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Risks of fire and the management of catchments for timber production and urban water supply

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Abstract

While previous studies have examined how forest management is influenced by the risk of fire, they rely on probabilistic estimates of the occurrence and impacts of fire. However, non-probabilistic approaches are required for assessing the importance of fire risk when data are poor but risks are appreciable. We explore impacts of fire risk on forest management using as a case study a water catchment in the Australian Capital Territory (south-eastern Australia). In this forested area, urban water supply and timber yields from exotic plantations are potential joint but also competing land uses. Our analyses were stimulated by extensive wildfires in early 2003 that burned much of the existing exotic pine plantation estate in the water catchment and the resulting need to explore the relative economic benefits of revegetating the catchment with exotic plantations or native vegetation. The current mean fire interval in the ACT is approximately 40 years, making the establishment of a pine plantation economically marginal at a 4% discount rate. However, the relative impact on water yield of revegetation with native species and pines is very uncertain, as is the risk of fire under climate change. We use info-gap decision theory to account for these non-probabilistic sources of uncertainty, demonstrating that the decision that is most robust to uncertainty is highly sensitive to the cost of native revegetation. If costs of native revegetation are sufficiently small, this option is more robust to uncertainty than revegetation with a commercial pine plantation.

Keywords: Economic return; Info-gap decision theory; Stochastic model; Uncertainty

1. Introduction

It has long been recognised that the possibility of fire and other catastrophic events can influence planning decisions in forest management (Lindenmayer *et al.*, 2004). For example, in the presence of fire risk, the optimal rotation length of native forests and plantations tends to be reduced (Martell, 1980; Routledge, 1980; Reed and Errico, 1985, 1986; Spittlehouse and Stewart, 2003). If this risk of fire is sufficiently large, financial losses may be expected from forest harvesting operations, and establishing some kinds of forest such as plantations may become economically unjustified. In addition to timber yields, other forest values are likely to be influenced by the occurrence of fires (Agee, 1993; McCarthy and Lindenmayer, 1998; McCarthy and Lindenmayer, 1999; Bradstock *et al.*, 2002). For example, in the mountain ash forests of Victoria, water yield is strongly influenced by the time since the last major disturbance, be it timber harvesting or fire (O'Shaunessy and Jayasuriya, 1991). In these forests, stream flow is reduced substantially in younger forests because of much greater rates of evapotranspiration.

An assessment of the impact of fire risk on economic returns provides a basis for making decisions about forest management. Stochastic models that account for the risks are useful tools for management in the face of uncertainty because it is usually difficult to determine the management consequences of risk subjectively (Burgman, 2005). The usual approach to assessing fire risk in forest management is to assume a certain annual risk of fire and model the loss of forest values (e.g., destruction of standing timber) that occurs as a consequence of fires. Using stochastic models of fire occurrence, it is possible to examine how water and timber yields are likely to be influenced by different forest management regimes and determine the optimal management policy (Martell, 1980; Routledge, 1980; Reed and Errico, 1985, 1986; Evans, 2004; McCarthy in press). Such an approach requires that both the loss of forest values in response to fire and the annual risk of fire can be determined reliably or at least probabilistically, for example, by placing meaningful confidence intervals on estimates.

Planning for the risk of fire is likely to be especially important if projected changes in climate eventuate (Lenihan *et al.*, 2003; Spittlehouse and Stewart, 2003). There appears to be a strong link between weather and the occurrence of fire, with annual rainfall being an especially important factor in southeastern Australia (Mackey *et al.*, 2002; Cary *et al.*, 2003; Lindesay, 2003). Climate models predict that rainfall in the region will be reduced in the future, and such changes are likely to impact risks of fire substantially (Cary, 2002). For example, in the Australian Capital Territory (ACT), the average interval between successive fires at points in the landscape is approximately 40 years, but this is predicted to halve under moderate climate change (Cary, 2002). In the face of such increased risks, the possibility of financial losses from timber harvesting operations is increased.

