RISK ASSESSMENT AND PEST DETECTION SURVEYS FOR EXOTIC PESTS AND DISEASES WHICH THREATEN COMMERCIAL FORESTRY IN NEW ZEALAND

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ABSTRACT

Regular surveys of port environs and forest areas are justified to detect new introductions of harmful insects or fungi. Early detection allows timely eradication or control action, so minimising losses of forest value. Historical records show an average 4.6 new introductions each year, and timely response to all of these will yield a maximum national benefit, excluding costs of detection, of $8.95 million per annum.

Effective forest health survey methods, in order of decreasing cost efficiency, include aerial survey, drive-through roadside survey, and random point sampling. Used in combination, at a range of regional survey intensities appropriate to risk and cost, they yield a maximum national net benefit of $7.33 million at survey levels which give 95% detection of new introductions.

This analysis justifies increasing current levels of survey towards 95% detection, while refining the methods and assumptions used so as to increase confidence in defining the point of maximum net benefit.

Keywords: forest health; forest surveillance; introduced insects; introduced diseases, aerial survey; random point sampling.

INTRODUCTION

Commercial forestry in New Zealand is dominated by a single conifer, *Pinus radiata* D. Don, with only small areas of other commercial species. All are exotic to New Zealand, and have been introduced to the country without most of their naturally associated pests and diseases. Because of this situation, and the country's geographic isolation, a unique opportunity exists to protect commercial forest values by excluding or preventing the establishment and spread of harmful agents.

With the progressive introduction in recent years of "user-pays" policies by the Government, the forest industry has been expected to fund an increasing proportion of the cost of forest health surveys. These are carried out as a second line of defence, after import quarantine, to detect new introductions at an early enough stage to allow action on either eradication or containment to be undertaken, if considered necessary.

In response to the demands for increased levels of funding, the forest industry has questioned the need for forest health surveillance. This paper reports the results of a study carried out in response to this question.

ASSESSMENT OF RISK TO PLANTATIONS FROM EXOTIC PESTS AND DISEASES

Nature of the Threat

Historically, import quarantine inspectors have intercepted many potentially harmful agents with an annual average over the past 31 years of 58 insects which were known or expected to affect *P. radiata* (Table 1). Total interceptions of insects, including live and dead adults and larvae, have averaged 270 per annum over the past 4 years (J. Bain, unpubl. data).

TABLE 1–Numbers of samples of intercepted insect species sent to FRI by quarantine officers over 31 years, classified according to the perceived threat they pose to *Pinus radiata* plantations

	Threat		
Year	High	Medium	Low
1958	1	1	10
1959	4	1	23
1960	2	5	52
1961	5	7	46
1962	7	2	45
1963	6	11	87
1964	8	8	88
1965	2	1	50
1966	–	–	10
1967	1	2	5
1968	3	2	18
1969	1	2	18
1970	4	1	17
1971	1	4	21
1972	5	–	40
1973	0	1	50
1974	7	1	86
1975	6	2	57
1976	6	–	60
1977	–	3	71
1978	5	5	82
1979	6	3	100
1980	2	1	32
1981	3	4	54
1982	–	2	80
1983	5	2	85
1984	6	3	95
1985	3	2	60
1986	3	1	54
1987	3	1	47
1988	2	5	73
Total	107/31 = 3.45/year	83/31 = 2.68/year	1616/31 = 52.13/year

Despite this history of successful quarantine action, however, the last 37 years have seen the annual introduction and establishment of an average of 2.2 new insects and 2.4 new fungi (Table 2) affecting commercial forest species in New Zealand and, with

TABLE 2–First records of species of insects and fungi found on living plantation tree species (Forest Research Institute, unpubl. data)

Biological region*	Insects (1950–87)	Fungi (1956–87)
Northland	7	8
Auckland	19	8
Waikato	1	3
Coromandel	1	0
Bay of Plenty	5	16
Taranaki	5	2
Taupo	1	10
Gisborne	3	0
Rangitikei	1	0
Hawke's Bay	3	2
Wanganui	6	4
Wellington	8	6
Wairarapa	1	4
Nelson	4	3
Marlborough Sounds	0	0
Marlborough	1	0
Brunner	0	1
Kaikoura	0	0
Westland	0	1
North Canterbury	0	0
Mid Canterbury	10	3
Mackenzie	0	0
South Canterbury	2	1
Otago Lakes	0	0
Central Otago	1	0
Dunedin	1	1
Fiordland	0	0
Southland	2	1
Stewart Island	0	0
Total	82	74
	Over 37 years 2.216/year +	Over 31 years 2.387/year
TOTAL	= 4.603/year	

* As defined by Crosby *et al.* (1975)

the increasing ease and frequency of international public travel, as well as increasing diversity and volumes of imports, it would be expected that the number of new introductions will increase. Of the average 4.6 new introductions per year, 0.73 had *P. radiata* as their host and 3.87 affected other species (P.D. Gadgil, unpubl. data).

The threat to plantations was further characterised by analysis of all known harmful insects and diseases which affect *P. radiata* worldwide but are not currently found in New Zealand. These 217 insects and 92 fungi were classified according to their detectability by different methods of survey, their eradicability, and expected physical impact. A likelihood of introduction and establishment index was also calculated, based on mode of dispersal and on the historical record of introduction of similar organisms (Table 3).

