Weed surveillance—how often to search?

SCIENCE FOR CONSERVATION 175

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Published by
Department of Conservation
P.O. Box 10-420
Wellington, New Zealand

Science for Conservation presents the results of investigations by DOC staff, and by contracted science providers outside the Department of Conservation. Publications in this series are internally and externally peer reviewed.

This report was prepared for publication by Science Publications, Science & Research Unit; editing and layout by Lynette Clelland. Publication was approved by the Manager, Science & Research Unit, Science Technology and Information Services, Department of Conservation, Wellington.

ISSN 1173-2946
ISBN 0-478-22029-4

Cataloguing-in-Publication data
Harris, Simon
Weed surveillance : how often to search? / Simon Harris, Jennifer Brown, Susan Timmins. Wellington, N.Z. : Dept. of Conservation, 2001.
1 v. ; 30 cm. (Science for conservation, 1173-2946 ; 175)
Includes bibliographical references.
ISBN 0478220294
1. Weeds—Management. 2. Weeds—Control. I. Brown, Jennifer II. TImmins, Susan M. (Susan May), 1957- III. Title. Series: Science for conservation (Wellington, N.Z.) ; 175.

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ABSTRACT

Weed control experience indicates that it is best to find weed incursions early to minimise control costs and prevent ecological damage. But how frequently must particular sites be revisited to ensure that new weed invasions are caught early enough? This report provides guidance on the appropriate time intervals for active weed surveillance. The suggested intervals allow for new weed incursions to be found while they can still be readily eradicated or contained and before the weeds have caused irreparable damage to the invaded habitat. A model was used to generate surveillance intervals. The model considered several factors: our ability to find a new weed incursion, the rate of spread of different weeds, and the costs of their control. The results of this study suggest that there is a significant net benefit in detecting and controlling even moderately invasive weeds at an early stage.

Keywords: weed surveillance, search frequency, eradication, weed control, public involvement, weed awareness, environmental weeds.

Harris, S.; Brown, J.; Timmins, S. 2001: Weed surveillance—how often to search? *Science for Conservation 175*. 27 p.

1. Background

1.1 INTRODUCTION

The Department of Conservation (DOC) has developed a weed surveillance system to facilitate the early detection and control of new invasive weeds (Braithwaite 1999; Braithwaite 2000). Weed surveillance is defined as the searching for, and documenting of new incursions of weeds of conservation concern, i.e. those that are new to an area or are of limited distribution. The aim is to detect new invasive weeds at a stage when eradication or containment is still possible. This minimises both the cost of control and the impacts of invasive weeds on conservation values (Braithwaite 2000).

Surveillance may be active, involving systematic checking of an area for new incursions (**active** surveillance). Alternatively, people engaged in other activities may notice new incursions (**fortuitous** surveillance). Weed surveillance must include both valuable sites and vulnerable sites. **Valuable** sites are those with high conservation values, particularly those places which are relatively weed-free. **Vulnerable** sites are those where weed invasion is most likely to occur, such as road and railway margins, rubbish dumps, places with low or disturbed vegetation, and other places modified by human activities. Surveillance of valuable places will protect sites of high conservation value; surveillance of vulnerable places will prevent weeds entering and spreading in a new geographic area (Braithwaite 2000).

It is widely recognised that it is best to find weed incursions early (Williams 1997). But how frequently must we revisit a particular site to ensure we catch a new weed invasion early enough, i.e. to minimise control costs and ecological damage? Further, at what surveillance frequency does the cost of searching exceed the cost savings of finding the weed early? This report gives guidance on how often a site should be visited to search for weeds to ensure that any new weed incursions are found and controlled **before** they are of a scale that requires a formal control programme. (For definitions, and a discussion of DOC's strategic approach to weed control, see Owen 1998).

Section 1 of this report explains the economic justification for surveillance and briefly outlines the model used to estimate appropriate surveillance intervals. Section 2 gives recommendations on surveillance intervals for a set of general habitat types and weed growth forms. This section also includes a guide for DOC managers on how to select the appropriate surveillance interval for their particular situation. Section 3 describes the development of the model and its assumptions. Section 4 discusses the results of the modeling exercise in different habitat types and how to use the surveillance intervals, plus some caveats to its use.

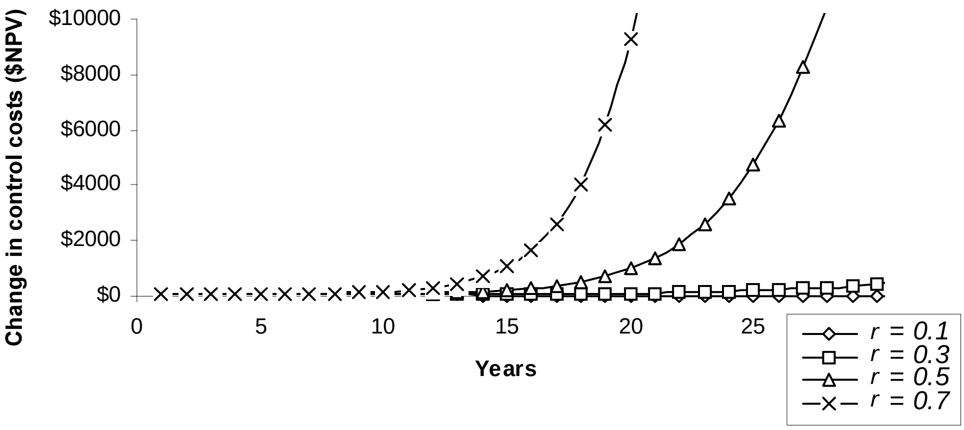
1.2 FINANCIAL BENEFIT OF WEED SURVEILLANCE

Within DOC, the Weed Surveillance Standard Operating Procedures (SOP) (Braithwaite 1999) are based on the premise that early detection of weeds delivers a net benefit to conservation. They assume that the cost of the surveillance activity itself is more than compensated for by cheaper control costs. To determine the accuracy of this assumption we did a simple cost analysis of early versus late control. The cost of finding and controlling a new weed incursion early was weighed against the cost of control at a later stage. We projected the increasing areal extent of a weed at a site, and concomitant increasing control costs, and found the difference in control costs over time.

