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Incorporating biological regeneration into economic assessments of mining in forest regions

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Assessments of the economic, environmental and social consequences of mining have usually produced an estimate of the commercial benefits that mining in the area would generate, with environmental costs being examined in physical terms only. A theoretical framework for calculating the threshold environmental value of an area (the minimum size of the environmental cost of mining required to make conservation the socially optimal choice) is developed, where both the potential mining benefits and the rate of biological regrowth following mine rehabilitation are known. Including the rate of biological regrowth allows for the calculation of a more meaningful figure, as the benefits generated by rehabilitation are explicitly considered.

1. Introduction

As community concern about environmental issues grows, there is an increasing demand for benefit–cost analysis of proposed mining operations to include environmental impacts. In most studies of this type (see, for example, ABARE, AGSO and BRS 1993 and RAC 1991), the net commercial benefits of mining are readily quantified. This is because the costs of mining and the prices received for future mine outputs can be estimated. On the other hand, environmental costs are often difficult to quantify, and are usually examined in physical terms only. When non-market values of the area in question are estimated (say, through contingent valuation), such values are often assumed to be completely forgone in the event of mining—that is, environmental regeneration is not considered.

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When the net commercial benefits of a proposed development can be estimated, but the non-market costs cannot, a 'threshold' approach is often developed, or adopted implicitly.¹ In these situations the measured economic benefits of mining have the interpretation: unless the environmental costs (discussed qualitatively) are greater than the benefits from mining (estimated quantitatively), then mining should proceed. This approach is often the only option available, because of the difficulties associated with valuing both the current level of environmental benefits and the physical damage that may result from mining. For certain types of mining activities, however, (such as bauxite mining, which covers wide areas and has minor offsite effects), the physical relationship between mining and environmental damage and subsequent regeneration is often measurable.

In this article a model is developed to incorporate data on the biological regeneration of forest ecosystems following minesite rehabilitation (along with the estimated net benefits of mining) into the calculation of a threshold amenity value. Including the benefits from biological regeneration produces a more meaningful threshold amenity value, which, unlike the mining benefits alone, may justifiably be compared with estimates of the non-mining value of the area in its initial condition.

2. The model

If the area is mined, it is assumed that benefits from mining (which are measurable and known) and benefits from the environment after mining and rehabilitation (which are unknown) will accrue. If mining does not occur, it is assumed that only amenity benefits from the environment will accrue, which are unknown. Amenity benefits are taken to mean all of the non-mining values which are derived from the area.

The threshold value is defined as the amenity value of a forest ecosystem in its initial (pre-mining) state that is required for the net benefits from mining and rehabilitation to equal the net benefits from conservation. This value will be at least equal to the mining benefits, which represent the threshold value in the limiting case of no rehabilitation benefits.

¹ The threshold approach has been extended in a number of case studies to incorporate growing demand for environmental amenities (and hence growth in environmental values) over time (see, for example, Krutilla and Cicchetti 1972). The approach adopted here differs in that growth in environmental amenity values is tied to the biological regeneration of the forest ecosystem.

The condition required to solve for the threshold value can be expressed as:

$$M - X + \int_0^\infty a_t e^{-rt} dt = \int_0^\infty a_p e^{-rt} dt = A^T \quad (1)$$

where

M = net economic benefits from mining (in period 0);

X = total rehabilitation costs following mining (assumed instantaneous in period 0);

a_t = flow of amenity values at time t during and after mining;

a_p = the flow of amenity benefits from the forest in its pristine (or initial) state (assumed to be constant over time);

r = discount rate;

A^T = threshold present value of amenity benefits.

Note that, for simplicity, and to focus our analysis on the flow of amenities, the net mining benefits and rehabilitation costs are assumed to occur instantaneously in period 0. Assume that the floral and faunal species affected by mining are re-established in a standard logistic fashion following rehabilitation and that this function adequately describes the environmental characteristics that provide amenity benefits.²

$$\begin{aligned} I_t &= \frac{\beta I_p}{1 + ce^{-gt}} \\ \frac{dI_t}{dt} &= gI_t \left(1 - \frac{I_t}{\beta I_p}\right); \\ c &= \frac{(I_p - I_0)}{I_0} \end{aligned} \quad (2)$$

where

² While almost any data for populations that increase to an asymptotic level will fit the logistic model to some degree, a better fit can be obtained in most cases with alternative models (Clark 1976).

I_p = maximum environmental index of forest in its 'pristine' (initial) state;
 I_0 = minimum environmental index of forest (immediately after mining);
 I_t = environmental index at time t ;
 g = instantaneous rate of growth when I_t is close to zero;
 β = the 'success' of rehabilitation, where $0 \leq \beta \leq 1$. For example, $\beta = 0.8$ implies the index converges towards 80 per cent of the initial index number at an exponential rate as t approaches infinity.

