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AN ECONOMIC TOOL FOR EVALUATING DISEASE MANAGEMENT IN THE JARRAH FORESTS OF WESTERN AUSTRALIA*

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A pathogenic, soil-borne fungus has been gradually spreading through the jarrah forest of Western Australia for most of this century. On some sites this fungus can cause almost total forest destruction. Infection is incurable and the effects are irreversible. This paper develops a means for evaluating disease control measures and identifying the optimal level of protection. Standard protection measures are warranted for high and moderate impact sites, over a wide range of risks. Increased expenditure on forest protection is warranted for high and moderate impact sites at especially high risk.

Introduction

Jarrah forests occur within the south-western corner of Western Australia and represent an important economic and conservation resource in the region. Progressively, parts of this forest are being changed due to the spread of *Phytophthora cinnamomi* Rands, a microscopic fungus believed to have been introduced to the State near the turn of the century (Podger, 1972). The pathogen can cause long-term changes in species composition, and the decline appears to be irreversible (Shearer, 1990).

The most recent estimate is that 235,700 hectares (about 15 percent) of the public jarrah forest is infected (CALM, 1994). According to Podger (1972), the affected area in the jarrah forest increases by four per cent per year. More recent estimates are not available, but it is clear that without intervention, the disease could spread to the majority of the jarrah forest.

Whilst the fungus is more commonly referred to as jarrah dieback, this is an unfortunate misnomer. The common name owes to its potential to kill the dominant eucalypt, jarrah (*Eucalyptus marginata* Donn ex Smith), but many other endemic species are also susceptible (Shearer, 1992). Outside the jarrah forest, some plant species face

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extinction because of their restricted range and susceptibility, and entire conservation reserves are threatened (Shearer *et al.*, 1991). Given the large areas already alienated for agriculture and urban development, this represents an enormous ongoing loss of natural heritage.

Clearly the disease is causing major ecological damage, but it has had its most direct economic impact on forest based industries, particularly mining and timber harvesting. These industries are bound by both legislative and moral obligations to manage their operations to control *P. cinnamomi* dieback. Shearer (1990) reports expenditure on dieback mapping, containment and research of $3.37 million in 1989.

Forest management subject to the risk of disease is not only more expensive, it is also much more difficult. Policy makers and resource managers must make decisions whose outcome is highly uncertain, but in the worst case can permanently damage a precious natural resource. The aim of this paper is to assist this difficult decision-making process by providing managers with a tool to help determine the level of protection warranted for a particular site, thereby improving the allocation of resources in the forest overall.

The next three sections are as follows. The first section provides a brief overview of disease management options, and the second section presents a model for the expected value of a site, subject to a risk that the forest may be irreversibly degraded. This model is used in the third section to derive a rule for choosing the level of forest protection. Standard protection measures are then evaluated using recent information on forest values and management costs. These protection measures appear to be amply justified for high and moderate impact sites, over a wide range of risks of infection. Increased expenditure on forest protection appears warranted for high and moderate impact sites at especially high risk. The final section briefly discusses limitations and further application of the model.

Disease Management Options

Eradication of *Phytophthora* species from the jarrah forests has never been thought practicable, and as yet there is no acceptable technique for broadscale control. The difficulty of determining whether or not a particular control method will be successful throughout a rotation is a possible hindrance to the implementation of controls in the forest. However, as explained by Shea (1979) and Shearer and Tippett (1989), there are five main options available to manage the disease.

Manipulation of Understorey Composition

This is a somewhat controversial practice, since the understorey is one of the most valued components of the jarrah forest. The principle behind this practice is that *Banksia grandis* is the main summer reservoir and favoured host of *P. cinnamomi*, and its removal helps to reduce potential sources of infection (Shea and Malajczuk, 1977). In addition, on some sites appropriate fire management regimes can result in the development of an understorey dominated by *Acacia* species, which are antagonistic to the fungus.