We used the net present value (NPV) approach so that the relative financial attractiveness of early control could be compared with delayed control. In this approach, all costs are expressed in today's terms and the differing value of money over time is allowed for using a discount rate. A discount rate of 10% was used—this is the rate currently used in the government sector to evaluate projects of this nature. Four different rates of increase in biomass cover were used in the model, expressed as differing *r* values. A low *r* value (0.1) meant a low rate of increase in biomass. The highest *r* value of 0.7 describes weeds such as Japanese honeysuckle in shrubland or gorse in a riverbed which quickly spread to cover a new site. In fact most, if not all, of the species currently listed as weeds of conservation concern (Owen 1997) have rates of growth and spread high enough to conform to an *r* value of 0.4 or greater.

By way of example, Fig. 1 shows how the costs of controlling a shrub infestation in short vegetation varies over time depending on the rate of increase in weed biomass. Each of the projected curves shows a lag period (period of minimal increase) in control costs that varies between 13 and 30+ years depending on the rate of increase in weed biomass. All the curves rise steeply when other forms of control (i.e. other than manual) become necessary.

Figure 1. Changes in control costs ($, net present value) with expansion of a shrub infestation in short vegetation from establishment at year 0, projected at four different rates of biomass increase (*r*).



Notes:
The dollar values used in these curves are the Net Present Value (NPV) of control costs, with the costs standardised to the present day using a discount rate of 10%. The *r* value represents differing rates of growth and spread of the weed (weed biomass). An *r* value of 0.1 represents weed species that are very slow to spread and 0.7 represents moderate to highly invasive species; all weed species considered in this study had an *r* value of 0.4 or greater.

The graph shows that for very low rates of growth (circa r = 0.1), early detection and control offers very little cost advantage; the fixed costs and the discount rate nullify any extra costs arising over time from an increase in the area that requires weed control. However, as soon as the value for r rises above 0.3, as is the case for all weeds DOC currently controls, there is a considerable saving in controlling the weed early. In other words, weeds of conservation concern spread faster than the change in the value of money over time. This holds true at any scale—particular site, a large region or the whole country—it is always cheaper to control early rather than later, at least in present value terms.

Missing the opportunity for early control of even moderately invasive weed species means costs will increase exponentially, both the nominal (unadjusted) costs as well as the costs expressed in net present value terms. In fact, the nominal costs of control rise even more rapidly than the costs in net present value terms. This means there is a **significant** benefit in detecting and controlling weeds early. Furthermore, in addition to increasing financial costs over time there is likely to be an increase in damage to conservation values as weeds spread.

1.3 MODEL TO ESTIMATE SURVEILLANCE INTERVALS

On the basis that surveillance is financially beneficial, a model was developed to determine appropriate surveillance intervals. Ideally, it needed to cope with the several factors that impinge on the weediness of a site and the urgency of detecting new weed incursions. The rate of arrival of weeds at a site varies with the proximity of the site to roads, towns and adjoining land use (Newell et al. 2000; Timmins & Williams 1991). Once a weed has arrived, its rate of spread depends on the properties of both the weed species and the vegetation type being invaded. The visibility of the weed, and hence the probability of finding it, varies with growth stage, growth form and the location of the infestation. The cost of controlling a particular weed incursion also influences the appropriate surveillance interval.

We took the precautionary approach of assuming that weeds **will** arrive at a particular site. Given that a weed has arrived, the model determines what surveillance interval would be needed to find it before it reaches a specified threshold cost of control at the site. The model is simple and assumes that as the weed occupies more of a site the infestation becomes more expensive to control. This assumption is supported by the work referred to above. A recent case study on projected future costs of wilding pines in Twizel (Theo Stephens, Northern Regional Office, DOC, unpubl. data) also confirms the assumption. The model chooses the longest surveillance interval that meets the required probability of finding a weed.

1.3.1 Factors included in the model

The model uses several variables and processes, briefly mentioned here and described in more detail in Section 2. The rate at which a weed species infests and spreads at a new site is a function of the weed's arrival rate at the site, the habitat type, the weed's growth form, and its inherent biological capacity for growth and spread. Five broad habitat types were used: forest, shrubland, short vegetation, wetland, and open habitat. For each habitat, the weed growth forms most likely to be of concern in that habitat were assessed (e.g. vine, shade-tolerant shrub, over-topping tree).

Our ability to find a particular weed is a function of its visibility and our search effort, experience and method. Weeds differ in their visibility—by species and through time. The range of growth forms used in the model accommodated this range in visibility. The longer the search effort at a site, the greater the chance of finding a weed. The larger the area to be searched the more time needed to complete the search. The model assumes a standard search effort of two hours per 10 ha of site. This was based on the experiences of field workers doing DOC weed inventory work—a systematic survey developed to record the exotic plant species present in the high priority protected natural areas in DOC Conservancies (the search effort information was provided at a DOC workshop; see Acknowledgements).

Both the expected costs of control and the maximum cost thresholds are important. Some weeds are easy to control; others—such as those requiring hand clearance of tubers—are more expensive. The model recommends surveillance intervals that enable weeds to be located when the cost of control can still be readily accommodated. It assumes a DOC Area Office—the local administrative unit of DOC—can absorb costs up to a $500 threshold. Reprioritising other work in the Area Office can accommodate costs from $500 to $5000. These do not include follow-up costs in subsequent years to ensure local eradication. Typically, a weed's invasion or occupation of an area follows a sigmoid curve. There is a long 'lag phase' in which the weed has a limited occupation of a site (or region or country). This is followed by a rapid expansion phase and, finally, a tapering off as the weed's occupancy plateaus out (see Fig. 2, p. 16). In practical terms the initial threshold of $500 appears to closely approximate the cost of controlling a weed as it emerges from its lag phase, and the cost threshold of $5000 occurs as the weed starts to expand rapidly (see Fig. 1).

2. Recommended surveillance intervals

The following guidelines are intended to assist managers in choosing surveillance intervals at particular sites.

2.1 GENERAL RECOMMENDATIONS

The surveillance interval ranges for each of five broad habitat types are given in Table 1. These general recommendations apply where there are no unusual features in the sites to be searched and when no specific weeds are expected. They apply throughout New Zealand. Surveillance interval refers to the number of years before the search should be repeated. The shorter interval provides for an 80% certainty of finding the worst weed below the control cost threshold of $500. The longer interval gives an 80% certainty of finding most weeds before the $5000 control cost threshold.

TABLE 1. RECOMMENDED RANGE IN FREQUENCY OF WEED SURVEILLANCE GIVEN IN NUMBER OF YEARS BETWEEN SEARCHES (INTERVAL) FOR EACH OF FIVE BROAD HABITAT TYPES AT 80% CERTAINTY OF FINDING A WEED IF IT IS PRESENT.