TABLE 3–Pests and diseases, not present in New Zealand, which are considered to have the potential to attack living *Pinus radiata*, if introduced here, classified according to: (a) their likely impact on the health of the host; (b) likelihood of their introduction; (c) the possibility of eradicating them; (d) their detectability from air

(a) Potential impact	High	Medium	Low	Total
Fungi	28	16	48	92
Insects	14	22	181	217
TOTAL	42 (14%)	38 (12%)	229 (74%)	

(b) Likelihood of introduction*	Introduction factor				
	1	6	10	32	42
Fungi	–	19	–	18	55
Insects	153	–	64	–	–

(c) Possibility of eradication†	Considered eradicable	Not considered eradicable
Fungi	61	31
Insects	104	113
TOTAL	165 (53%)	144 (47%)

(d) Detectability from air‡	Detectable from air	Not detectable from air
Fungi	37	55
Insects	4	213
TOTAL	41 (13%)	268 (87%)

* The introduction factor is based on historical records of insects and fungi of *P. radiata*, with different modes of transport, which have been introduced into New Zealand. The ratio of introduced insects to fungi recorded on *P. radiata* is 1:4, yet there are approximately twice the number of recognised insect threats, so it is concluded that fungi, on average, are eight times more likely to be introduced and establish successfully than insects. Allocation of "introduction factors" was then made, based upon the limited historical data:

Introduction factor 1 = insects transported only on living plant material
6 = fungi with soilborne propagules
10 = insects found only in wood
32 = fungi with splash-dispersed spores
42 = fungi with airborne spores

† Eradicability is based on an assessment of the rate of spread of the pest or disease and assumes that up to 100 ha would have to be felled in the eradication attempt and that the pest or disease will be detected before it has spread over more than 20 ha. At best, it is a more or less informed guess.

‡ Detectability from the air is based on whether or not the pest or disease produces symptoms in the upper crown of the host which can be seen in the course of a normal forest health aerial survey.

It is recognised also, from the historical records of introductions affecting *P. radiata*, that for every two known threats, there is one unknown threat equally likely to be introduced.

By combining the number of expected introductions (conservatively assuming a rate of introduction equal to that of the historical record), and the likelihood of their establishment and probable impact, the number of expected introductions per year by impact category was derived. In the absence of detailed evidence, it is assumed that threats to other commercial species exist in the same ratios as for *P. radiata* (Table 4.).

Effect on Value of Forests

Because the potential impact on forest value would obviously differ for each of the 309 known threats, an average expected value loss was taken for introductions from within each of the high, medium, and low impact categories, using estimates of loss

TABLE 4—Expected introductions of pests and diseases per year, based on past records weighted according to their ease of introduction and classified according to their likely impact on the host

Impact	Expected ratio of introductions* (a)	Mean introduction factor† (b)	Expected ratio of introductions weighted according to introduction factor (axb)	Expected introductions per year‡
Pinus radiata				
High	0.14	18.90	(2.65) 0.215	0.157
Medium	0.12	15.74	(1.89) 0.153	0.112
Low	0.74	10.52	(7.79) 0.632	0.461
Total	1.00		1.000	0.729
Species other than *P. radiata*§				
High			0.215	0.832
Medium			0.153	0.594
Low			0.632	2.448
Total			1.000	3.874
TOTAL				4.603

* *See* Table 3.

† Mean of introduction factors (Table 3) for all pests and diseases in a given impact category.

‡ *See* Table 2.

§ Data not available. Assumed to be in the same ratio as for *P. radiata*.

from two known diseases of *P. radiata* already present in New Zealand for which objective data were available (D. New, unpubl. data). To improve these estimates more individual impact analyses need to be carried out. The examples chosen were *Dothistroma pini* Hulbary as a high-impact threat showing an actual average loss of $5.49/ha of the national exotic forest estate and *Diplodia pinea* (Desmazieres) Kickx as a low-impact threat showing a loss of $0.15/ha. For the purposes of this analysis, value losses per hectare per annum for *P. radiata* of $5.40 for high-, $2.00 for medium-, and $0.10 for low-impact categories were assumed. In fact, the effect on total expected loss per hectare is by far the greatest from the high-impact category, contributing 74% to the total, so the analysis is most sensitive to changes in this estimate.

Loss in value for the total forest estate from the expected number and nature of new introductions was then calculated, scaling the estimated impact for harmful introductions affecting commercial species other than *P. radiata* down by a factor of 0.0093. This factor is derived from the assumption that a new introduction would not affect all 142 000 ha of other species, but would be restricted to an area in certain species or genera, assumed to cover an average 10 000 ha, compared with the *P. radiata* area of 1 072 000 ha. These calculations are presented in Table 5.

Costs of eradication or control of pests and the benefits derived therefrom were then calculated. It was assumed that eradication action will be carried out whenever justified, and control action considered for the other introductions. Only 53% of known threats are categorised as being eradicable (Table 3) and at the calculated costs of eradication, new introductions in all impact categories except those for "species other than *P. radiata,* medium impact" and "species other than *P. radiata,* low impact"

TABLE 5–Expected value loss

Impact	Expected No. of introductions (a)	Value loss/ha/annum ($)* Per introduction (b)	 Total (axb)	NPV of value loss over national estate/introduction
Pinus radiata				
High	0.157	5.400	0.847	81,368,602
Medium	0.112	2.000	0.224	30,136,519
Low	0.461	0.100	0.046	1,506,826
Species other than *P. radiata*				
High	0.832	0.050	0.042	759,339
Medium	0.594	0.019	0.011	281,237
Low	2.448	0.001	0.002	14,062
TOTAL	4.603		1.172	

*Value loss is the estimated annual loss spread over the total national exotic forest estate.

(1.562 expected introductions) will have benefit greater than cost (Table 6). Hence only 53% of the 1.562, i.e., 18% of the total expected introductions, are expected to justify eradication action. The balance of 82% would be considered for control but, again, assumed benefit will exceed cost only for "*P. radiata,* high impact" and "*P. radiata,* medium impact", giving only 82% of 0.269 expected introductions per year (4.8% of total introductions) where control action will be justified (Table 7).

Over the possible range in "proportion of new introductions detected", net benefit was calculated, ranging up to $7.37/ha at 100% detection (Table 8).

Assumptions made for these calculations are:

(1) Eradication cost is $7000/ha for 100 ha, a total of $700,000/eradication. All eradication attempts (18% of introductions) are successful, and benefit is 100% of expected value loss over 30 years.

(2) Control costs amount to $1/ha/annum across the national exotic forest estate area, and benefit amounts to 50% of expected annual value loss. Costs and benefit are calculated for 2 years, representing the gain attraibutable to earlier instead of later casual detection.