Increasing Host Resistance

This is achieved through selective breeding programmes. A number of breeding lines that show high resistance to the fungus are undergoing development at Murdoch and Edith Cowan universities, in a joint project also involving the Western Australian Department of Conservation and Land Management (CALM) and funded by ALCOA.

Quarantine

In the mid 1970s, large areas of the southwestern forest estate were quarantined. These areas became known as 'disease risk areas', covering up to 36 per cent of state forests from Mundaring through Walpole (Forests Department, W.A. 1982). Some roads have been closed and vehicle access into these areas is restricted, particularly when road surfaces are moist.

Chemical Controls

Disinfectants have been used with varying success to sterilise vehicles, entrances and equipment in nurseries and road surfaces within bauxite minesites. However, most of these chemicals are phytotoxic and therefore cannot be used to control infections in desirable vegetation. Systemic fungicides are available which will inhibit and sometimes kill *Phytophthora* mycelium growing in host plants. Recent research indicates that phosphorous acid may hold promise for disease control in discrete areas.

Hygienic Operations

Hygiene is the most important of the disease management tools, and is the focus of the rest of this paper. The fundamental principle is to limit, or better still prevent, the movement of infected soil into uninfected areas. Hence, the basis of any hygienic operation is a knowledge of the location of infected areas. This information is presented on a map known as a hygiene plan, which shows the extent of existing infections and some other important categories which are managed as separate units during forest operations. For roading, mining and timber harvesting operations, it is a prerequisite that a current dieback hygiene plan be prepared and relevant boundaries from it be demarcated in the field.

Activities involving soil movement are subject to a 'seven-way test', which is integral to the Dieback Hygiene Evaluation Manual (Underwood and Murch, 1984; CALM, 1993). The test is a formal process to evaluate the proposed operation, first in terms of the risk of introducing the pathogen, and second in terms of the likely impact (or hazard) that would result if an infection were introduced to both the operational area and the area downslope of it.

There are three broad categories of disease in the jarrah forest, defined by the level of 'impact' inherent at a site (Shea, 1992). 'Low impact' sites are those that generally support a range of resistant species, and deaths due to disease are not readily observed. 'Moderate impact' sites are characterised principally by death of most *Banksia grandis*, some scattered deaths of other components of the shrub layer (e.g., *Xanthorrhoea* species), and 'minimal' deaths of the jarrah overstorey. 'High impact' sites are characterised by *almost total* destruction of the understorey and a large proportion of the susceptible midstorey, and the death of many of the jarrah.

The 'seven-way test' prescribes the guidelines and conditions that will apply to the operation. Supervising CALM staff must be satisfied that the preventative measures prescribed will adequately minimise the risk of introduction and spread of the disease. Essentially, approval for an operation is granted if the forest manager *perceives* that the hazard is manageable and outweighed by the benefits of allowing the activity to proceed.

The decisions required by forest managers are difficult and carry potentially severe consequences for the health of the forest. The aim of the next two sections is to provide forest managers with some formal guidance in this difficult decision making process, in a form that is convenient and applicable so that it can best contribute to real management decisions.

The Site Value under Risk of Infection

Evaluating the benefits of the hygiene treatments requires a means of relating the hygiene treatments to the risk of infection. Reed (1984 and 1987) developed a model for the site value subject to the risk of fire. However, the risk of infection by *P. cinnamomi* is very different from that posed by fire. Fire can terminate an existing stand at no risk to future stands, but an infection by *P. cinnamomi* can decimate both the existing jarrah stand and all future ones, inherently changing the quality of the site and degrading the site value forever. Incorporating the risk of infection by *P. cinnamomi* in the site value requires a model involving a risk that the site value may change permanently at any time. The following develops a model for the expected value of a site subject to such a risk.