Assume, further, that the amenity values from the forest can be translated into dollar equivalents, and that there exists a continuous and well-defined function which relates dollar benefits, a_t , to the level of the environmental index, I_t . As the purpose is to calculate the threshold amenity value, a simple environmental benefit function will be specified, allowing one of the parameters to be solved for

$$a_t = \lambda I_t^\alpha \quad (3)$$

where $0 < \alpha \leq 1$; and λ is any positive number.

In equation 3 a value for α will be assumed (which will affect the rate at which amenity benefits diminish as the index of environmental quality increases); however, a value for λ (which determines specific dollar values for different levels of environmental quality) will not be specified. Note that $\alpha < 1$ implies decreasing marginal amenity benefits, while $\alpha = 1$ implies constant marginal amenity benefits.

Substituting equations 3 and 2 into equation 1 gives:

$$M - X + \lambda \int_0^\infty \left(\frac{\beta I_p}{1 + ce^{-gt}} \right)^\alpha e^{-rt} dt - \lambda \int_0^\infty I_p^\alpha e^{-rt} dt = 0 \quad (4)$$

or

$$M - X + \lambda \left[\left\{ \int_0^\infty \left(\frac{\beta I_p}{1 + ce^{-gt}} \right)^\alpha e^{-rt} dt \right\} - \frac{I_p^\alpha}{r} \right] = 0$$

Then define:

$$\int_0^\infty \frac{e^{-rt}}{(1 + ce^{-gt})^\alpha} dt \equiv \int_0^\infty y(t) dt = Y \quad (5)$$

and note, $y(0) = \frac{1}{(1 + c)^\alpha}$ and as $t \rightarrow \infty$, $y(t) \rightarrow 0$.

Since Y converges, there exists only one λ which satisfies the threshold condition. It can be shown that the solution to Y involves Gamma functions, for which no analytical formulations are available (see Gradshteyn and Ryzhik 1980, p. 305, equation 3.312.3, for a general formulation of

equation 5). In calculating the threshold amenity value, and evaluating how this value changes with respect to changes in key parameters, numerical solution techniques must therefore be employed.³

Substituting equation 5 into equation 4 enables the unique λ to be solved for:

$$\lambda = \frac{X - M}{I_p^\alpha \left(\beta^x Y - \frac{1}{r} \right)} \quad (6)$$

Having determined the only unknown parameter of the environmental value function (λ), it is possible to solve for the threshold amenity value, a_p , by rearranging equation 6 and substituting into equation 3 in the case where $a_t = a_p$:

$$a_p = \frac{M - X}{\frac{1}{r} - \beta^x Y} \quad (7)$$

Equation 7 is the threshold value expressed as a per unit time flow (in period 0 terms). Note that a_p is not changed if the environmental index is rescaled by any multiplicative constant. In this case, therefore, a_p is only affected by the relative difference between I_p and I_0 and not the choice of units.

In many cases it will be more appropriate to present the threshold value as the present value of all future amenity benefits resulting from conservation.

$$\int_0^\infty a_p e^{-rt} dt = \frac{a_p}{r} = A^T \quad (8)$$

3. Case study: bauxite mining in jarrah forests

The following case study uses actual and approximated data and relationships to examine the threshold amenity value of a hypothetical bauxite deposit that is overlain by jarrah forest. Bauxite mining in Western Australia provides a useful example of a mining activity for which the effects of biological regeneration following mining could be significant. It involves the removal of an entire lateritic soil profile which is rich in iron and aluminium oxides. Alcoa of Australia Ltd is the largest bauxite producer in Australia. Most of Alcoa's bauxite reserves lie within a 4200-square kilometre area of state forest to the south east of Perth. With current production of around 20 million tonnes of bauxite per year, approximately

³ In the quantitative exercise presented later, Y is evaluated numerically using ExtendTM simulation software.

500 hectares of jarrah forest is cleared each year. Since 1966, Alcoa has rehabilitated 7120 of the 9300 hectares cleared since 1962 (Elliot, Gardner, Allen and Butcher 1996).