HABITAT TYPE	SURVEILLANCE INTERVAL
Forest	1–2 years
Shrubland	1–9 years
Short vegetation	5–10 years
Wetland	5–10 years
Open habitat	1–4 years

Notes:

1. **Habitat types** Forest, both warm and cold temperate, includes disturbed and regenerating forest and forest edge. Shrubland, both induced and natural shrubland, includes subalpine, coastal, disturbed and regenerating shrubland. Short vegetation includes induced and natural tussock grasslands, herbfields, and other low vegetation types. Wetland includes freshwater and estuarine, semi-permanent and permanently wet vegetation but does not include aquatic habitats. Open habitat includes riverbeds and sand dunes.
2. **Surveillance interval** Refers to the gap in years between active searches. Thus a 2-year surveillance interval suggests searching in year 1 and then again in year 3.

2.2 SPECIFIC RECOMMENDATIONS

More specific surveillance interval recommendations, by growth form for each of the five habitats and at different levels of detection certainty, are given in Table 2. In developing the model that generated these recommendations we assumed:

- A search intensity of two hours per 10 ha.
- Standard costs of control for each habitat type and growth form (as given in Table 3).
- Standard distances at which different types of weeds are visible in the five general habitat types (as given in Table 4).

TABLE 2. RECOMMENDED FREQUENCY OF WEED SURVEILLANCE GIVEN IN NUMBER OF YEARS BETWEEN SEARCHES (INTERVAL) BY BROAD HABITAT TYPE FOR DIFFERENT WEED GROWTH FORMS WITH TWO DIFFERENT PROBABILITIES OF FINDING A NEW WEED INCURSION IF IT IS PRESENT (80% OR 95% CERTAINTY) BEFORE A COST THRESHOLD IS REACHED ($500, $5000).

HABITAT TYPE[1]	WEED GROWTH FORM[2]	SURVEILLANCE INTERVAL (YEARS) 80% CERTAINTY		SURVEILLANCE INTERVAL (YEARS) 95% CERTAINTY	
		$500 COST THRESHOLD	$5000 COST THRESHOLD	$500 COST THRESHOLD	$5000 COST THRESHOLD
Forest	Climbing vine	1	3	<1[3]	1
	Ground creeper	3	7	1	4
	Shade-tolerant shrub or tree	6	10	3	6
Shrubland	Vine	1	9	1	5
	Tree or tall shrub	2	9	1	5
Short vegetation	Short weed	2	5	1	3
	Shrub or tree	5	10	3	6
Wetland	Short weed	3	7	1	4
	Shrub	10	10	6	10
	Tree	10	10	10	10
Open habitat	Short weed	1	6	1	3
	Taller weed	4	9	2	5

Notes:

1. **Habitat types** See Table 1.
2. **Weed growth form** Forest: climbing vine, one that reaches the canopy e.g. old man's beard; ground creeper e.g. wandering Jew; shade-tolerant shrub or tree, e.g. Darwin's barberry. Shrubland: vine, e.g. Japanese honeysuckle; tree or tall shrub, e.g. privet, bone-seed. Short vegetation: short weed, e.g. hawkweed; shrub or tree, e.g. broom, wilding pine. Wetland: short weed, e.g. introduced sedge or grass; shrub, e.g. broom; tree, e.g. willow. Open habitat: short weed, e.g. Russell lupin in riverbeds; taller weed, e.g. shrub or tree.
3. The <1 year surveillance interval given in this table is an artifact of the model. The workshop group felt that surveillance at a greater frequency than annually was unlikely to improve the chances of detection. Rather, it is probably better to increase the search effort at a site.

To select the most appropriate surveillance interval for your site or situation, use the following steps:

1. Select the level of certainty of finding an infestation, if it is present, that you need to achieve on the basis of the conservation value of the site. For the most valuable sites select a 95% certainty. For all other sites use the 80% certainty. (Use the biodiversity scoring system given in Appendix 5 of Owen (1998) to assess the value of a site).
2. Choose the habitat category listed in Table 2 that most closely matches your site.
3. Determine whether any specific weeds are likely; select the weed growth form that most closely matches the expected weed. If no weed threats are known or more likely, choose the general weed growth form with the highest surveillance frequency for your habitat in Table 2.
4. Decide whether it is important to find the weed below the $500 or the $5000 threshold. Financial considerations in the Area Office and the conservation value of the site will influence this decision.

TABLE 3. COSTS OF CONTROL FOR DIFFERENT WEED GROWTH FORMS IN DIFFERENT HABITATS.

HABITAT TYPE	WEED GROWTH FORM	MANUAL CONTROL FIXED COSTS	COST OF MANUAL CONTROL OF 5 ha SITE WITH 5% WEED COVER	MECHANICAL CONTROL FIXED COSTS	COST OF MECHANICAL CONTROL OF 20 ha SITE WITH 50% WEED COVER
Forest	Climbing vine	$80	$4000	?	?
	Ground creeper	$80	$1250	NA	NA
	Shade-tolerant shrub or tree	$80	$600	NA	NA
Shrubland	Vine	$80	$1250	$1200 (helicopter)	$5000
	Tree or tall shrub	$80	$800	$1200 (helicopter)	$5000
Short vegetation	Short weed	$80	$625	?	?
	Shrub or tree	$80	$600	$1200 (helicopter)	$5000
Wetland	Short weed	$80	$600	NA	NA
	Shrub	$80	$600	$1200 (helicopter)	$5000
	Tree	$80	$600	$300 (digger)	$25 000
Open habitat	Short weed	$80	$600	$1200 (helicopter)	$5000
	Taller weed	$80	$800	$300 (digger)	$15 000

Notes:
For explanation of terms used in habitat type and weed growth form, see notes associated with Tables 1 and 2. In the mechanical costs column, ? = data not available, NA = mechanical control not usually applicable. Manual control includes grubbing and knapsack spraying. Fixed costs are the one-off costs that could be expected with this sort of control operation before any control actually happens, e.g. to get people to the site and, in the case of mechanical costs, to get the helicopter or other machinery on site. The costs used are the average costs associated with controlling a 5 ha site that has 5% coverage of the worst weed in this category. Mechanical control refers to any control that uses machinery such as diggers and helicopters (with or without chemicals). The costs are those associated with controlling a 20 ha site which has 50% weed coverage. If your site is smaller (or larger) with a lower (or higher) degree of weed infestation, then compare your expected costs proportionally.