Like the standard Faustmann model, the model includes a rotation length that is the same for all future forest generations. The model can be used to characterise the optimal rotation length and the optimal level of hygiene expenditure for a site, in terms of the risk of infection, likely impact and other exogenous values. That is beyond the scope of this paper, though, and is not necessarily relevant in the actual management of the jarrah forest. Virtually all of the jarrah forest is publicly-owned and is managed for both timber and non-timber values. Due to the significant but as yet unquantified non-timber values of the jarrah forest, the rotation length is set administratively at a level that forest managers believe appropriately balances the timber and non-timber values. Therefore, for the purposes of this study, the rotation length is taken as fixed and exogenously determined. The model is used in the next section to evaluate preventative measures in general, and the hygiene treatments in particular, in terms of the minimum required reduction in the risk of infection.

Consider an uninfected site at the beginning of a rotation. Let Π denote the *site value*: the present value of all future benefits from the site. The time of infection (if ever) is random, so Π is a random variable. Let $E_n[\Pi]$ denote the conditional expected value of Π if the site is infected in the *n-th* rotation. Assuming constant market conditions, the expected value of the site at the *start* of the *n-th* rotation is the same as the expected value of the site infected in the first rotation, $E_1[\Pi]$. Thus, $E_n[\Pi]$ can be expressed as the present value of the first n-1 uninfected rotations, plus the present value of $E_1[\Pi]$:

$$
\begin{aligned}
E_n[\Pi] &= \pi + \pi\delta^R + \cdots + \pi\delta^{R(n-2)} + E_1[\Pi]\delta^{(n-1)R} \\
&= \pi\frac{1-\delta^{(n-1)R}}{1-\delta^R} + E_1[\Pi]\delta^{(n-1)R}
\end{aligned}
\qquad (1)
$$

where π is the present value of one uninfected rotation, R is the rotation length and δ is the annual discount factor. (The second equality results from the formula for the sum of the first n-1 terms of the geometric series in δ^R.) Note that $\pi/(1-\delta^R)$ is the value of a site that remains uninfected forever — the standard Faustmann model. Denoting this by Π_U, expression (1) becomes

$$
\begin{aligned}
E_n[\Pi] &= \Pi_U(1-\delta^{(n-1)R}) + E_1[\Pi]\delta^{(n-1)R} \\
&= \Pi_U + (E_1[\Pi] - \Pi_U)\delta^{(n-1)R}
\end{aligned}
\qquad (2)
$$

Let p denote the probability of infection in any one rotation. The probability of infection in the *n-th* rotation is the probability of infection in that rotation times the probability that the site is not infected previously: $p(1\text{-}p)^{n\text{-}1}$. The unconditional expected value of Π is then

$$(3)\qquad \mathrm{E}[\Pi]=\sum_{n=1}^{\infty}\mathrm{E}_n[\Pi]\,p(1-p)^{n-1}.$$

$$=\mathrm{E}_1[\Pi]p+\sum_{n=2}^{\infty}\left(\Pi_{\mathrm{U}}+(\mathrm{E}_1[\Pi]-\Pi_{\mathrm{U}})\delta^{(n-1)R}\right)p(1-p)^{n-1}.$$

Applying the standard formula for the infinite sum of a geometric series, expression (3) reduces to

$$(4)\qquad \mathrm{E}[\Pi]=\frac{\Pi_{\mathrm{U}}(1-\delta^{R})(1-p)+\mathrm{E}_1[\Pi]p}{1-(1-p)\delta^{R}}.$$

(Algebraic details are available from the first author.) Note that when there is no risk of infection (p=0), the expected site value is the uninfected site value ($\mathrm{E}[\Pi]=\Pi_{\mathrm{U}}$); and when the site is already infected (p=1), the expected site value is the infected site value ($\mathrm{E}[\Pi]=\mathrm{E}_1[\Pi]$, which is derived below). Also, for long rotations or small discount rates (δ^R small), the expected site value is approximately the mean of the uninfected and expected infected site values ($\mathrm{E}[\Pi] = \Pi_{\mathrm{U}}(1-p) + \mathrm{E}_1[\Pi]p$).

