate the cost of implementing this approach in this study, the apparent cost differential between early and late control is so large that the obvious conclusion is that land management agencies should put even more emphasis on early control work.

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Appendix 1

BREAKDOWN OF THE OPERATIONAL COSTS OF THE 28 DOC WEED CONTROL PROJECTS USED FOR DEVELOPING THE STANDARD COST ESTIMATES

DOC AREA OFFICE	PROJECT NAME	COSTS ASSOCIATED WITH WEED CONTROL BY COST COMPONENT ($)								
		WAGES	CONTRACTOR	SALARY	HERBICIDE AND MATERIALS	OVERHEADS	MACHINERY	VEHICLE	ADMINISTRATION	TOTAL
Auckland	Invasive weeds	32 366	19 588	27 554	3552	15 981		1800	52	100 893
	Tiritiri Matangi	26 666			2930	0		547	30	30 173
	Motutapu biodiversity	56 248		262	10 658	152		2697	7517	77 534
	Rangitoto	48 856		6061	2053	3515		1103	1854	61 389
	Motutapu invasive weeds	20 551	63 560	2537	15 500	1471				103 620
	North Head	0	24 461		7290	0				31 751
	Auckland Mainland weeds			2136	527	1239	74		372	4349
	Motuihe	2610			350	0				2960
	Motutapu restoration	9307			4031	0			284	13 622
Hauraki	Endangered flora	1772				0				1772
	Mt Moehu weeds	23 720	0	3985	1010	2311		7729	1502	40 257
	Celastrus Tairua	1770			4374	0	1235	0		7379
	Boxthorn, Mercury Is	5259	700	7241	2300	4200		1084	562	21 346
	Brown's Island	817	9945			0				10 762
Buller	Old man's beard, Buller	0	2208	3480	1281	27 625		36		34 630
	Old man's beard, Karamea	710		380	1233	220				2543
Hokitika	Parrot's feather	234		533	2751	309				3827
	West Coast core weeds	219	11 032	23 087	5707	13 390			164	53 599
	Spiraea japonica	1176	3200	2033	1819	1179			338	9745
South Westland	Lower Moeraki multiple	1665	10 150			0				11 815
Raukapuka	Geraldine core weeds			7927	3957	4598	1170			17 652
	Russell lupin, Forbes River		1760		1351	0			260	3371

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Appendix 2—continued

DOC AREA OFFICE	PROJECT NAME	COSTS ASSOCIATED WITH WEED CONTROL BY COST COMPONENT ($)								
		WAGES	CONTRACTOR	SALARY	HERBICIDE AND MATERIALS	OVERHEADS	MACHINERY	VEHICLE	ADMINISTRATION	TOTAL
Mahaanui	Kaitorete restoration	2248	4247	6709	2714	3891		41	694	20 544
	Pingao, Kaitorete	2450			48	0				2498
	Spartina, Lyttelton	1858		395	1017	229	1161		519	5179
	Marram grass, Kaitorete	151	6735		83	0			300	7269
	Purple loosestrife	9045		3021	9138	1752		173	668	23 797
Total		**249 698**	**155 378**	**96 069**	**85 820**	**55 720**	**31 265**	**15 174**	**15 153**	**704 277**
Average		**10 856**	**11 952**	**6004**	**3731**	**2064**	**6253**	**1686**	**947**	**26 084**
Proportion total costs (%)		**35**	**22**	**14**	**12**	**8**	**4**	**2**	**2**	**100**