However, in assessing the risks posed by unplanned fires, the impacts of fire on forest values and the annual risk of fire can both be difficult to estimate. Making decisions in the face of such uncertainty is problematic for the usual methods of risk assessment when uncertainty cannot be characterised probabilistically. However, non-probabilistic uncertainty is important because decisions that ignore it are likely to lead to sub-optimal outcomes. Because of the need for making robust decisions in the face of severe uncertainty, Ben-Haim (2001) developed info-gap decision theory, which is suitable to situations that include non-probabilistic uncertainty. The basis of this method is to determine the management option that is most robust to uncertainty while achieving some minimum prescribed performance requirement. The method is being used increasingly in the field of conservation biology (Regan *et al.*, 2005; Halpern *et al.* in press) and other disciplines (Ben-Haim, 2001). Rather than optimising the expected outcome, the info-gap approach asks how wrong can one be and still get an acceptable result. The best decision is the one that is most robust to uncertainty, by guaranteeing an acceptable outcome under the greatest degree of uncertainty.

In January 2003, fires burnt a substantial proportion of the ACT, the administrative territory that surrounds Canberra, Australia's capital city (ACT Government, 2003). A substantial majority of the existing pine plantations was destroyed by these fires (Bartlett *et al.*, 2005). Many of the plantation areas were located within the catchments that supply water to Canberra for domestic and commercial uses (e.g. the Lower Cotter Catchment). Following the fire, revegetation is needed to protect the water catchments from erosion and other forms of environmental damage (White *et al.*, 2005). The two main options for revegetating the catchment are to use native species or the exotic *Pinus radiata* (Monterey pine), the main commercial plantation species used in the region (Bartlett *et al.*, 2005).

Jaakko Pöyry Consulting (2003) prepared a business plan for the ACT Government in which they recommended re-establishing approximately 80% of the forest estate as a commercial pine plantation, with the remaining area to be revegetated with native species. The business plan suggested that substantial profits would be obtained from the pine plantations. While the plan mentioned insurance against losses from further fires (and self insurance), it did not explicitly calculate the risks of loss from fire.

In comparing the two revegetation options (native and pines), the ACT Forest business plan assumed that they would have equivalent impacts on water yield, based on a single field study in a region remote from the ACT. In contrast, modelling studies predict that revegetation with native plants is likely to lead to greater water yields than using pines (Vertessy, 2001). Given the projected increases in the human population of the ACT and high demand for the water that is currently available, it is important to assess the sensitivity of management decisions to projected losses of water yield. On this basis, we analyse in this paper the expected reduction in the financial return from pine plantations that will arise from the occurrence of future unplanned fires in the ACT. We recognise that efforts will be made to reduce the occurrence of fires, but that destructive unplanned fires will continue to occur given realistic constraints on the ability of humans to control fires in extreme weather events. We compare the two different management options by determining the effect of pines on water yield that would be necessary to make establishing pine plantations a poorer economic option compared to native forest revegetation. Because many of the parameters of the problem, such as the risk of fire and the effect of pines on water supply, are highly uncertain, we analyse the problem using info-gap methods (Ben-Haim, 2001). The info-gap approach to decision theory is particularly well-suited to this decision problem because there is severe uncertainty that cannot be reliably described probabilistically. The kinds of analyses we present in this paper are important in a far broader context than simply the ACT water catchments and plantation forests because they are pivotal to examining conflicts over resource use. This is particularly true when there is considerable uncertainty about relevant parameters of the problem, for example, when there are little data or the future is very uncertain (e.g., when predicting impacts due to climate change).

2. Methods

A model was developed of the costs and revenues from timber harvesting that are expected over a prescribed time period from a stand of pines in the ACT forest estate. The model is based on the financial analysis conducted by Jaakko Pöyry Consulting (2003) but also included the occurrence of unplanned fires. The influence of unplanned fires on timber yields from the pine plantation was assessed using stochastic simulation. Three thinnings prior to the final clearfelling of the pine plantation (at 30 years) are expected to provide revenue 12, 18 and 25 years after planting (Table 1 based on Jaakko Pöyry Consulting, 2003).