Using expression (4) to evaluate expenditure on disease prevention requires further specification of both $\mathrm{E}_1[\Pi]$ and p. Let p_0 denote the probability of infection during harvest, and let p_1 denote the annual probability of infection between harvests. The latter is the 'background' environmental risk due to sources other than timber harvests (natural runoff from infected sites, infected soil spread by animals, etc.) The fungus is spread mostly by timber harvests and other disruptive forests interventions, so $p_1 \ll p$). We assume p_1 is constant. This is not strictly true in practice, since there is an increased risk of infection when thinnings occur. This effect can also be included in the model, but it would add complexity and detail that is not warranted given availble information on disease management. Under this assumption, the probability of infection during one rotation is

$$(5)\qquad p=1-(1-p_0)(1-p_1)^{R-1}$$

Given that an infection occurs in the first rotation, the probability that it occurs at time $t \geq 1$ is

$$(6)\qquad P_t=p_1(1-p_0)(1-p_1)^{t-1}/\,p$$

Since there is no cure for infection, we assume that once the site is infected, it remains so forever. So if the site becomes infected during harvest, the site value is fixed at Π_I. Assume that an infection in the last year of the rotation has no effect on the value of the rotation. In this case, the site value is the same as an infection that occurs during harvest: $\pi+\Pi_I\delta^R$. The effect of an infection at an intermediate stage in the rotation depends on a variety of factors, and is largely unknown. A linear interpolation between time 0 and R-1 gives the site value for an infection at time t as

$$\text{(7)} \quad \Pi_I + \frac{\pi - \Pi_I(1-\delta^R)}{R-1} t = \Pi_I + \beta\, t$$

Note that the ratio β in expression (7) can be considered as the annual benefit of infection-free growth.

If an infection occurs in the first rotation, the expected value of the site equals the infected site value plus the expected benefit of any years of infection-free growth. From expressions (6) and (7), this is

$$\text{(8)} \quad E_I[\Pi] = \Pi_I + \sum_{t=1}^{R-1} P_t \beta\, t$$

Substituting expression (8) into expression (4) gives a formula for the unconditional expected value of the site. The result can be simplified considerably, but the algebraic manipulations are fairly long and tedious, and are not shown. (Details are available from the first author.) The result of the simplification is

$$\text{(9)} \quad E[\Pi] = \frac{\Pi_I + (1-p_0)\left(\pi(\alpha + (1-p_1)^{R-1}) - \Pi_I(\alpha(1-\delta^R) + (1-p_1)^{R-1})\right)}{1-\delta^R(1-p_0)(1-p_1)^{R-1}},$$

where

$$\text{(10)} \quad \alpha = \frac{(1-p_1R(1-p_1)^{R-1} - (1-p_1)^R)}{p_1(R-1)}.$$

Choosing Forest Protection Levels

In practice, a standard hygiene regime is applied in all timber harvesting operations, regardless of the risk of infection or the likely impact. This is clearly a sound forest management practice, given the limited knowledge of the benefit of different treatment regimes. This section aims to develop a practical means for identifying the optimal level of protection for a site with a given rotation length, and to evaluate the current measures to control spread of the disease.

As described above, current protection measures involve a variety of procedures. Applying these procedures involves high fixed costs, so there is limited scope for varying disease management expenditures continuously. Instead of a continuum of expenditure, the protection measures are best viewed as a series of discrete regimes, each regime consisting of a set of procedures. From the set of all possible regimes, the regimes that involve higher cost without a reduction in the risk of infection can be eliminated, resulting in a subset of cost-effective regimes.

Consider two possible disease management regimes, A and B. Assuming the forest manager is risk-neutral, regime B is superior to A if $E[\Pi|B] > E[\Pi|A]$, and conversely. Each regime has an associated probability of infection, denoted $p_0(A)$ and $p_0(B)$. If the forest manager knows these probabilities — as well as the other terms in the expected site value — then straightforward computation using the formula for the expected site value will reveal whether treatment A or B is superior. Comparison of the costs of all cost-effective regimes would reveal the optimal regime.