Appendix 2

ACTUAL CASHFLOW DATA FOR THE 35 DOC WEED CONTROL OPERATIONS USED IN THE ANALYSES OF DELAYED AND LATE CONTROL

WEED	SCIENTIFIC NAME	DOC AREA OFFICE	SITE NAME	TIME[a] DELAY (YEARS)	TOTAL COST OF CONTROL (DISCOUNTED FOR DELAY)[b]	TOTAL COST OF CONTROL (NPV)[c]	YEAR 1 (YEAR CONTROL STARTED)[d]	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7–10	YEAR 11[f]
Asiatic knotweed	*Reynoutria japonica*	Hokitika	Hokitika	8	$9861	$17 623	$3169	$3169	$3169	$3169	$3169	$1584	$1584	$0
Banana passionfruit	*Passiflora* sp.	Hokitika	Ross	2	$700	$809	$69	$122	$122	$122	$122	$122	$122	$0
Banana passionfruit	*Passiflora* sp.	Raukapuka	Talbot	8	$577	$1031	$306	$122	$122	$122	$122	$122	$122	$0
Boneseed	*Chrysanthemoides monilifera* subsp. *monilifera*	Waikato	Raglan township	20	$39 112	$80 812	$17 250	$17 250	$17 250	$17 250	$17 250	$3450	$3450	$0
Boxthorn	*Lycium ferocissimum*	Hauraki	Mercury Islands	20	$48 399	$100 002	$21 346	$21 346	$21 346	$21 346	$21 346	$4269	$4269	$0
Cathedral bells	*Cobaea scandens*	Buller	Karamea	8	$7887	$14 095	$3209	$3209	$1590	$1590	$1590	$1590	$1590	$0
Chilean rhubarb	*Gunnera tinctoria*	Franz Josef Waiau	Franz Josef	8	$8621	$15 406	$3000	$3000	$3000	$3000	$3000	$1500	$1500	$122
Chocolate vine	*Akebia quinata*	Waikato	Roadside	15	$7721	$11 099	$11 079	$122	$122	$122	$122	$122	$122	$0
Climbing asparagus	*Asparagus* scandens	Hauraki	Little Barrier	20	$226 916	$468 851	$62 185	$62 185	$62 185	$62 185	$62 185	$62 185	$62 185	$31 093
Climbing spindleberry	*Celastrus* scandens	Hauraki	Tairua	9	$15 330	$29 457	$8060	$8060	$8060	$4030	$4030	$806	$806	$0

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Appendix 2—continued

WEED	SCIENTIFIC NAME	DOC AREA OFFICE	SITE NAME	TIME[a] DELAY (YEARS)	TOTAL COST OF CONTROL (DISCOUNTED FOR DELAY)[b]	TOTAL COST OF CONTROL (NPV)[c]	YEAR 1 (YEAR CONTROL STARTED)[d]	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7–10	YEAR 11[f]
Crack willow	*Salix fragilis*	Waikato	Whanga-marino	94	$91	$40 530	$13 000	$13 000	$10 500	$10 500	$122	$122	$122	$0
Darwin's barberry	*Berberis darwinii*	Grey-mouth	Waimea	20	$12 119	$25 041	$8597	$4299	$4299	$4299	$1719	$1719	$1719	$122
Elaeagnus	*Elaeagnus x reflexa*	Hokitika	Hokitika	10	$29 936	$29 936	$4262	$4262	$4262	$4262	$4262	$4262	$4262	$0
Evergreen buckthorn	*Rhamnus alaternus*	Auckland	Rangitoto	30	$496 306	$2 118 803	$200 000	$200 000	$200 000	$200 000	$200 000	$200 000	$200 000	$200 000
Tiritiri weed[g]		Auckland	Tiritiri Matangi	33	$63 089	$334 845	$45 808	$30 233	$30 233	$30 233	$30 233	$30 233	$30 233	$30 233
False tamarix tamarix	*Myricaria germanica*	Waimaka-riri	Waimaka-riri	20	$148 482	$306 792	$65 609	$65 609	$65 609	$32 804	$32 804	$32 804	$13 122	$13 122
Heather	*Calluna vulgaris*	Twizel	Mt Cook	13	$42 578	$52 934	$11 206	$11 206	$11 206	$11 206	$11 206	$2241	$2241	$122
Japanese spiraea	*Spiraea japonica*	Hokitika	Hokitika	20	$8554	$17 675	$9789	$2500	$2500	$2500	$2500	$122	$122	$122
Kahili ginger	*Hedychium gardnerianum*	Buller	Buller	25	$109 542	$325 339	$99 225	$99 225	$49 612	$49 612	$49 612	$4961	$4961	$4961
Kahili ginger	*Hedychium gardnerianum*	Greymouth	Greymouth	25	$18 505	$54 961	$8630	$7630	$7630	$7630	$7630	$7630	$7630	$122
Marram grass	*Ammophila arenaria*	Mahaanui	Kaitorete	23	$27 196	$69 860	$9884	$9884	$9884	$9884	$9884	$9884	$9884	$122
Moth plant	*Araujia sericifera*	Hauraki	Cuvier I	13	$168 429	$209 396	$54 253	$54 253	$27 127	$27 127	$27 127	$27 127	$13 563	$122
Old man's beard	*Clematis vitalba*	Buller	Karamea	20	$9840	$20 331	$2560	$2560	$2560	$2560	$2560	$2560	$2560	$2560
Old man's beard	*Clematis vitalba*	Buller	Buller Gorge	35	$39 761	$243 994	$34 677	$34 677	$34 677	$34 677	$34 677	$34 677	$34 677	$122
Old man's beard	*Clematis vitalba*	Greymouth	Greymouth	20	$17 794	$36 766	$6449	$6449	$4730	$4730	$4730	$4730	$4730	$122