TABLE 6–Cost of eradication and benefit from eradication relative to the proportion of new introductions detected and treated (note that only 53% of new introductions are deemed to be eradicable)

Proportion of new introductions detected in a year	Eradication Cost ($)	 Benefit ($)
0.00	0	0
0.10	57,916	923,995
0.30	173,748	2,771,986
0.50	289,580	4,619,977
0.70	405,412	6,467,968
0.90	521,244	8,315,958
0.95	550,202	8,777,956
1.00	579,161	9,238,954

TABLE 7–Cost of and benefit from control relative to the proportion of new introductions detected

Proportion of new introductions detected in a year	Control	
	Cost ($)	Benefit ($)
0.00	0	0
0.10	29,555	58,875
0.30	88,664	176,624
0.50	147,773	294,372
0.70	206,882	412,121
0.90	265,991	529,871
0.95	280,768	559,308
1.00	295,545	588,745

TABLE 8–Net benefit

Proportion of new introductions detected in a year	Eradication plus control		Net benefit	
	Cost ($)	Benefit ($)	Total ($)	Per hectare ($)
0.00	0	0	0	0.00
0.10	87,471	982,870	895,399	0.74
0.30	262,412	2,948,610	2,686,198	2.21
0.50	437,353	4,914,349	4,476,997	3.69
0.70	612,294	6,880,089	6,267,795	5.16
0.90	787,235	8,845,829	8,058,594	6.64
0.95	830,970	9,337,264	8,506,293	7.01
1.00	874,706	9,828,699	8,953,993	7.37

SURVEYS FOR DETECTION OF EXOTIC PESTS AND DISEASES

A range of survey methods for detection of pests and diseases were analysed. These were random point sampling, drive-through surveys, aerial surveys, and observations made by forest staff. Probability of detection and costs were calculated for each method for a range of sampling intensities allowing for varying target infection area, "efficiency" of detection relative to random point sampling, and factors such as forest isolation and area. In addition to these forest survey methods, the probability of detection of new introductions by carrying out ground surveys of the environs of ports was also considered.

Random Point Sampling

The probability of detection of an infected area using point sampling with square or circular plots is given by the formula:

$$P = 1-(1-p)^n$$

where: P = probability of detection

p = proportion of total units of forest area infected

n = number of units sampled

For instance, take a 20-ha infection site (assumed to be circular) in a 1000-ha forest, using 1-ha plots.

$$P = 1 - (1-0.02)^n = 1 - (0.98)^n$$

then:	n =	1	5	10	20	50	100
	P =	0.02	0.096	0.183	0.332	0.636	0.867

However, if long thin rectangular plots (essentially, transect lines) are used, an "edge effect" caused by plot shape significantly increases probability of detection. For instance, on average across a range of plot orientations, a 1-ha plot 500 m long by 20 m wide will detect the infection if the centre point of the plot is closer than 130 m from the edge of the infection (Fig. 1). Mean distance from plot centre to infection, to detect is $\frac{250 + 10}{2} = 130$ m.

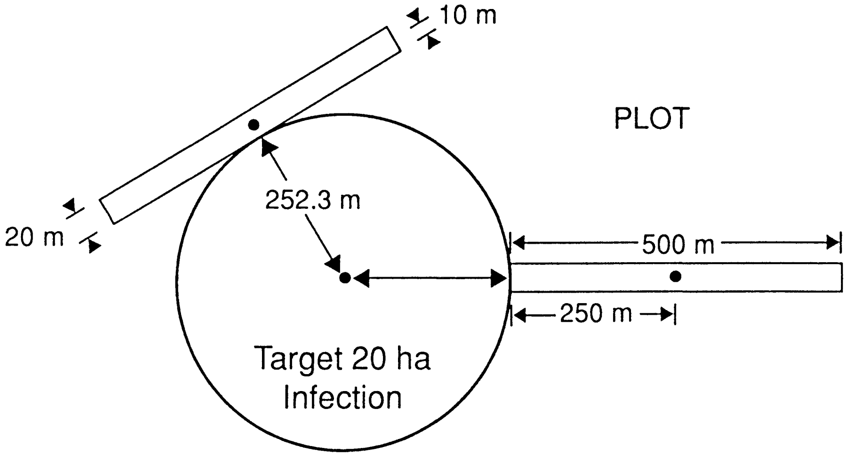

FIG. 1 — Diagrammatic representation of extremes of transect line plot orientation, relative to target, used to calculate probability of detection using transect lines.

Hence, "net target area" is equivalent to the area of a circle with radius 252.36 + 130 m = 382.36 m radius = 45.92 ha.

So, taking account of this "edge effect" from transect-type plots, for the same 20-ha circular infection in a 1000-ha forest

$$P = 1 - (1 - 0.04592)^n = 1 - (0.9548)^n$$

then:	n =	1	5	10	20	50	100
	P =	0.045	0.206	0.370	0.603	0.901	0.990

It is also worth noting that if the infection or target area is oval or irregular in shape, the probability of detection with "edge effect" increases. Further work to quantify the extent of such increase may be justified.

Using these principles, probability of detection was calculated for random point sampling with a range of sample intensities from 0 to 20% and circular infection target sizes from 10 to 100 ha (Fig. 2).