5. Use Table 2 to select the appropriate surveillance interval for your chosen level of certainty, habitat, weed growth form and cost threshold.
6. Modify the surveillance interval, or the time spent at each site, if your situation falls outside the parameters given in Tables 2–4. Be aware that these estimates are guides only; they are no substitute for local knowledge and experience.

For example, to find a shrub weed in short vegetation with high conservation value below the $5000 cost threshold will require a surveillance interval of 6 years. The area would be surveyed in year 1, then 6 years later in year 7, and a further 6 years later in year 13. To find a ground creeper in forest below the $500 threshold requires a surveillance interval of 3 years. If the control costs are likely to be unusually high, or the expected weeds are extremely invasive, hard to spot or very difficult to clear, then increase the frequency of surveillance. The surveillance interval should not be reduced below 50% of the indicated interval, and should not be undertaken more frequently than annually. As an

TABLE 4. MAXIMUM DISTANCE (m) OVER WHICH DIFFERENT TYPES OF WEED ARE VISIBLE TO A PERSON ON FOOT, WITH 80% RELIABILITY. DISTANCES GIVEN BY HABITAT TYPE, WEED GROWTH FORM AND AGE OF WEED (YEARS).

HABITAT TYPE	WEED GROWTH FORM	AGE OF WEED (YEARS)	MAXIMUM VISIBILITY
Forest	Climbing vine	<2	1 m
		3-4	5 m
		5+	2 m, 100 m*
	Ground creeper	<2	1m
		3-4	5 m
		5+	7 m
	Shade-tolerant shrub or tree	<2	1 m
		3-10	5 m
		10+	7 m
Shrubland	Vine	<5	1 m
		5+	2 m, 100 m*
	Tree or tall shrub	<2	1 m
		3-5	5 m
		5+	2 m, 100 m*
Short vegetation	Short weed	<1	1 m
		5+	3 m
	Shrub or tree	<2	1 m
		3-4	5 m
		5+	20 m
Wetland	Short weed	0	1 m
	Shrub	<2	1 m
		3+	30 m
	Tree	<3	1 m
		3+	100 m
Open habitat	Short weed	< 2	1 m
		3+	3 m
	Taller weed	<2	1 m
		3+	20 m

Notes:
For explanation of terms used in habitat type and weed growth form, see notes associated with Tables 1 and 2.
* The visibility of the weed extends out to 100 m if viewed from a vantage-point overlooking the invaded vegetation.

alternative to conducting surveillance more regularly, the amount of time spent at each site can be increased above the two hours per 10 ha level.

The recommended surveillance intervals are based on best practice field surveillance as outlined in the Weed Surveillance SOP (Braithwaite 1999). In particular, the following guidelines should be observed in the field:

- Use a search intensity of two hours per 10 ha—this is the search effort assumed in the model. Less effort than this will require more frequent visits, and more effort will increase the certainty of detection.
- Search in both a systematic and focused fashion. Search systematically so the search effort covers as much of the area as possible. Pay particular attention to places where weeds are more likely to be found, e.g. track entry points, high-traffic areas, light wells, bush edges and other disturbed areas such as slips.
- Determine the source of any weed found and, if it looks likely that the weed has spread, also search a wider area to check if it has established elsewhere.

3. Developing the surveillance interval model

The surveillance interval model described in Section 2 provides a simple way of deciding weed surveillance intervals. To do this, several assumptions have been made. The assumptions were generated in a workshop with DOC weed staff (people experienced in the identification, ecology and control of weeds, see Acknowledgements). The assumptions reflect the workshop participants' understanding of how surveillance intensity interacts with weed invasiveness, weed visibility and the cost of control. To rigorously test the model we needed data such as the propagule rain at a given site, the probability of any weed propagule that arrives at a site establishing and the time it would then take to spread to a given percentage cover at a site. We also needed quantitative data on the probability of finding a weed incursion if it is there. All of these parameters are hard to quantify and so data are not readily available. Thus, the model has not been empirically verified. Each of the model's variables and assumptions are described below.

3.1 WEED GROWTH AND INFESTATION

3.1.1 Habitats

The classification of New Zealand's habitats was a critical part of the modeling process. Habitat type influences both the rate of incursion and the rate of spread of a weed. It also affects the ease of finding and controlling a new weed incursion. Five broad habitat types are used: forest, shrubland, short vegetation, wetland, and open habitat.

Forest includes both warm and cool temperate forest and all forest communities (e.g. beech, podocarp, broadleaved forest). While there are some differences in the weed species likely to affect these different forest types, their visibility, rate of infestation, and costs of control are fairly similar at the level of detail at which the model is operating.

Shrubland includes subalpine, ultramafic, coastal and induced shrublands.

Short vegetation includes induced and natural grassland, herbfield, and other short vegetation types (<1 m tall). Initially these were separated into induced and natural short vegetation but again the level of similarity, as described for forest, meant separation was not warranted.

Wetland includes freshwater and estuarine, semi-permanent and permanently wet vegetation. It does not include streams, rivers or lakes; i.e. bodies of water vulnerable to invasion by aquatic weeds.

Open habitat includes riverbeds, sand dunes and other natural and induced open habitats.

Marine habitats were not included because of the difficulties in defining variables such as arrival rates, growth rates and control costs.

3.1.2 Growth form

The weed growth forms most likely to be of concern in each habitat, i.e. those that would cause major changes in vegetation composition and ecosystem function (see Tables 2–5) were selected.

TABLE 5. RATES OF BIOMASS INCREASE AND SPREAD (*r* VALUES) FOR DIFFERENT WEED GROWTH FORMS IN GIVEN HABITATS.