The revenue obtained from these operations was simulated for a single stand over a 100-year time frame. The model simulated the random occurrence of fire each year, with the annual risk equal to the reciprocal of the average fire interval. The average fire interval for the ACT is approximately 40 years (Cary, 2002), although results were obtained from a sensitivity analyses using average fire intervals ranging between 20 and 100 years. This range reflects the spatial variation in fire risk as well as the projected increase in fire risk in response to climate change (Cary, 2002).

If a fire occurred in the previous year, it was assumed in the model that the trees in the stand were killed, their value as timber was lost, and various costs incurred such as debris removal, salvage logging, etc (see Table 2). Costs of removing the debris ($1130 per ha) were incurred in the year following all fires except for the initial year. The cost of removing debris in the initial year (2003) was not incorporated into the analysis because it was assumed that the removal of the burnt timber would occur regardless of the decision to re-plant a *Pinus radiata* plantation. Costs of re-establishing the pine plantation ($2000 per ha) also were incurred following fire or clearfelling, with the initial replanting incorporated into the analysis.

In the absence of fire, any revenues from thinning or clearfelling were obtained. Upon reaching the clearfelling age, the stand was cleared and replanted with *Pinus radiata*, with future returns obtained from a subsequent rotation of the pine plantation. Future costs and revenues were geometrically discounted at rates of 2, 4 and 6% per annum to cover a range of rates that are typically used for forest investments (Ferguson, 1996). The present net value of a stand of *Pinus radiata* plantation was determined. The expected economic return over the next 100 years was calculated as the average return per ha from 10 million stochastic simulations.

The analysis outlined above indicated the expected financial return from establishing a pine plantation and the sensitivity of that return to the risk of fire. However, the managers of Canberra's water catchments are faced with a decision about whether to replant a pine plantation or whether to replant with non-commercial native species (Bartlett *et al.*, 2005). Given the greater diversity of species required for native revegetation and the ready commercial availability of *Pinus radiata* seedlings compared to many native species, the cost of replanting with native species could be greater than for *Pinus radiata*. Jaakko Pöyry Consulting (2003) estimated that the cost of replanting with native species is three times that of pines, and we use their figure in this analysis. However, the estimated cost of native revegetation used by Jaakko Pöyry Consulting (2003) is large compared to other estimates within Australia (Schirmer and Field, 2000). The actual costs will be very sensitive to the planting density during revegetation operations. Given that there is already some natural regeneration in parts of the catchment, the cost of native revegetation is likely to be substantially reduced. Therefore, we also conducted an additional analysis in which the cost of native revegetation was $4000 per ha, which is still approximately twice the cost of large revegetation projects examined by Schirmer and Field (2000) for temperate regions of Australia.

One of the potential costs of the pine plantation is that the pine trees will consume more water than the native revegetation. In Canberra's water catchment, pine trees grow much more vigorously than the native vegetation (Chilvers and Burdon, 1983; Burdon and Chilvers, 1994), and this greater vigour may lead to greater water use. Given the seasonal variability of streamflow, estimating the relative hydrological impacts of native vegetation and pine plantations from field studies is difficult. Based on a single field study that did not show appreciable effects, Jaakko Pöyry Consulting (2003) assumed that pines and native vegetation would have equivalent impacts on water yield. However, Vertessy (2001), when modelling impacts of eucalypt and pine reafforestation, predicted that pine forests would yield an equivalent of 50 mm less annual rainfall as streamflow (for catchments equivalent to those of the ACT) than native forests.

Given the uncertainty about the effects of different vegetation on water yield, we determined the reduction in water yield that would make replanting with a commercial pine plantation less economically efficient than revegetation with native plants. To do this, we calculated the reduction in annual water yield that would be required from planting pines (relative to native revegetation) so that the present net value of the two options would be equal. In this analysis, we assumed that the value of water was 50 cents per kilolitre, the smallest price paid by consumers after accounting for supply costs, and the returns from water were discounted at the same rate as timber yields. We also assumed that annual maintenance costs of pines and native revegetation (e.g., weed control, recreation management) would be identical.