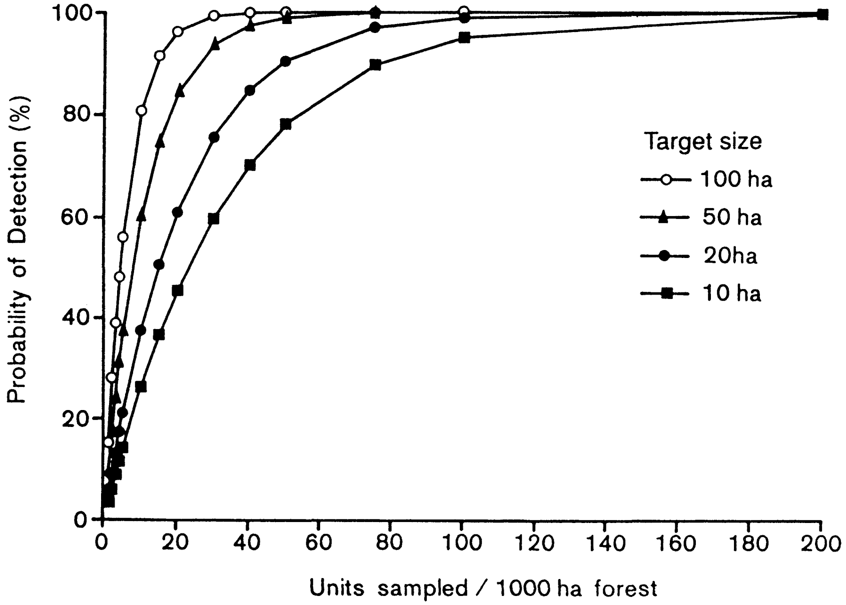

FIG. 2 — Probability of detection of target using random point sampling

Drive-through Roadside Surveys

Probability of detection was calculated for a sampling system with the plot area being a continuous strip along each side of the forest road. Sample size is dependent upon the distance into a forest stand that symptoms can be detected from a moving vehicle, and the density of roading in the forest.

Also, because the observer will be driving and inspecting at the same time, "efficiency" of detection will not be as great as if the observer was walking. It is assumed that efficiency of detection of symptoms at the forest margin is 100%, but trials indicate that efficiency declines to only 30% for symptoms up to 10 m within the stand (P.D. Gadgil, unpubl. data). Actual efficiency of detection would obviously vary from stand to stand depending on factors such as stand age, crop and weed densities, and topography.

Roading densities typically vary from 15 m/ha for the establishment phase, up to 30 m/ha for the harvesting phase of production forestry. Taking a 15-m/ha example, the "typical" hectare is shaped 15 m × 666.7 m, with a road through the centre. Assuming an intersecting pattern of roading, on average roads are then 1333 m apart, and "typical" units of forest can be portrayed (Fig. 3).

Assuming a 20-ha target infection occurs randomly with respect to road location, the probability of its centre being closer to a road than its radius of 252.3 m is:

$$\frac{252.3 \times 2}{1333} = 0.378$$

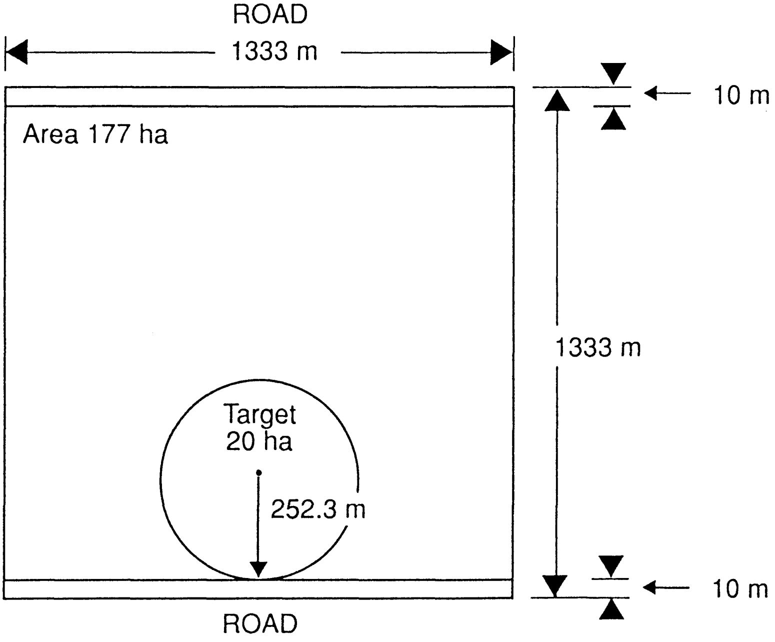

FIG. 3 — Diagrammatic representation of target in typical forest with 15 m roads/ha, used to calculate probability of detection from roadside surveys

The probability of its margin being between 0 and 10 m from the road is:

$$\frac{10 \times 2}{1333} = 0.015$$

With efficiency of detection in this 0–10 m strip at only 30%, this gives a combined probability of detection of 0.378 + 0.3 (0.015) = 0.3825. If target infection size is greater than 139 ha, and circular, probability of detection becomes 1.0 (at average road spacing) because the infection will overlap the road. Similarly, at a roading density of 30 m/ha, the "typical" unit of forest becomes 666 m square, or 44.36 ha, and probability of detection can be calculated for a range of target sizes, up to 1.0 (at average road spacing) for a target of 34.8 ha.

Using these principles, estimated probability of detection is presented for a range of roading densities surveyed, from 0 to 40 m/ha and target infection sizes from 10 to 100 ha (Fig. 4).

Aerial Survey

Probability of detection from aerial survey is primarily a function of "efficiency" of detection, rather than of sample intensity, because it is relatively cheap and easy to achieve a 100% sample when surveying from the air. Trials carried out in the past (Forest Research Institute, unpubl. data) have indicated a range of efficiencies of