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Appendix 2—continued

WEED	SCIENTIFIC NAME	DOC AREA OFFICE	SITE NAME	TIME[a] DELAY (YEARS)	TOTAL COST OF CONTROL (DISCOUNTED FOR DELAY)[b]	TOTAL COST OF CONTROL (NPV)[c]	YEAR 1 (YEAR CONTROL STARTED)[d]	YEAR 2	YEAR 3	YEAR 4	YEAR 5	YEAR 6	YEAR 7–10	YEAR 11[f]
Parrot's feather feather	*Myriophyllum aquaticum*	Hokitika	Hokitika farm	20	$4936	$10 198	$3850	$3000	$1500	$1500	$385	$385	$385	$122
Purple loosestrife	*Lythrum salicaria*	Mahaanui	Mahaanui	10	$23 043	$23 043	$23 797	$122	$122	$122	$122	$122	$122	$122
Russell lupin	*Lupinus polyphyllus*	Rauka-puka	Forbes River	30	$4493	$19 179	$4039	$4039	$4039	$4039	$4039	$808	$808	$122
Russell lupin	*Lupinus polyphyllus*	Rauka-puka	Rauka-puka rivers	30	$2627	$11 214	$4048	$2024	$2024	$2024	$2024	$405	$202	$122
Russell lupin	*Lupinus polyphyllus*	Rauka-puka	Ashburton lakes	30	$1557	$6647	$1228	$1228	$1228	$1228	$614	$614	$614	$122
Spartina	*Spartina*	Hauraki	Coromandel	22	$9518	$22 737	$4623	$4623	$4623	$2311	$2311	$2311	$2311	$122
Spartina	*Spartina*	Mahaanui	Lyttelton	14	$34 557	$46 196	$7781	$7781	$7781	$7781	$5188	$5188	$5188	$3000
Tree lupin	*Lupinus arboreus*	Twizel	MacKenzie Basin	50	$7173	$130 738	$24 440	$24 440	$24 440	$24 440	$24 440	$24 440	$2444	$2444
Wandering Jew	*Tradescantia fluminensis*	South Westland	South Westland	40	$7485	$66 025	$14 000	$14 000	$14 000	$14 000	$14 000	$2800	$2800	$122
Wildings	*Pinus* spp	Raukapuka	Cameron	50	$303	$5520	$3102	$0	$0	$0	$1551	$0	$0	$0
Average					**$47 000**	**$142 000**	**$23 000**							

[a] Years between discovery of weed infestation and control commencing.
[b] The total cost of the control programme, expressed in the dollars of the year that the weed was first reported at the site.
[c] Total cost of the control programme, expressed in dollars of the year the weed control started, assuming a discount value of 7%.
[d] The year control started in the particular weed control programme.
[e] The cost per year for each of the years 7–10, where relevant. Combined into one column for brevity.
[f] Surveillance costs were extended out to 10 years—$122/year was added where needed.
[g] A range of weeds are controlled on Tiritiri Matangi. The cost of control is similar for each, because all are at low density meaning that most of the cost in the searching.