While the above analyses indicated the difference in water yield that would be necessary before it was optimal to switch between pines and native plant revegetation, it does not actually indicate the best management decision because this difference is very uncertain. In such circumstances, info-gap decision theory can find the management decision that is most robust to uncertainty (Ben-Haim, 2001). Info-gap decision theory finds the management strategy that permits the greatest degree of uncertainty (possible error in the predictions) while meeting a given performance requirement.

In the case of timber yield in the ACT region, one of the greatest sources of uncertainty in the expected yield is the average fire interval, which has been estimated to be approximately 40 years, but could be as little as 20 years under future climate change scenarios (Cary, 2002). Thus, robustness can be measured by the proportional change in the mean fire interval from 40 to 20 years. The info-gap analysis then asks, how short can the mean fire interval be while still achieving the minimum present net value per ha that is required by the managers (the performance requirement)?

Similarly under native forest revegetation, the annual water yield could be 50 mm (500 kL/ha) higher than under pines (Vertessey, 2001), although the difference also might be negligible. Thus, robustness can be measured as the proportional difference between a 50 mm increase in water yield of native vegetation relative to pines and an increase of zero. The info-gap analysis then asks, how small can the increase in water yield be while still achieving the present net value per ha that is required by the managers? The required measure of performance under the two options can then be compared to find the one that is most robust to the uncertainty, i.e., has the highest robustness for a required level of performance. By comparing the trade-off between the performance requirement and robustness of the two management options, one can determine the management option that has the greatest robustness for a given performance requirement. In the face of severe uncertainty, the best management decision is the one that is most robust.

3. Results

The present net value over the next 100 years of establishing the pine plantation was highly sensitive to the risk of fire (Fig. 1). At a discount rate of 4%, the pine plantation is only expected to return a profit if the average time between fires is more than approximately 35 years. At a less stringent rate of 2%, a profit can be expected if fires occur with an average interval of more than 25 years. However, this threshold for the average fire interval at which a profit is obtained is inflated to 70 years at a 6% discount rate (Fig. 1). Given that the average fire interval of the ACT is approximately 40 years and may be reduced to 20 years or less under climate change (Cary 2002), establishing a pine plantation in the ACT is only marginally profitable.

For the purposes of this paper, we estimated that there were increased costs of native plant revegetation relative to replanting with *Pinus radiata* (Table 2), so the former option for replanting the ACT's water catchments is only economically preferable to establishing pine plantations if the pines cause a reduction in stream flow. Given the economic returns in response to different fire intervals (Fig. 1), the reduction in stream flow from pines (relative to that from native forest) would need to be greater than a specified threshold for the pines to become less profitable. This threshold is approximately 45-60 mm for an average fire interval of 40 years, reducing to approximately 20-35 mm for an average fire interval of 20 years (Fig. 2). These reductions are within the realm of possibility (Vertessy, 2001), meaning that in the presence of the risk of fire, replanting the ACT's catchments with native vegetation may be more economically efficient than establishing pine plantations. However, if the cost of revegetating with native species was reduced or the price of water was increased beyond that assumed here, then native vegetation would be more likely to be the profitable option. For example, if the cost of revegetating with native species was reduced to $4000 per ha, replanting with pines becomes the less profitable option when the reduction water yield is greater than 35-40 mm for an average fire interval of 40 years and 10-13 mm for an average fire interval of 20 years.

The most robust strategy of the two options depended on the level of performance required. If the ACT government had a requirement to at least break even with its financial investment, then revegetation with pines is most robust to uncertainty at discount rates of 4% if the cost of native revegetation is $6000 per ha (Fig. 3). For this cost of native revegetation and over the range of discount rates considered, native revegetation only provides the greatest insurance against error if the performance requirement is to obtain at least $4000 per ha at a 2% discount rate. Pines provided the most robust solution for other combinations of the discount rate and performance requirement. However, if costs of native plant revegetation could be reduced, then native plant revegetation would provide greater financial robustness than pines. The straight line representing native revegetation in Fig. 3 would be raised by any saving in revegetation costs. For example, reducing native plant revegetation costs to $4000 per ha would make the lines cross and native plants would become the most robust revegetation strategy when the aim is to at least break even financially at a 4% discount rate (Fig. 4). Thus, decisions about the most appropriate revegetation strategy are particularly reliant on obtaining accurate estimates of revegetation costs.