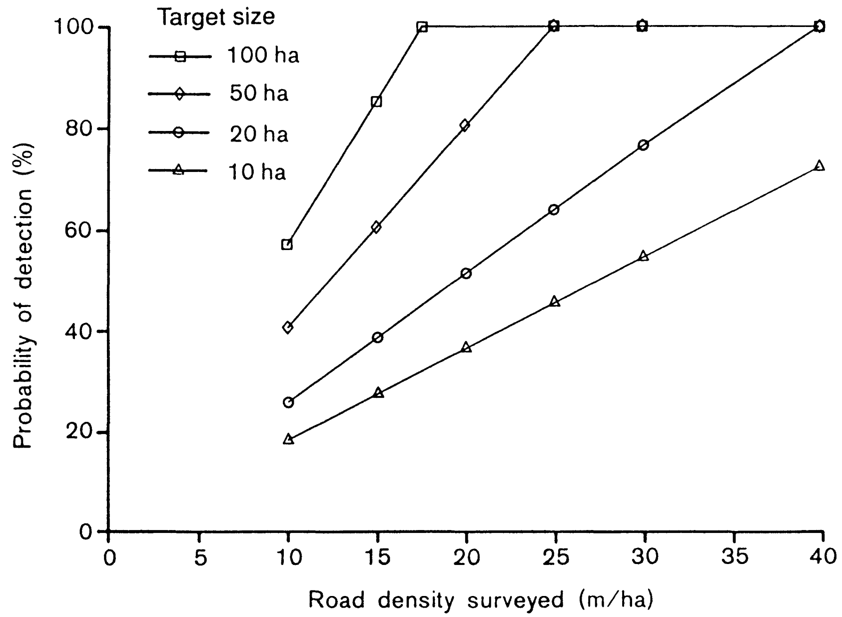

FIG. 4 — Probability of detection of target at various roading densities

detection, depending upon the magnitude of colour change in tree crowns, age of stand, and area infected, although targets set up for trial detection have not involved groups of trees covering more than a few square metres in area. The trials showed that where visible crown yellowing or browning was present, efficiency of detection was 30% in stands 0–2 years after establishment and 60% in older stands, and these figures are used in probability calculations. It is also assumed that successive passes allowing a different angle of view with respect to topography, and different light angles, have an equal probability of detection, such that probability of detection is given by:

$$P = 1-(1-Pe)n$$

where: P = probability of detection from n passes

Pe = probability of detection from each pass (efficiency)

n = number of passes

Using this formula, probability of detection where crown symptoms are visible was calculated for a range of flight line spacings across a forest with "normal" or even age-class distribution (Fig. 5).

Assumptions made for these calculations were:

(1) Flight altitude is 325 m above ground level;
(2) Effective visible survey width is 2000 m;
(3) Blind spot beneath aircraft is 162.5 m (50% of altitude);
(4) Efficiency is 30% for 0- to 2-year-old stands, 60% for >3-year-old stands.

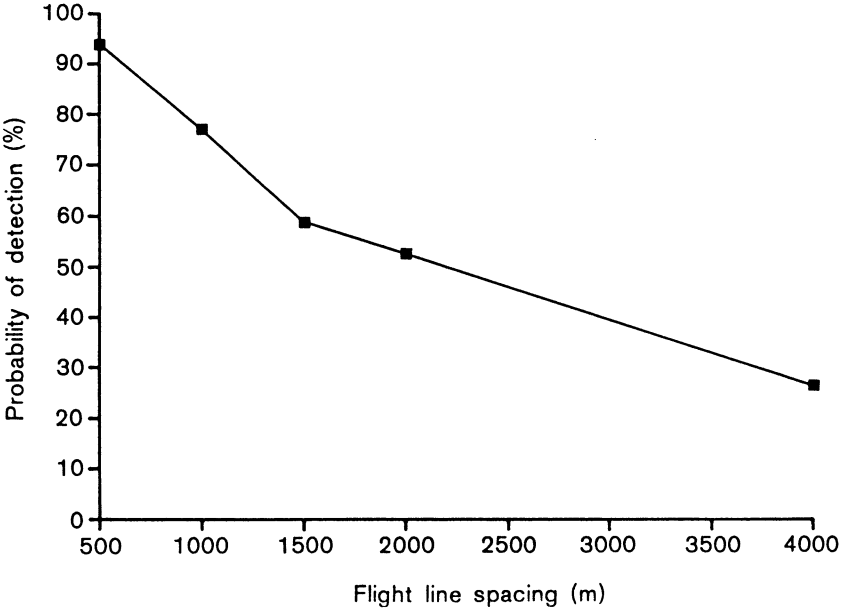

FIG. 5 — Probability of detection of target at various flight line spacings

Of the expected introductions (Table 3), only 13% are considered to be likely to cause crown symptoms early enough to be detected from aerial survey. The calculated theoretical probability of detection as given in Fig. 5 should therefore be scaled down by a factor of 0.13, to give probabilities ranging up to a maximum of 0.122 or 12.2% for flight line spacing at 500 m.

Observations by Forest Staff

It was considered that staff working in the forest may make a significant contribution to overall probability of detection through observation, both while driving and while carrying out their normal duties within the forest. Trials were recently established by FRI, however, in three major forests in the central North Island and, even though the blocks chosen were undergoing a range of forest operations, no reports of any of the "simulated" forest health problems were recorded. This indicates that although coverage or potential sample intensity by forest staff may be significant, current "efficiency" of detection is extremely low. Accordingly, for this exercise no contribution from forest staff has been counted towards the combined over-all probability of detection.

Survey of Port Environs

There are a total of 41 "ports" currently recognised in New Zealand; these include seaports and airports, as well as major industrial sites handling significant quantities of imported crated products. Survey around each port covers a 5-km-radius circle (8000 ha) and involves walk-through inspection of parks, reserves, plantations, and other areas where a wide range of potential host species can be sampled. Full systematic or random sampling of the port environs is not considered practical because of the distribution of host species. Also, many of the ports fall in urban areas, and so there are problems with access.

For the purpose of this review, and because of a lack of objective data, it was assumed that each port survey gave a probability of detection of 50%. This was based on an estimate of the proportion of trees that would be inspected in a single survey through the parks and gardens. It was also assumed that subsequent independent surveys would have an equal probability of detection. (These assumptions may not be strictly valid, and further work to quantify probability of detection better is required).

Using these assumptions, however, probability of detection is estimated for a range of survey frequencies, using the same formula as for aerial survey:

then: $P = 1 - (1 - P_e)^n$

Surveys per year	(n) =	1	2	3	4	5	6	7	8
Prob. of detection	(P) =	0.500	0.750	0.875	0.937	0.969	0.984	0.992	0.996

Cost of Surveys

Costs were calculated for all survey methods, based on resources required and standard unit costs. For each system, except port surveys, a range of cost estimates was derived. Details of assumptions used and calculations are given in Appendices 1–4.

Cost and probability of detection of a 20-ha circular target were then combined, to allow calculation of cumulative cost of achieving increasing levels of probability for each survey method (Table 9).