HABITAT TYPE	WEED GROWTH FORM	*r* VALUE
Forest	Climbing vine Ground creeper Shade tolerant shrub or tree	0.9 0.6 0.4
Shrubland	Vine Tree or tall shrub	0.7 0.6
Short vegetation	Short weed Overtopping shrub or tree	0.9 0.9
Wetland	Short weed Shrub Tree	0.5 0.6 0.4
Open habitat	Short weed Taller weed	0.9 0.7

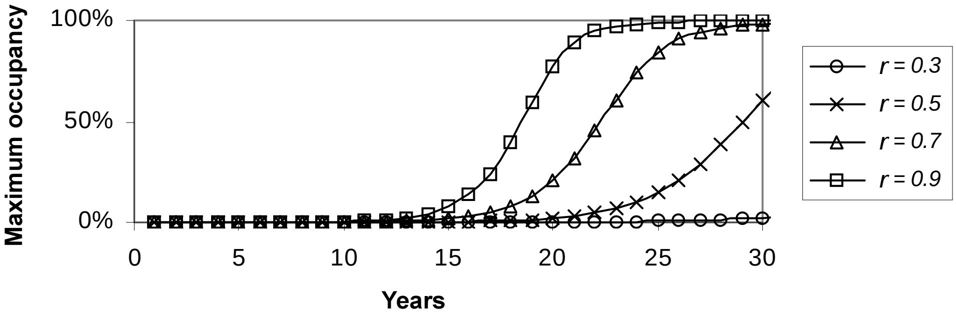
Notes:
The above *r* values represent the rate of biomass increase for each weed growth form / habitat couplet where $r = 0.1$ is low and $r = 0.7$ is high. These *r* values were derived from data on the estimated time taken for each weed growth form to reach 10%, 50% and 90% of its maximum occupancy of a site in a given habitat type.

3.1.3 Infestation expansion

Different weed species grow and spread at different rates, taking varying lengths of time to reach their maximum coverage at a site. The rates vary with habitat as well. Population growth is usually modeled by estimating the total number of individuals present over time. This measure of population size does not work well for weeds because many species do not have distinguishable individuals. Furthermore, the expansion of the infestation at a site is a function of the growth rate of individual plants plus the rate at which new propagules are produced and the rate at which new propagules arrive at the site. To accommodate these factors we used estimates of the rates of biomass increase for each weed growth form / habitat couplet (the *r* values in Table 5). These *r* values were derived from data on the estimated time taken for each weed growth form to reach 10%, 50% and 90% of its maximum occupancy of a site in a given habitat type. The estimations were best guesses of the time taken **once** a propagule has arrived and established and were supplied by the workshop participants (see Acknowledgements).

Figure 2 shows how quickly a weed incursion reaches maximum occupancy of a site at different rates of biomass increase and spread (*r* value). The growth curves represent spread from a single low-level infestation at a site. The model assumed weed propagules would arrive at a site and used the equation given in Appendix 1.

Figure 2. Occupation of a site by a weed over time expressed as a percentage of maximum occupancy (0–100%) for four different rates of weed biomass increase (r), where r = 0.1 is a low rate of biomass increase and r = 0.7 or higher is a high rate.



3.1.4 Weed spread

The model assumes that the spread of the new incursion is confined to the search zone—a sub-set of the search area, the zone in which a searcher could reasonably be expected to see a weed when searching in an area. The model also assumes that the infestation can be controlled within the budget thresholds. However, a weed that has already dispersed propagules may well have established at other new loci in the general area. Similarly, further new infestations could well be sourced from outside the search zone. When an infestation is found, it is useful to search further to trace where the weed came from, and to check for other new infestation loci. These issues of extra search effort are not specifically accommodated in the model for determining surveillance intervals.

3.1.5 Arrival rate

The model assumes that arrival and establishment of new weeds is a relatively infrequent event and that, at the most, only one arrival is likely to establish in the search zone in the inter-surveillance period. For those areas where more frequent arrivals and consequent establishment are likely, more frequent surveillance will be needed (e.g. areas bordering seed sources).

3.2 ABILITY TO FIND A WEED

3.2.1 Surveillance effort

The greater the search effort at a site, the greater the chance of finding a weed. The model assumes a fixed surveillance effort of two hours to search a 10 ha surveillance area. This is the amount of time that is likely to be put into finding weeds at each locale, based on staff experience with weed inventory. Thus the larger the area to be searched, the longer the time needed to complete the search. Conversely, for smaller areas the search could be completed more quickly.

A hierarchy of terms has been adopted. The ‘surveillance area’ is the locality where surveillance will be undertaken. This could be a DOC-managed reserve. Alternatively, it could be a site managed by another agency that is likely to be invaded by weeds of conservation concern—perhaps a graveyard or a dump. The site may be adjacent to a protected natural area (a ‘vulnerable site’ in weed surveillance jargon). The ‘search area’ describes the part(s) of the surveillance area the searcher walks through. The search zone is a sub-set of the search area—the portion in which weeds could be expected to be visible.

3.2.2 Weed visibility

Species differ in their visibility. Similarly, visibility may vary with a plant's stage of maturity and degree of infestation. For example, initially a vine in a forest has very low visibility to searchers within the forest. Visibility increases slightly as the vine grows through the subcanopy, and then decreases as it reaches the canopy. However, at this latter stage, visibility from vantage points above the canopy increases.

The model uses estimates of the maximum distance at which a person walking through a particular habitat type would see a given weed growth form with 80% confidence. These estimates are based on DOC staff experience in searching for weeds.

Some weeds will be relatively invisible on the ground, even at short distances, but more visible if viewed from above. The recommendations assume that the search zone is not viewed from above. If it is possible to view a site from above, e.g. from a nearby hill, the probability of finding some weeds, particularly vines, might increase.

3.3 COSTS OF CONTROL

3.3.1 Cost of control

The cost of control is estimated at a standard rate for different weed growth forms. These constitute a fixed cost for travel, set-up and clean-up, and a variable cost of clearing each square metre of the weed. The costs, estimated from DOC data, are based on typical expenditures for clearing the particular weed growth form.

3.3.2 Thresholds for cost of control

The recommendations in this study have been prepared to enable weeds to be located at a stage of their infestation when the cost of control can be readily accommodated by a particular DOC Area Office. The lower cost threshold was set at $500, which is considered a reasonable level of expenditure that could be directly absorbed by an Area Office. These costs include staff time and materials and roughly equate to a half-day's work. The higher threshold level of effort was set at $5000, considered a reasonable level of expenditure for an Area Office to accommodate by reprioritising other Area Office weed work. The costs of control are related to Area Office expenditure because this is the operational level within the DOC structure.