4. Discussion

This paper demonstrates the importance of evaluating the impacts of fire risk on timber harvesting operations. For example, Jaakko Pöyry Consulting (2003) demonstrated that in the absence of fire, pine plantations are economically appealing. However, the current mean fire interval in the ACT is approximately 40 years (Cary, 2002) making the establishment of a pine plantation economically marginal at a 4% discount rate (Fig. 1). Given that fires are expected to become more prevalent under even moderate climate change (Cary, 2002; Spittlehouse and Stewart, 2003), we predict that financial losses would be expected in the future from the proposed plantation estate.

While the economic return of pine plantations is reduced by fire, an important question is what is the best method for revegetating Canberra's water catchments? If pines and native plants have the same impact on water yield, then pines provide the most economically efficient means of revegetation because they are cheaper to plant and provide an economic return. However, at average fire intervals of 40 years, pines would only need to reduce water yields by approximately 50 mm per annum compared to native revegetation to become less economically efficient. Conceivably, the difference in water yield between the two revegetation options could be negligible, as much as 50 mm of streamflow per year, or more (Vertessy, 2001; Jaakko Pöyry Consulting, 2003), placing the threshold for the management decision (~50 mm) within the realms of possibility.

If the ACT Government wished to maximise the expected benefit, they would need to assess the relative likelihood of the water yield reduction being less than or greater than 50 mm. This clearly presents the ACT government with somewhat of a dilemma because the relative impact of pines and native revegetation on water yields is very uncertain. The benefit of using an info-gap approach to the problem is illustrated in these circumstances, because the government merely needs to decide on a minimum level of performance and then determine the option that was most robust to error in meeting the required performance (Ben-Haim, 2001). It is not for us to decide what this level of performance should be given the other costs and benefits of the two options that need to be considered b y the ACT Government. However, we will note that for the costs used by Jaakko Pöyry Consulting (2003), pines provide the most robust strategy to breaking even financially for discount rates of between 2 and 6% (Fig. 3). However, if native plant revegetation cost only $4000 per ha, it would become the preferred strategy.

Caveats and limitations

Additional factors could be built into the analysis if information on the possible magnitude of error could be obtained. For example, future prices for both timber and water are uncertain, but could be substantially different from the values assumed here. Uncertainty in future prices has been treated probabilistically in previous studies (Brazee and Mendelsohn 1988). However, the magnitude of the uncertainty in these prices and the difficulty of making probabilistic predictions of prices decades into the future mean that an info-gap approach to this problem may be particularly useful.

Some of the other benefits that could be considered in assessing the relative merits of pines and native revegetation are biodiversity and recreation. We have not included these here because of difficulties in deriving market prices for them. It is likely that greater biodiversity benefits would be derived from native plant revegetation given that there is generally a paucity of native animal species in pine plantations compared to remnant native forests (reviewed by Lindenmayer and Hobbs, 2004). However, the biodiversity benefits of native revegetation compared to pines is largely unknown but existing work on areas revegetated with native plants indicates they can have important values for fauna of some groups of animals (e.g. birds; Kinross, 2000; Greening Australia, 2001; Martin *et al.*, 2004).

In this paper we assumed initially that the cost of establishing native vegetation was $6000 per hectare. However, this may be an overestimate in a substantial proportion of the area that was burnt in 2003. For example, large numbers of *Acacia* trees and smaller numbers of *Eucalyptus* trees have germinated from soil-stored seed in some areas that formerly supported stands of *P. radiata* (M. Butz, personal communication; A. Manning and D. Lindenmayer, personal observation). The costs of revegetation with native forest in these areas may be significantly less than $6000 per ha and may only require limited underplanting of additional *Eucalyptus* spp. trees. Because such planting would require a much reduced density of seedlings, the cost of revegetating these areas would be reduced substantially. As illustrated in the sensitivity analysis, if the reduction in the cost of native revegetation was sufficiently large, it would become the most economically robust option.