The probabilities of infection are the targets of the protection measures. But in addition to being the most important factors, they are also subject to the most uncertainty. Due to the limited experience with the range of alternative protection measures and the wide variety of factors involved, the forest manager is apt to have only vague ideas about the probability of infection for different regimes. Given this uncertainty, the most useful information to the forest manager is the range of probabilities over which one regime is superior to another. The forest manager can then compare his or her estimates of the probabilities of infection, however vague, to the ranges over which each regime is superior, and then act accordingly.

Solving the inequality $E[\Pi|B] > E[\Pi|A]$ for $p_0(B)$ yields

$$(11) \qquad p_0(B) < 1 - \frac{E[\Pi|A] - \Pi_I}{\delta^R (1-p_1)^{R-1} E[\Pi|A] + \Delta}$$

where

$$(12) \qquad \Delta = \pi(B)\left(\alpha + (1-p_1)^{R-1}\right) - \Pi_I\left(\alpha(1-\delta^R) + (1-p_1)^{R-1}\right)$$

Regime A is superior to B if the inequality is reversed, and the two regimes have the same value if the relationship holds as an equality. The term on the right-hand side of the above inequality thus separates the risks of infection under both regimes into a region in which A is superior to B, and a region in which B is superior to A.

Note that the term on the right of inequality (11) does not involve $p_0(B)$, so the boundary between the two regions can be expressed as a function of $p_0(A)$ and the other parameters:

$$(13) \qquad f(p_0(A),\ldots) = 1 - \frac{E[\Pi|A] - \Pi_I}{\delta^R (1-p_1)^{R-1} E[\Pi|A] + \Delta}$$

This relationship is most easily inspected using a graph. The boundary f can be calculated and plotted for a range of values of $p_0(A)$, and for given values of the other variables. The forest manager can determine by inspecting the plot which regime has the greater value, based on his or her beliefs about the probabilities of infection under the different regimes. The given variables in the relationship can be changed and the relationship re-plotted to determine how sensitive the decision is to these variables.

For example, this technique is used below to evaluate the single most important component of the current protection measures, the preparation of the hygiene plan and subsequent field demarcation, in terms of its minimum required effectiveness in disease risk reduction. That is, let regime B be the implementation of the hygiene plan and A be the regime involving no special measures of disease control. REgime B is beneficial wherever it can reduce the probability of infection below the value calculated for the boundary f.

The variables required to compute the boundary include the cost per hectare of implementing the two regimes, h_A (= 0) and h_B; the rotation length (R); the discount factor (δ); the present value of one uninfected rotation (π); the site value for an infected site (Π_I); and the annual risk of infection (p_I), which is taken to be the same under both regimes. The values that were assigned to these variables are given below.

Cost of the Hygiene Plan

In 1990, a hygiene plan was prepared for 2,235 hectares of the Wilson Forest Block, an area approximately 100 km south of Perth. Total cost of the hygiene plan and demarcation was \$31,350, resulting in a per hectare cost h_B = \$13.50 (Brennan, 1994).

Rotation Length

The jarrah forest has considerable non-timber values, but the optimal rotation for total social benefit is not known. The preferred rotation for timber production is thought to be around 80 years, whilst the rotation for maximum social benefit is somewhat longer than this. Rotation lengths up to 200 years have been proposed, but the rotation length here is set at R = 150 years, a value roughly consistent with current policy on management of the jarrah forest (CALM, 1992).

Discount Factor

From 1981 to 1993 the average real yield on 10-year Australian Government Treasury bonds was 5.9 per cent. Since the jarrah forest is managed in the long-term public interest, the real interest rate is set below this at 3 per cent, giving a discount factor δ = 0.971. Given the long rotation length, the results are not sensitive to choice of the discount factor.

Present Value of One Rotation

As mentioned previously, the non-timber values of the jarrah forest are believed to be substantial, though they have not been quantified. Thus the present value of one rotation is unknown. The site value at the optimal rotation for timber management (80 years) is approximately $210, not including the hygiene costs (Brennan, 1994). Since the rotation length for maximum social benefit is (presumably) greater than 80 years, the site value for maximum social benefit must be greater than $210 per hectare. For the purposes of this study, the optimum site value is set at $250, which gives the present value of one rotation π = $247. Site values can be expected to vary considerably across the jarrah forest, and the value used here is intended only as a plausible lower bound.