4. Modelling results

Table 2 gave recommendations on how often to do weed surveillance, for different weed growth forms in five broad habitat types, to be sure (80% or 95% certain) that new weed incursions can be detected before the cost of their control exceeds two cost thresholds. Table 6 compares these surveillance intervals with the number of years the model predicts it takes a newly established incursion to grow and spread such that its cost of control would be more than the $500 or $5000 thresholds. Without exception, the surveillance interval is less than the predicted number of years for the weed to spread to nuisance levels (compare columns 5–8 with columns 3–4 in Table 6). The shorter surveillance intervals allow for the possibility that a new weed incursion may not be detected at the first, or subsequent, surveillance visit after a weed's establishment. It also allows for the possibility that a weed might arrive and establish immediately after a site has been searched. The intervals in

TABLE 6. PREDICTED NUMBER OF YEARS FOR A WEED INCURSION TO SPREAD COMPARED WITH THE RECOMMENDED SURVEILLANCE INTERVAL, TO MEET THE COST THRESHOLDS ($500, $5000) BY HABITAT TYPE AND WEED GRPWTH FORM AT TWO LEVELS OF CERTAINTY OF WEED DETECTION (ALL VALUES GIVEN IN YEARS).

HABITAT TYPE	WEED GROWTH FORM	YEARS FOR WEED INFESTATION TO EXCEED COST THRESHOLD[1]		SURVEILLANCE INTERVAL (YEARS)[2]			
				80% CERTAINTY OF DETECTION		95% CERTAINTY OF DETECTION	
		$500 COST THRESHOLD	$5000 COST THRESHOLD	$500 COST THRESHOLD	$5000 COST THRESHOLD	$500 COST THRESHOLD	$5000 COST THRESHOLD
Forest	Climbing vine	9	13	1	3	<1[3]	1
	Ground creeper	15	20	3	7	1	4
	Shade-tolerant shrub or tree	23	30	6	10	3	6
Shrubland	Vine	12	16	1	9	1	5
	Tree or tall shrub	12	18	2	9	1	5
Short vegetation	Short weed	13	22	2	5	1	3
	Shrub or tree	16	24	5	10	3	6
Wetland	Short weed	19	25	3	7	1	4
	Shrub	16	24	10	10	6	10
	Tree	23	30	10	10	10	10
Open habitat	Short weed	12	18	1	6	1	3
	Taller weed	14	20	4	9	2	5

Notes:

1. The predicted number of years it would take a new incursion to grow and spread such that its cost of control would exceed the two cost thresholds. The estimated rates of biomass expansion (*r* values) given in Table 5 and the standard costs given in Table 3 were used in these calculations.
2. The frequency of surveillance required to detect a new weed infestation early enough to keep the costs of control at or below the cost thresholds. The intervals allow for the possibility that a new weed incursion may not be detected at the first (or subsequent) surveillance visits after a weed's establishment or that a weed might arrive and establish immediately after a site has been searched.

Table 6 thus err on the side of caution. The table of surveillance intervals illustrates some of the interactions between conspicuousness and cost of control and growth of a weed. The more visible weeds typically have longer surveillance intervals. Population growth rates are important at the extremes; those weeds with a very slow rate of spread at a site typically have longer surveillance intervals. The results for each habitat type are discussed below.

4.1 FOREST

A vine is the most difficult weed growth form to identify at an early stage. Seedlings and young plants are often cryptic and have a potentially rapid growth rate. A minimum of annual surveillance is required if forest vines are to be found before the $500 cost threshold with 80% certainty of detection. If greater certainty of detecting the weed is required (95%) then the intensity of searching should be increased. Once vines have reached the canopy, there is also a high risk that they may seed and spread beyond the search zone. The surveillance interval extends out to 3 years if the $5000 cost threshold can be adopted.

A slightly longer surveillance interval is acceptable for ground creepers because they generally have a slower rate of invasion and lower cost of control—3 and 7 years for the $500 and $5000 cost thresholds respectively with 80% probability of detection. However, if the ground creeper is expensive to control, it may require more frequent surveillance. Surveillance for shade-tolerant shrub and tree weeds in forest can be reasonably infrequent (every 6 or 10 years respectively) because these species are usually slower to establish and spread.

The appropriate surveillance interval for forest habitats depends on the growth form of the most threatening invader expected. Where no particular weeds are more likely than others, a surveillance interval of 1–2 years is appropriate. If greater certainty in finding any invasive weeds is required then surveillance should be annual with more time spent at each search area.

4.2 SHRUBLAND

The surveillance intervals for shrubland fall between those for forest and those for short vegetation. This reflects the moderate visibility and slightly slower rates of infestation of shrub weeds compared with forest weeds, and the higher costs of control than weeds of short vegetation. Surveillance for vine weeds must be annual if they are to be found below the $500 control cost threshold, and every 9 years to find them below the $5000 control cost threshold. For canopy-forming weeds that overtop the existing vegetation, the longer surveillance interval reflects their greater visibility. The recommended surveillance intervals are 2 and 9 years respectively for the $500 and $5000 control cost thresholds. A surveillance interval of 1 to 9 years seems appropriate for this type of habitat, depending on the threats faced and importance of the protected area.

4.3 SHORT VEGETATION

The surveillance interval for short weeds in short vegetation is recommended at 2 years to locate a weed below the $500 threshold, and 5 years to find weeds below the $5000 threshold, with 80% certainty. For more visible weeds this surveillance interval extends to 5 years and 10 years respectively for the two control cost thresholds. More frequent surveillance **may** increase the probability of finding weeds. However, short weeds, such as herbs or grasses, have relatively low visibility in short vegetation, such as grasslands. This means that surveillance is likely to find weeds only when they have infested a reasonably large area so that the searchers are more likely to encounter a weed on their search path. The risk of distant seed spread from wind-dispersed grass weeds is high, and it is probable that even very intensive annual surveillance could not prevent this occurring. The return on surveillance effort for this type of weed in this habitat is commonly low. The recommended surveillance interval for these habitats is therefore 5–10 years depending on the importance of the habitat and the cost thresholds chosen. The longer interval will detect short weeds below the $5000 control cost threshold and more visible weeds within the $500 threshold.

4.4 WETLAND

Wetland habitats generally have longer surveillance intervals because wetland weeds usually have slow growth rates. Short weeds in wetlands are invariably hard to detect. A surveillance interval of three years is recommended to meet the $500 threshold, and seven years to meet the $5000 threshold. Taller weeds—shrubs and trees—are very visible in wetlands once they emerge above the canopy level of the native wetland plants. A surveillance interval of 10 years surfices to detect shrub and tree weeds invading wetlands.

These results give us some confidence in going to longer surveillance intervals in wetlands. For those weeds that can be fairly readily identified there is little to be gained by too frequent visits because it is likely that, even with long surveillance intervals, the weed will be found while still in the lag phase of infestation. The shorter, less visible weeds are unlikely to be detected, even with a very intensive surveillance programme. Thus there is little benefit in undertaking surveillance more regularly than indicated. A surveillance interval of 5 to 10 years is recommended for this habitat type.