In the models considered in this paper, fire risk did not change as a function of time since fire. However, in these forest types, the risk of fire would be expected to be low immediately after fire and increase towards an asymptote as the litter layer accumulates (McCarthy *et al.*, 1999) While such changes in the risk of fire could be expected, a model of fire in the ACT region (Cary, 2002) predicts a relatively rapid increase in the annual risk fire, reaching an asymptote within about 3 years (McCarthy and Cary, 2002). Given that the asymptotic fire risk is reached well before the first economic returns at 12 years (Table 1), the model of a constant fire risk, while simple, is likely to provide a reasonably good approximation.

A further issue not considered in this paper was the actual financial return rather than the expected return. For example, while the stand-based expected return indicates the average that would be obtained from the entire forest estate, the actual financial return from timber harvesting would depend on the actual incidence of fire across the estate. Such a model would require information on variation in the proportion of the plantation estate that burns each year. Such considerations would increase the likelihood of the plantation yielding losses, but we were unable to determine sufficiently reliable estimates of the annual variation in fire occurrence to model the results. Similarly, we ignored annual variation in the difference in water yield between pines and native revegetation, although at least some variation would be expected. As a result, our results will tend to underestimate the true level of uncertainty in this decision problem.

Other differences in costs associated with pine and native revegetation such as impacts on water quality, weed control and prescribed burning were not considered. Water quality is likely to be reduced to a greater extent (or require greater maintenance costs to ameliorate the impacts) in production forests because of the need for a wide road network to operate the plantation and high road usage (Grayson *et al.*, 1993). Pine plantations also contribute to weed invasion (especially blackberry and pine seedlings) into native remnants (Lindenmayer and McCarthy, 2001), increasing costs of weed control. Furthermore, prescribed burning to reduce fuel loads and assist fire management is more difficult to achieve in pine plantations than native vegetation, meaning that costs of fire management may be greater if pines are used for revegetation rather than native species. In combination, these issues would tend to favour the use of native species for revegetation over the use of pines.

5. Conclusion

Because of the long time horizons involved, forest management decisions entail considerable economic risks. Probabilistic models have been developed to account for these risks in forest management, but in many cases data are not available to provide reasonable estimates for the parameters that are required. In such circumstances, it may be tempting to ignore the risks and base management decisions on deterministic analyses. However, such an approach is likely to lead to sub-optimal solutions when the risks are appreciable but hard to estimate. In this paper, we have shown that info-gap decision theory (Ben-Haim, 2001) can be used to help make forest management decisions that are robust to non-probabilistic uncertainty.

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Table 1. Proposed timing and revenue of timber harvesting operations over the 30 year rotation of *Pinus radiata* plantations in the Australian Capital Territory (Jaakko Pöyry Consulting 2003).

Operation	Year	Revenue per ha
First thinning	12	$551.70
Second thinning	18	$2195.16
Third Thinning	25	$2386.20
Final Clearfall	30	$8744.26

Table 2. Costs of timber harvesting operations for *Pinus radiata* plantations in the Australian Capital Territory(Jaakko Pöyry Consulting 2003).

Operation	Cost per ha
Removal of burnt timber	$1130
Planting of *Pinus radiata*	$2000
Native revegetation	$6000

Fig. 1. Discounted return over the next 100 years of a stand of *Pinus radiata* versus the average time between fires for three different annual discount rates (2, 4, and 6%). The horizontal dotted line is the "break even" point at which the present net value is zero.