TABLE 9–Probability of detection and costs of surveys

Random survey								
Probability of detection (%)	37	61	76	85	90	97	99	100
Low cost ($/ha)	0.21	0.38	0.55	0.72	0.89	1.31	1.74	3.44
High cost ($/ha)	0.45	0.86	1.28	1.69	2.10	3.13	4.16	8.28
Roadside survey								
Probability of detection (%)	22	51	77					
Low cost ($/ha)	0.05	0.10	0.15					
High cost ($/ha)	0.11	0.22	0.33					
Aerial survey								
Probability of detection (%)	3	7	8	10	12			
Low cost ($/ha)	0.021	0.024	0.026	0.031	0.045			
High cost ($/ha)	0.061	0.064	0.066	0.071	0.085			
Port survey								
Probability of detection (%)	50	75	88	94	96	98	99	100
Cost ($/ha)	0.11	0.22	0.33	0.45	0.56	0.67	0.78	0.89

For the three forest survey systems, cost per percentage point of probability increases from aerial to roadside to random survey, and cumulative probability from the combination of these independent surveys is given by:

$$P = 1 - (1 - P_1) \times (1 - P_2) \times (1 - P_3)$$

where: P = combined Probability of detection
P_1 = Probability of detection from aerial survey
P_2 = Probability of detection from roadside survey
P_3 = Probability of detection from random survey

Combined cumulative cost and probability of detection for both high- and low-cost forest locations (150 km and 50 km respectively each way, to and from the forest) are presented in Fig. 6. Probabilities up to 12% are achieved from aerial survey, followed by combining aerial with roadside survey up to 54%, and finally combining both with random survey, taking probabilities to 100%. These curves have been characterised using regression analysis and can be modelled approximately with the following functions:

Low cost (\$/ha) $= -0.35454 \times \text{Ln}(1-P)$
High cost (\$/ha) $= -0.89305 \times \text{Ln}(1-P)$

Port cost is also modelled by:

Cost (\$/port) $= -1286 \times \text{Ln}(1-P)$
where: P = combined probability of detection
$\text{Ln} = \log_e$

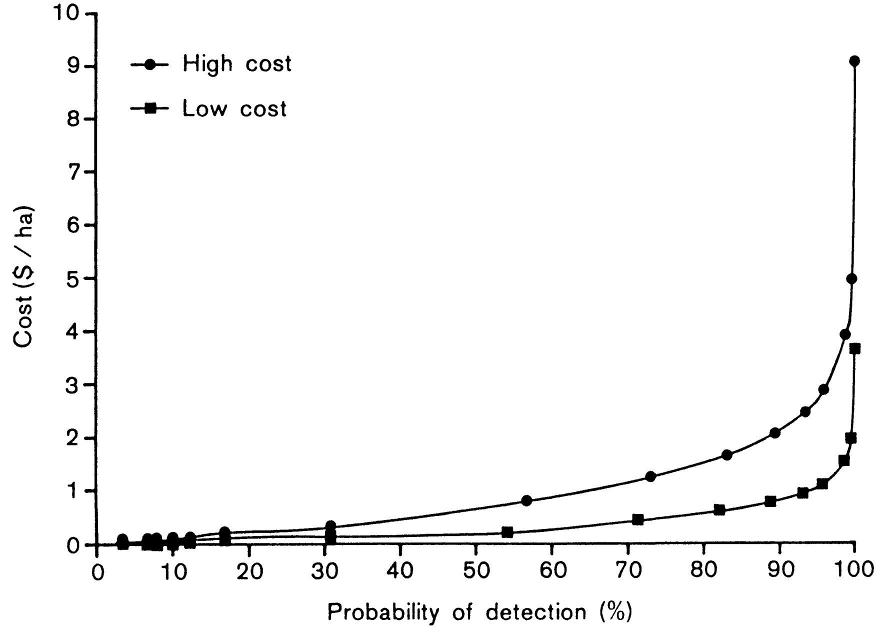

FIG. 6 — Cumulative cost and probability of detection for high- and low-cost locations (150 and 50 km each way, to and from the forest)

COSTS AND BENEFITS OF DETECTION SURVEYS

Variation in Costs in Different Regions

To allow optimal national allocation of survey effort, an analysis of the historical records of new detections was carried out (P.D. Gadgil, J. Bain, pers. comm.) which provides an estimate of the expected average number of future new introductions per annum by region and port (Table 10).

Using this estimate of introductions per annum by region and assuming that the introductions will be in the exotic forest area of the region, the number of years and the area over which survey will need to be carried out, and the regional net present value of the costs incurred in this survey, can be calculated to achieve a range of probabilities of making one new detection. For example, in the Northland region, the expected number of new introductions per annum is 0.361, or one every 2.77 years. Forest area is 120 300 ha and, using the low estimate of survey cost (50 km travel distance) and a 7% interest rate, regional cost to achieve a given probability of detecting one new introduction is given by area × years of survey × mean discounted survey cost for given probability of detection.

This can be compared with Taupo region, with a similar expected number of introductions at 0.35 per annum, or 1 every 2.86 years, but a larger area to survey of 193 180 ha. Regional costs are proportionally higher (Table 11).

Marginal Cost

Because the benefit of early detection should allow action to prevent or minimise the rate of spread of a new introduction, it is assumed that each detection provides equal benefit, irrespective of region within which it is detected. Therefore, by calculating the marginal cost of improving the probability of detecting one new introduction by each percentage point for each region, the optimum allocation of detection effort can be determined across regions for any given level of expenditure. This is done by selecting the level of survey in each region where the marginal costs are equal, so giving the allocation of effort nationally which will maximise the number of detections per dollar spent.

Using this method to allocate survey intensities to regions, with associated regional detection levels, the relationship between accumulated national (low) cost and detections was derived. This curve has been characterised by a logarithmic function and takes the form:

National (low) cost estimate $= -0.25568 \times \mathrm{Ln}\,(1 - D)$
where cost = accumulated regional direct survey costs ($/ha)
D = proportion of new introductions detected
Ln $= \log_e$

(Caution: This function is derived from only three points between $D = 0.72$ and 0.90.)