The comments in this wetland section do not pertain to invasive aquatics. Those weeds often grow and spread extremely rapidly. They can be difficult to detect and generally someone with particular knowledge of aquatic plants is needed to identify the plants and, indeed, to recognise a new incursion.

4.5 OPEN HABITAT

Quite different surveillance intensities are required to detect short weeds (<1 m) compared with taller weeds (shrubs or trees) in open habitats. Weeds readily establish and spread quickly in open habitats. Unfortunately, the (in)visibility of short weeds such as grasses means that they are hard to find, even in an open environment such as a riverbed. A surveillance interval of one year is required to meet the $500 cost threshold and an interval of six years to meet the higher threshold with 80% certainty. In contrast, taller weeds are usually much more conspicuous, simply because of their height, so the surveillance interval extends to four years for the lower cost threshold and nine years for the higher threshold. Generally, an interval of one to four years will be appropriate for open habitats, since they are vulnerable to weed invasion and often the weeds can readily spread beyond the search zone.

4.6 MODEL LIMITATIONS

The model described in this report is based on a set of assumptions about weed behaviour, visibility and cost of control (see Section 3). The recommendations that flow from the model are only valid for a given situation if it complies with the assumptions. Thus, applying exact values from the model to practical situations should be done with caution. Rather, the recommendations should be treated as guidelines to assist managers in developing a regular surveillance programme. Further, while the model uses the best information available, the guidelines that result from it should always be used in conjunction with local experience of weeds and habitats, and certainly never displace this knowledge. Some factors that must be taken into account before making surveillance decisions have already been outlined in Section 3. Some issues regarding the way the model was developed and its sensitivity to the assumptions made about cost, rate of spread and visibility, are described below.

4.6.1 Spread of propagules

The model assumes that the weed remains generally contained within the search zone, i.e. where it can be seen by a searcher, and that the weed's propagules are only spread locally. This is not always the case. For example, a vine with wind-dispersed seeds in a forest canopy, or a pine tree at a take-off point (a high point in the prevailing wind), can spread seeds several kilometres. A surveillance programme cannot hope to prevent this spread since these weeds would need to be found prior to seeding, i.e. generally in less than five years after invasion. This would mean a complete search of such a site annually—this is unlikely to be practical. When a surveillance search finds a new incursion it is recommended that an assessment be made of the risk that the weed has already spread beyond the search zone. Where appropriate, wider searches should be undertaken to find other new loci, to determine the source of the weed and to prevent any re-infestation.

4.6.2 Growth form

The growth form categories are not all inclusive. For example, there is no explicit category for a light-demanding shrub or tree in a forest, a vine that does not reach the canopy but does more than just creep along the ground, e.g. climbing asparagus, or a shade-tolerant shrub that does not reach the canopy. Rather, the growth form categories represent the worst case scenarios for at least one of the parameters—rate of spread, visibility or cost of control. Further, the model does not accommodate species-level differences in growth and spread at a site.

4.6.3 Costs of control

The cost thresholds indicated here are the costs for initial control. Follow-up control in subsequent years is often required to eliminate an infestation, and these costs have not been included.

4.6.4 Weed infestation

The model assumes standard infestation behaviour: a weed infestation progressing steadily and reaching sexual maturity relatively quickly. Some weeds—such as wilding trees—do not fit this pattern but rather spread in an episodic manner. For such weeds it may be necessary to set the surveillance interval in relation to sexual maturity of expected invaders rather than using the model results presented here. These types of invaders may be better treated with an interactive surveillance interval model, such as that being developed by Simon Harris for DOC (unpubl. data).

Similarly, infestations that have a continuing propagule rain from an adjacent source will expand more quickly than is indicated by the model. That scenario was not considered in the model because the rate of propagule rain is unknown and will vary tremendously between sites. The model simply assumed weed propagules would arrive at a site. Any variation in weed arrival rates also could not be accommodated in the model because this has not been quantified in New Zealand.

4.6.5 Surveillance method

The modeling assumes ground-based surveillance; the most likely form of surveillance in most habitats. However, some weeds, e.g. wilding conifers, may require surveillance methods such as helicopter-based surveys in order to be able to see the invading weeds or to cover large areas of country efficiently. The surveillance intervals recommended in this report may not be applicable to other methods of surveillance.

4.6.6 Aquatic environments

Aquatic environments such as streams, rivers and lakes have not been addressed in this exercise. It seems that even with annual surveillance there is a high probability that an aquatic weed will have already reproduced and spread beyond the initial search zone by the time it is first sighted. This implies that surveillance for aquatic weeds should focus on very vulnerable areas and would be required at least six-monthly to catch new incursions early enough.

4.6.7 Running the model with different scenarios

Appendix 2 shows what happens to the recommended surveillance interval when the model is run under a few different scenarios such as variations of expected cost of control, growth rate and chance of finding the weed in the search zone. It demonstrates the importance of finding a new weed incursion before its expansion becomes exponential. Finding the weed relies on the infestation being within the search zone, i.e. visible to the searcher. If it is not in the search zone, then it will remain undetected for that search. Even if the incursion is in the search zone, at an 80% certainty of finding the weed, there is a 20% chance that it won't be detected. The probability of an infestation remaining undetected compounds with subsequent searches. If the costs of control double, then the weed quickly becomes too expensive to control; however, the relationship varies with habitat type and growth form.

These different scenarios demonstrate that there is no one key factor determining appropriate surveillance intervals. Rather, they are a function of the visibility and rate of spread of a weed incursion and the cost of subsequent control. However, the weighting of each factor varies with the habitat-growth form couplet. To fully explore these relationships requires an interactive surveillance interval model, such as that being developed by Simon Harris (referred to earlier, see Section 4.6.4).

5. Acknowledgements

This report originated from work carried out under Department of Conservation investigation no. 3104.

The project has been made possible with the assistance of many staff in the Department of Conservation who provided input and feedback on the proposals and assumptions used. In particular, we would like to thank the following weed technical and field staff, who participated in a workshop in Christchurch on 17 June 1999: Neil Bolton, Helen Braithwaite, Melanie Newfield, Di Robertson and Chris Woolmore (all from DOC) and Rob McCaw (Canterbury Regional Council).

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Appendix 1

The equation used in the model to predict appropriate surveillance intervals.