Value of an Infected Site

Optimal management of infected sites has not been determined, so site values are not available. Instead, the value of an infected site is measured as a percentage reduction *i* in the value of an uninfected site: $\Pi_I = \Pi_U(1-i)$. The impact *i* can be varied freely, but it is taken as 10, 50 and 90 per cent for low, moderate and high impact, respectively.

Annual Risk of Infection

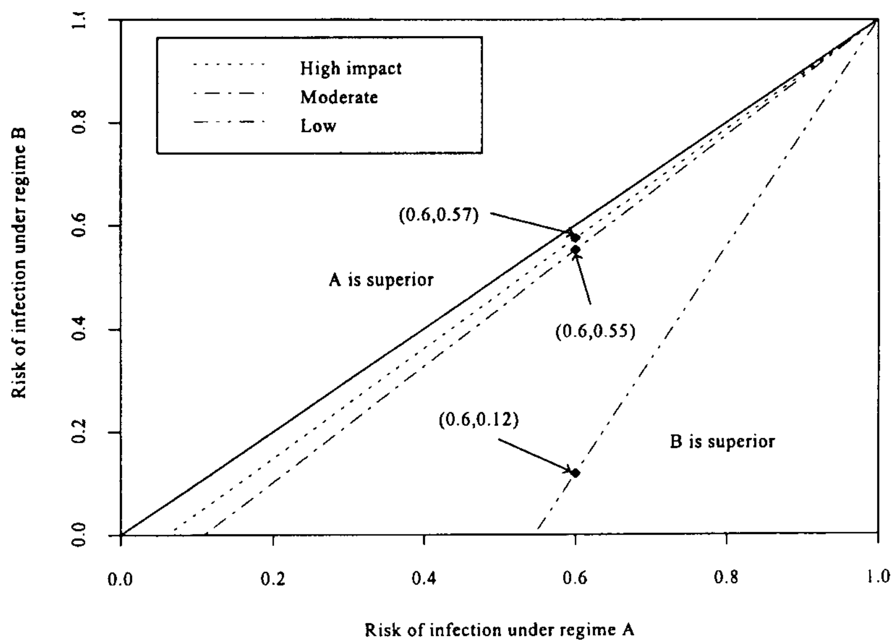
This risk (p_I)has not been quantified, but it is apt to be quite low since the fungus is spread largely by human activity — timber harvesting and other disruptive forest intervention. It is set at $p_I = 0.01$ for regimes A and B, but the results are (approximately) independent of the annual risk of infection, as will be seen below.

Figure 1 shows the calculated boundaries for high, moderate and low impact sites. The hygiene plan (regime B) is beneficial wherever the risk of infection under B is below the respective line for each level of impact. Note that Figure 1 says nothing about the *actual* effectiveness of B, but only what the *minimum* effectiveness must be for the expenditure to be worthwhile. The distance between the 45° line and the respective boundaries shows *how much* the risk of infection must be reduced under B for it to be beneficial.

For every level of risk of infection under regime A, regime B must be more effective as the impact decreases. As shown by the co-ordinate points in Figure 1, when the risk of infection for a high impact site is 60 per cent under A, the risk of infection under B must be less than 57 per cent for it to be beneficial — *the minimum required reduction in risk is only 3 per cent.* For moderate impact sites, the risk must be reduced only another 2 per cent to 55 per cent. But for low impact sites the risk must be reduced to below 12 per cent, a reduction in risk of 48 per cent.