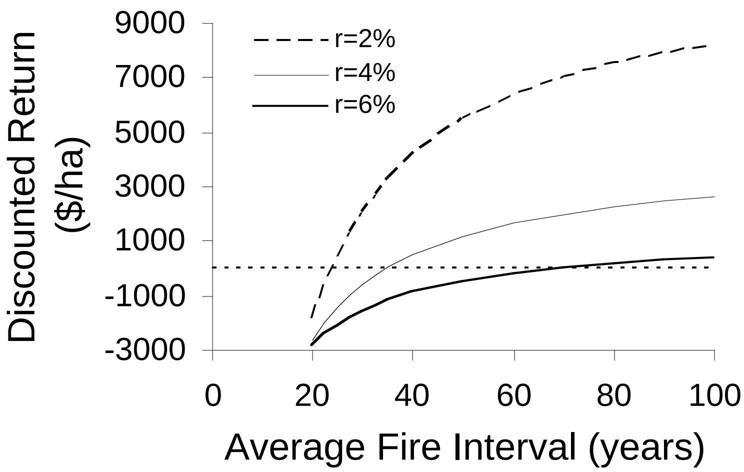

Fig. 2. Reduction in annual water yield of pines compared to native revegetation that would be necessary to make pines economically inferior to non-commercial native revegetation versus the average time between fires. The results are shown for three different annual discount rates (2, 4, and 6%).

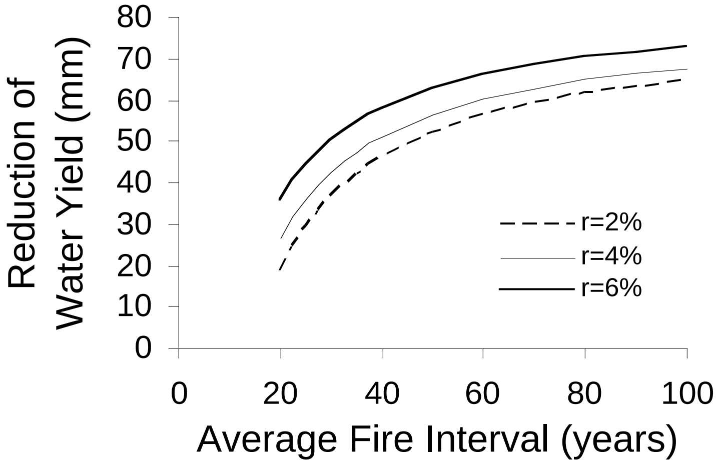

Fig. 3. The minimum performance requirement versus robustness for revegetation with pines and native plants at an annual discount rate of 4% and assuming native revegetation costs $6000 per ha. The most robust strategy for a given level of performance is represented by the right-most of the two curves.

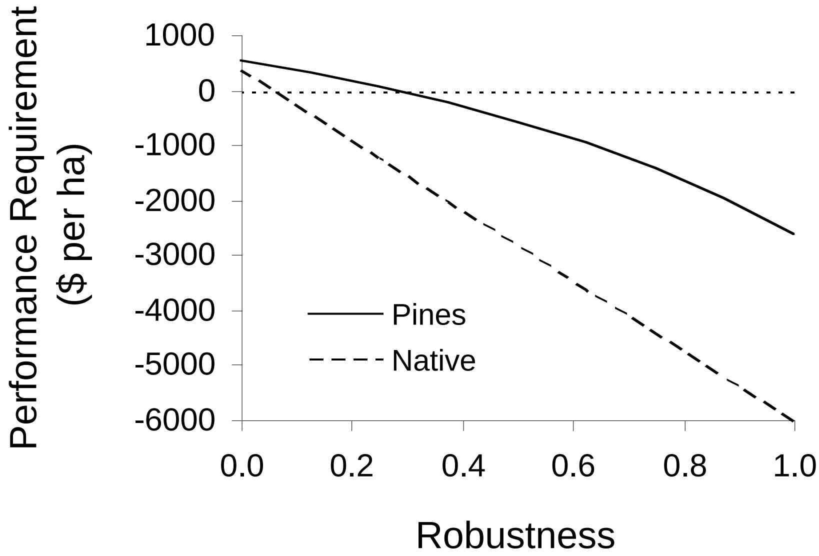

Fig. 4. The minimum performance requirement versus robustness for revegetation with pines and native plants at an annual discount rate of 4% and assuming native revegetation costs $4000 per ha. The most robust strategy for a given level of performance is represented by the right-most of the two curves.