A logistic curve equation, which incorporates the effect of density-dependence, was used to model the expansion of the infestation over time. The equation used was:

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

N_t is the occupancy of the infestation in year t

r is the logistic per capita growth rate, i.e. an increase in weed biomass over time which follows a sigmoid curve of slow initial increase, followed by exponential growth rate and finally a tapering off as the weed reaches its maximum occupancy (K)

K is the maximum occupancy of the infestation within the site

θ is a shape parameter

In the equation, N_t measures the infestation's proportional occupation of the site relative to its maximum occupation (K, where K = 1 or 100%).

Appendix 2

A demonstration of what happens to the surveillance interval when three of the parameters in the model are altered, indicating the sensitivity of the model to alteration in the parameters.

TABLE A2.1. RECOMMENDED SURVEILLANCE INTERVALS BASED ON SEVERAL DIFFERENT SCENARIOS. THREE OF THE PARAMETERS ARE ALTERED: EXPECTED COST OF CONTROL, GROWTH RATE (*r* VALUE), CHANCE OF FINDING THE WEED IN THE SEARCH ZONE.

HABITAT	WEED GROWTH FORM	SURVEILLANCE INTERVAL TO MEET $500 COST THRESHOLD (YEARS)					SURVEILLANCE INTERVAL TO MEET $5000 COST THRESHOLD (YEARS)				
		STD *r*, STD COST, 80% CERTAINTY	STD *r*, 2 × COST, 80% CERTAINTY	1.5 × *r*, STD COST, 80% CERTAINTY	1.5 × *r*, 2 × COSTS, 95% CERTAINTY	STD *r*, STD COSTS, 80% CERTAINTY 50% CHANCE	STD *r*, STD COST, 80% CERTAINTY	STD *r*, 2 × COST, 80% CERTAINTY	1.5 × *r*, STD COST, 80% CERTAINTY	1.5 × *r*, 2 × COSTS, 95% CERTAINTY	STD *r*, STD COSTS, 80% CERTAINTY 50% CHANCE
Forest	Climbing vine	1	1	1	<1	1	3	2	2	1	1
	Ground creeper	3	2	2	1	2	7	6	5	2	4
	Shade-tolerant shrub or tree	6	4	4	1	3	10	10	8	4	6
Shrubland	Vine	1	1	1	<1	1	9	7	6	2	5
	Tree or tall shrub	2	1	2	1	1	9	7	7	3	5
Short vegetation	Short weed	2	1	1	1	1	5	4	4	1	3
	Shrub or tree	5	4	4	1	3	10	8	8	3	5
Wetland	Short weed	3	2	2	1	1	7	6	5	2	4
	Shrub	10	9	8	4	5	10	10	10	6	8
	Tree	10	10	10	5	8	10	10	10	8	10
Open habitat	Short weed	1	1	1	<1	1	6	4	5	1	3
	Tall weed	4	3	3	1	2	9	8	6	3	5

Notes:
Std *r* refers to the standard rate of biomass expansion in the weed incursion, i.e. *r* values given in Table 5; *r* × 1.5 and *r* × 2 is a rate of expansion one and a half or two times faster than the rate given in Table 5; std costs is the average expected costs of control given in Table 3; % certainty is the certainty of finding a weed incursion during a surveillance visit if one is present at the site; % chance is the likelihood of finding a weed incursion in the search zone, the subset of the search area over which a searcher could be reasonably expected to see a weed if it is present.

TABLE A2.2. DATA USED TO PRODUCE TABLE A2.1.

HABITAT	FOREST			SHRUBLAND		SHORT VEGETATION		WETLAND			OPEN HABITAT	
WEED GROWTH FORM	CLIMBING VINE	GROUND CREEPER	SHADE-TOLERANT SHRUB OR TREE	VINE	TREE OR TALL SHRUB	SHORT WEED	SHRUB OR TREE	SHORT WEED	SHRUB	TREE	SHORT WEED	TALL WEED
(Expected costs) × 2, 80% certainty of finding weed incursion												
r value	0.9	0.6	0.4	0.7	0.6	0.9	0.9	0.5	0.6	0.4	0.9	0.7
Surveillance interval to meet $500 cost threshold*	1	2	4	1	1	1	4	2	9	10	1	3
Surveillance interval to meet $5000 cost threshold*	2	6	10	7	7	4	8	6	10	10	4	8
Years for the weed to exceed $500 cost threshold	8	13	20	11	14	11	11	17	14	20	11	12
Years for the weed to exceed $5000 cost threshold	12	19	28	20	22	15	16	23	22	27	16	19
(Rate of biomass increase) × 1.5, 80% certainty of finding weed incursion												
r value	1.35	0.9	0.6	1.05	0.9	1.35	1.35	0.75	0.9	0.6	1.35	1.05
Surveillance interval to meet $500 cost threshold*	1	2	4	1	2	1	4	2	8	10	1	3
Surveillance interval to meet $5000 cost threshold*	2	5	8	6	7	4	8	5	10	10	5	6
Years for the weed to exceed $500 cost threshold	7	11	16	10	12	9	9	14	12	16	9	11
Years for the weed to exceed $5000 cost threshold	10	15	22	16	18	12	14	18	18	21	14	15
(Rate of biomass increase) × 1.5, (Expected costs) X 2, 95% certainty of finding weed incursion												
r value	1.35	0.9	0.6	1.05	0.9	1.35	1.35	0.75	0.9	0.6	1.35	1.05
Surveillance interval to meet $500 cost threshold*	<1	1	1	<1	1	1	1	1	4	5	<1	1
Surveillance interval to meet $5000 cost threshold*	1	2	4	2	3	1	3	2	6	8	1	3
Years for the weed to exceed $500 cost threshold	6	10	14	9	10	8	8	12	11	14	8	9
Years for the weed to exceed $5000 cost threshold	9	14	20	15	16	11	12	17	16	20	12	14
Standard costs and rate of biomass increase, 80% certainty of finding weed incursion, (Chance of finding the weed in search zone) × 0.5												
r value	0.9	0.6	0.4	0.7	0.6	0.9	0.9	0.5	0.6	0.4	0.9	0.7
Surveillance interval to meet $500 cost threshold*	1	2	3	1	1	1	3	1	5	8	1	2
Surveillance interval to meet $5000 cost threshold*	1	4	6	5	5	3	5	4	8	10	3	5
Years for the weed to exceed $500 cost threshold	9	15	23	13	16	12	12	19	16	23	12	14
Years for the weed to exceed $5000 cost threshold	13	20	30	22	24	16	18	25	24	30	18	20

*Surveillance interval in years