Maximum Net Benefit

Combining the benefit-per-hectare curve (adjusted by a factor of 0.7873 for increased area, to include port environs) with the detection cost curve, net benefit can be derived by subtraction, across the full range of proportion of new introductions

TABLE 10–Historical record of new detections in (A) port environs within biological regions and (B) biological regions excluding ports

Biological region	Insects	Fungi	Total	Average/year*
A. Port environs				
Northland	2	1	3	
Auckland	15	3	18	
Bay of Plenty	1	1	2	
Taranaki	3	2	5	
Gisborne	3	0	3	
Hawke's Bay	3	0	3	
Wanganui	1	1	2	
Wellington	3	3	6	
Nelson	3	0	3	
Mid Canterbury	4	2	6	
South Canterbury	1	0	1	
For all port environs				1.473
B. Biological regions excluding port environs				
Bay of Plenty	4	15	19	0.592
Northland	5	7	12	0.361
Taupo	1	10	11	0.350
Auckland	4	5	9	0.269
Wanganui	5	3	8	0.232
Wellington	5	3	8	0.232
Mid Canterbury	6	1	7	0.194
Wairarapa	1	4	5	0.156
Waikato	1	3	4	0.124
Nelson	1	3	4	0.124
Southland	2	1	3	0.086
Hawke's Bay	–	2	2	0.065
Dunedin	1	1	2	0.059
South Canterbury	1	1	2	0.059
Taranaki	2	–	2	0.054
Brunner	–	1	1	0.0123 average per region
Westland	–	1	1	
Coromandel	1	–	1	
Rangitikei	1	–	1	
Marlborough	1	–	1	
Central Otago	1	–	1	
North Canterbury	–	–	–	
Gisborne	–	–	–	
Mackenzie	–	–	–	
Stewart Island	–	–	–	
Otago Lakes	–	–	–	
Fiordland	–	–	–	
Kaikoura	–	–	–	
Marlborough Sounds	–	–	–	

* The average number/year has been calculated as (No. of insects/37 years) + (No. of fungi/31 years).
Source: Forest Research Institute, unpubl. data.

TABLE 11–Regional costs

Probability of detecting one introduction	0.1	0.3	0.5	0.7	0.9
Northland regional cost ($)	10,972	37,142	72,180	125,374	239,776
Taupo regional cost ($)	18,120	61,341	119,208	207,060	396,000

detected (Fig. 7). From this, the point of maximum net benefit can be selected, involving survey at a range of levels within the regions, which combine to give a proportion detected of 95%, a national average (low) cost estimate of $0.76/ha (total cost $1.18 million), benefit of $5.52/ha, and a net benefit of $4.76/ha (total net benefit $7.33 million).

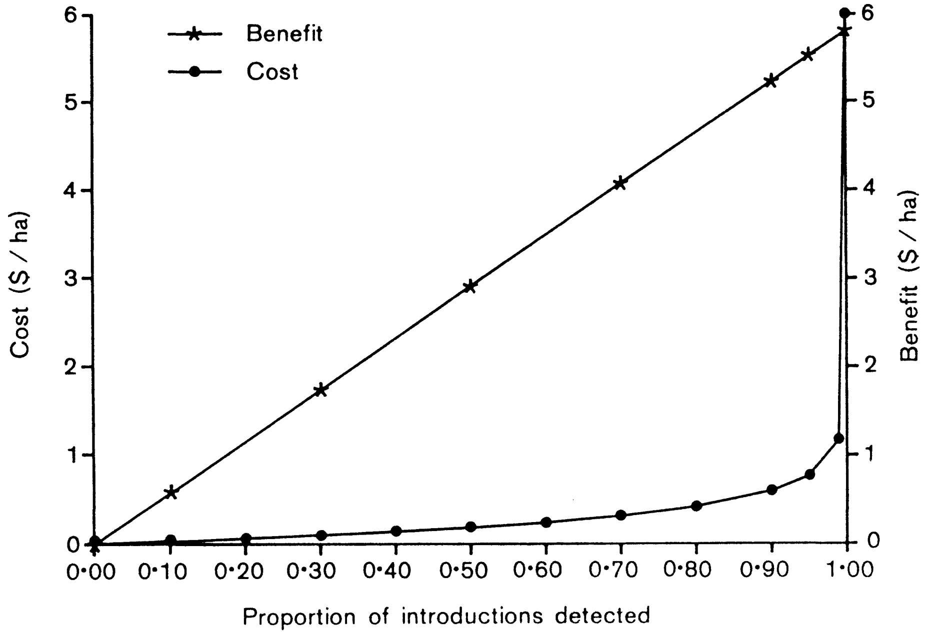

FIG. 7 — National cost and benefit of various proportions of introductions detected

CONCLUSIONS

Using this model, regional levels of survey are defined which account for costs, areas, and levels of risk, which combine to give a national survey that maximises net benefit. Using assumptions as detailed in this paper, maximum net benefit is achieved at survey levels which will detect 95% of all new introductions, compared with current operational levels of survey in New Zealand which are estimated theoretically to have achieved less than 50% detection over current years.

It appears justified to increase current national levels of survey progressively, while at the same time refining the analysis and further examining the assumptions made to define the point of maximum net benefit more confidently. The model presented provides a framework for ongoing analysis and justification of future levels of forest health survey in New Zealand, and may also be applicable, using appropriate local data, to other situations, both within New Zealand and overseas.

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APPENDIX 1

COSTS OF RANDOM POINT SAMPLING

Assumptions

(1) Walking speed while surveying 3 km/h (= 20 minutes for 1-ha plot involving a 1-km walk).

(2) Time taken for driving from one plot to another = 5 minutes per 100 ha irrespective of speed and roading density.

(3) Labour cost = $35/h.

(4) Cost of running a vehicle = $0.50/km.