FIGURE 1

Risks of Infection Without Protection (Regime A) versus the Hygiene Plan (Regime B),for Three Levels of Impact
(high i = 90, moderate i = 50 and low i = 10 per cent)



The point where the boundary intersects the horizontal axis, denoted p^*, gives the minimum risk of infection under which B is beneficial. For risks below p^*, B is not beneficial, even if it can completely eliminate the risk of infection. In Figure 1, the three horizontal intercepts are $p^* = 6$, 11 and 55 per cent for high, moderate and low impact sites, respectively. So regardless of its effect on the risk of infection, B cannot be justified on low impact sites where the risk of infection under A is below 55 per cent. In this case, it would be prudent to shift expenditure from these sites to those where the likely impact or the risk of infection is higher.

Note that all three boundaries intersect at $p_0(A)=1$. That is, when the risk of infection is certain, the expected site value equals the infected site value, and the numerator in the expression for f equals 0, regardless of the value of the other terms. So all three boundaries are anchored at the point (1,1). Note also that the curves appear to be linear, even though f is highly non-linear in $p_0(A)$. This results from the large value assigned to R, the rotation length. It can be shown that for the values used in this study,

$$(14) \qquad f(p_0(\mathrm{A}),\ldots) \cong \frac{h_\mathrm{A} - h_\mathrm{B}}{\Pi_\mathrm{U}(i - \delta^R) - h_\mathrm{B}} + p_0(\mathrm{A}) \frac{\Pi_\mathrm{U}(i - \delta^R) - h_\mathrm{A}}{\Pi_\mathrm{U}(i - \delta^R) - h_\mathrm{B}}.$$

(Algebraic details are available from the first author.)

With the boundary approximately linear and fixed at (1,1), only one other point is required to determine the boundary. Changes in the boundary can thus be analysed purely in terms of changes in this point. The most convenient point to use for this purpose is the point where the boundary intersects the horizontal axis. Setting *f* in expression (14) equal to 0 and solving for $p^*=p_0(\mathrm{A})$ gives

$$(15) \qquad p^* = \frac{h_{\mathrm{B}} - h_{\mathrm{A}}}{\Pi_{\mathrm{U}}(i - \delta^R) - h_{\mathrm{A}}}$$

This expression completely characterises what is important in determining the level of expenditure on disease control in long rotation forestry. Note that p^* does not involve the annual risk of infection, p_1, even though this is an important variable in the expected site value. This is a particularly useful outcome, since the annual risk of infection is unknown. Inspection of the equation (15) shows that p^* increases as the site value (Π_{U}) and the impact (i) decrease, and as the cost of the hygiene treatments under B (h_{B}) increases — i.e., the hygiene treatments must become increasingly effective in reducing the risk.

Discussion

This paper has developed a means for evaluating different levels of protecting forest from infection by *P. cinnamomi*. The model has practical potential for evaluating the relative merit of current and future approaches to disease management. For instance, it could be used to compare the effectiveness of the two methods commonly used to produce hygiene plans. The first involves a combination of shadowless, large-scale (1:4500) colour air photos and ground inspection. The second is less expensive and involves systematic ground surveying alone.

Using the model developed here to find the optimal level of protection is straightforward, provided the relationship between protection and the probability of infection is known. However, there is currently little or no information about this, and the relationship is likely to remain highly uncertain for some time to come. Thus the analysis here has assumed nothing about this relationship, and has focussed on the minimum required effectiveness of different levels of protection. In the absence of better information, this will at least provide forest managers with a rough guide for choosing the appropriate level of expenditure, and a range for required effectiveness of different levels of protection.

Finally, although some values have been quoted on a per hectare basis, the analysis above has freely used the term 'site' without explicitly defining the term. The analysis assumes that a site may be subject to external influences (the pathogen enters a site from outside), but it has no external influences itself. This is unlikely to hold if, for example, a site is taken as a small parcel of land within a large forest block.

Depending upon site characteristics, an infection that occurs on a site within a large forest block may increase the likelihood of infection throughout the forest. In this case, the model for the expected site value may underestimate the value of protection on the forest overall. Thus in any application of the model, the 'site' needs to be defined so that its external influences are negligible. Depending on circumstances, this may require that the site be defined as an entire forest block. In that situation, it may be necessary to take the site as less extensive and to try to accommodate external influences by erring on the side of caution in evaluating protection levels.

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