Costs

A. *Travel costs within a forest*

(1) Cost of vehicle running: 20 km/1000 ha = $10
(Roading density 10 m/ha: each road travelled twice)
(Roading density 20 m/ha: each road travelled once)
(Roading density 30 m/ha: not all roads travelled)

(2) Travel time within a forest: 50 minutes/1000 ha = $29.17
Total cost of travel within a forest = $39.17/1000 ha.

B. *Travel time to and from forest, and productivity*

Distance each way (km)	Speed (km/h)	Time/return trip (h)	Total time/ day (h)	Productive time (h)	Plots/ day
50	70	1.43	8	6.24	18.7
100	70	2.86	8	4.81	14.4

Productive time = (total time) – (travel time + 0.33 h smoko)
Plots per day = Productive time/average time per plot

Costs

Distance each way (km)	Travel cost/day		Plots/day	Travel cost/plot
	Labour ($)	Vehicle ($)		
50	50.05	50	18.7	5.34
100	100.10	100	14.4	13.85

C. *Total costs*

Sample intensity (%)	Cost per 1000 ha forest (%)				Total cost/ha ($)	
	Survey	Travel within forest	50 km travel	100 km travel	50 km travel	100 km travel
1	116.65	39.17	53.40	138.50	0.21	0.29
2	233.31	39.17	106.80	277.00	0.38	0.55
3	349.97	39.17	160.20	415.50	0.55	0.88
4	466.62	39.17	213.60	554.00	0.72	1.06
5	583.27	39.17	267.00	692.50	0.89	1.32
7.5	874.91	39.17	400.50	1038.75	1.31	1.95
10	1166.55	39.17	534.00	1385.00	1.74	2.59
20	2333.10	39.17	1068.00	2770.00	3.44	5.14

APPENDIX 2

COSTS OF DRIVE-THROUGH, ROADSIDE SURVEY

Assumptions

(1) Average speed on survey: 12 km/h.

(2) Half the roads are travelled once and half twice.
(This assumption is made to allow for travel on "no exit" roads). The actual distance travelled on survey is therefore 1.5 times the actual length of the roads in the forest.

(3) Labour cost: $35/h.

(4) Vehicle running cost: $0.50/km.

Costs

A. *Travel within a forest*

(1) Cost of vehicle running = 1.5 × 0.50 = $0.75/km of forest road.

(2) Labour cost = $35/12 km = $2.92/km of forest road.

	Roading density (m/ha)		
	10	20	30
Survey cost/ha ($)	0.037	0.073	0.11

B. *Travel time to and from forest, and productivity*

Distance each way (km)	Speed (km/h)	Time/return trip (h)	Total time/ day (h)	Productive time (h)	Area/day (ha) Roading density (m/ha)		
					10	20	30
50	70	1.43	8.0	6.24	7488	3744	2496
100	70	2.86	8.0	4.81	5772	2886	1924
150	70	4.29	8.0	3.71	4061	2030	1354

Productive time = (total time) – (travel time + 0.33 h smoko)
Area/day = (Productive time × 12 000 m/h)/roading density (m/ha)

C. *Total costs*

Distance each way (km)	Travel cost/ha ($)* Roading density (m/ha)			Travel + survey cost/ha ($) Roading density (m/ha)		
	10	20	30	10	20	30
50	0.013	0.027	0.04	0.05	0.10	0.15
100	0.035	0.069	0.10	0.07	0.14	0.21
150	0.074	0.15	0.22	0.11	0.22	0.33

* Travel cost/ha = (labour cost/h × time/return trip) + (vehicle cost/km × km/return trip)/(area/day (ha))

APPENDIX 3

COSTS OF AERIAL SURVEY

Assumptions

(1) Flying speed on survey: 80 knots (160 km/h)

(2) Flight line spacing: 500, 1000, 1500, or 2000 m.

(3) Labour cost: $35/h ($70/h for the two officers required)

(4) Aircraft cost (including landing fees): $153/h for a Cessna 172.

Costs

A. Productive flight time and costs

Flight line spacing (m)	Flight km/ 100 ha	Surveyed area (ha/h)	Productive time (h/100 ha)	Cost/100 ha ($)
500	2.0	8 000	0.012	2.79
1000	1.0	16 000	0.006	1.39
1500	0.7	24 000	0.004	0.93
2000	0.5	32 000	0.003	0.70

B. Costs other than those of productive time

The actual costs for 1988–89 for a flight line spacing of 2000 m are known for some regions. Using these and the calculated cost of productive time for this spacing, other costs associated with survey (ferrying, preparation, travel to airport) can be calculated.

Region	Actual cost ($/100 ha)	Productive cost ($/100 ha)	Other cost ($/100 ha)	Proportion of other cost (%)
Bay of Plenty				
Central	2.4–2.9	0.7	1.7–2.2	71–76
Remote	5.7	0.7	5.0	88
North Auckland	3.0	0.7	2.3	77
Canterbury, Westland	6.1–6.4	0.7	5.4–5.7	88–89

C. Total costs

The "other" costs will remain the same for any flight line spacing because they are not dependent on the time spent flying over the forest. Total costs given below are calculated using "other" costs for central Bay of Plenty, North Auckland, and Canterbury/ Westland.

"Other" costs ($/100 ha)	Total costs ($/100 ha) Flight line spacing (m)			
	500	1000	1500	2000
1.7	4.49	3.09	2.63	2.40
2.3	5.09	3.69	3.23	3.00
5.7	8.49	7.09	6.63	6.40

APPENDIX 4

COSTS OF PORT SURVEY

Assumptions

(1) The port survey covers an area with a radius of 5 km = 8000 ha.

(2) All parks, plantations, and some roadside trees within this area are examined.

Costs

The 1988–89 actual costs were \$56,163 to cover 22 ports twice a year and 19 ports once a year.

Average cost/port/survey = (\$56,163)/(22 × 2) + (19) = \$891.50.

No. surveys/annum	Cost/port ($)	Cost/ha ($)
1	891.50	0.11
2	1730.00	0.22
3	2674.50	0.33
4	3566.00	0.45
5	4457.50	0.56
6	5349.00	0.67
7	6240.00	0.78
8	7132.00	0.89