Prior to mining, overlying vegetation is cleared and sometimes used for timber. The topsoil is then stripped and stockpiled or immediately transferred to another site for later use. Following mining, the underlying clay is deeply ripped and the topsoil replaced. If the topsoil is replaced quickly it still contains living soil fungi, bacteria and microfauna (Hore-Lacy 1992). Early rehabilitation in Western Australia saw exotic pine species and eucalyptus species native to the eastern states planted. Since 1988, species which are indigenous to the areas being mined have been seeded, with the objective of restoring a self-sustaining jarrah forest ecosystem (Elliot *et al.* 1996). Ward and Koch (1996) recently examined the biomass and nutrient distributions in a 15.5-year-old forest growing on a rehabilitated bauxite minesite. The 9.85-hectare site had been seeded and planted with a mixture of eastern state acacia understorey and eucalyptus overstorey species, and fertilised with 150 kilograms per hectare mono-ammonium phosphate. Ward and Koch found that, within 15.5 years, the total biomass on the site had increased to 23 per cent of that in a nearby jarrah forest containing 60-year-old pole-stand jarrah (Ward and Koch 1996, pp. 312–13).⁴

3.1 Economic assumptions

For the actual application of this method, it would be necessary to estimate the value of the option to mine bauxite within the case study area. Unlike many types of mineral deposits, there are usually good resource estimates available for bauxite because of its surficial nature, so that estimating this value would be feasible. In this case study, however, a threshold multiplier, s , has been constructed which illustrates the factor by which the net benefits ($M - X$) must be multiplied to obtain the threshold value. That is:

$$A^T = \frac{a_p}{r} = (M - X)s \quad (9)$$

where s is defined as the threshold multiplier.

Substituting equation 7 into equation 9:

$$s = \frac{1}{1 - \beta^x Y r} \quad (10)$$

⁴It should be noted, however, that the forest cleared for bauxite mining is often regrowth forest.

In this example it is assumed that the social discount rate is 6 per cent, and that the social value function for amenity benefits produced from the area displays constant marginal benefits. The value of α (equation 3) is therefore set equal to unity.

3.2 Biological assumptions

For simplicity, it is assumed that growth in environmental quality (on which non-market values are based) can be represented by an index of above ground cellulose biomass, using the logistic function shown in equation 2. The growth function index is scaled such that $I_p = 100$ and $I_0 = 1$.

As mentioned above, Ward and Koch (1996) measured the growth in above ground cellulose biomass on a rehabilitated minesite and compared this to the biomass in a nearby 60-year-old pole-stand of jarrah. The Ward and Koch result of 23 per cent biomass regrowth within 15.5 years would be consistent with a growth rate of 0.22 for equation 2. However, because the Ward and Koch data were based on eastern state species (which grow somewhat faster than jarrah) and compared with only a 60-year-old stand of trees, a growth rate of 0.12 is used in this example (implying 23 per cent regeneration after around 29 years and 80 per cent regeneration after around 50 years). In addition, it is assumed that rehabilitation is completely successful, so that β is set equal to unity.

3.3 Results and sensitivities

Using the above base case assumptions, it was found that the threshold multiplier is 1.17. Hence, the effect of including biological regeneration is to raise the threshold amenity value of the forest area by 17 per cent of the estimated net mining benefits. In figure 1 the present value of each of the annual amenity benefits (an index, with $a_p = 100$) from rehabilitation and preservation is shown from t_0 to t_{100} . Essentially, equation 8 sets the area between the two curves in this diagram equal to the net benefits of mining. It can be seen that, given a discount rate of 6 per cent, the initial regrowth is the most important, and that which occurs past 60 years does not affect the results significantly. Sensitivity analyses were conducted using the base case assumptions of the case study, whilst varying the key variables over a relevant range. The results from these are summarised in the following discussion.

Sensitivity to α

Under the currently assumed functional form of the amenity value function (equation 3), the threshold multiplier becomes less sensitive to α as α increases (see figure 2). Setting α to unity, as was done in the case

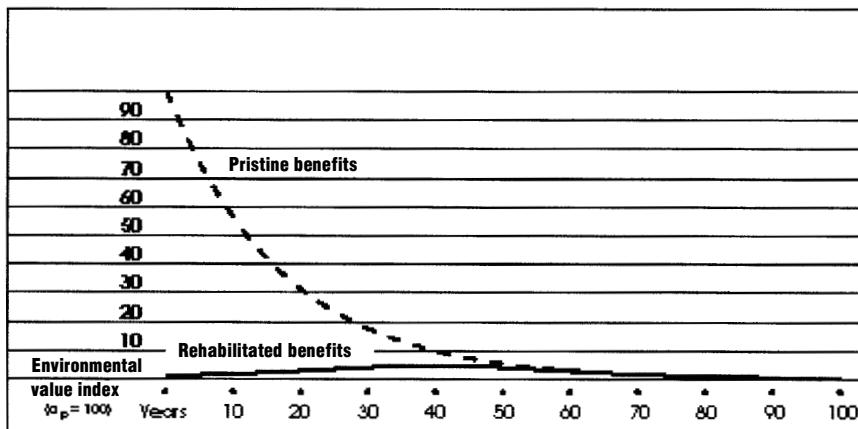


Figure 1 Present value of annual rehabilitated and pristine benefits in the threshold case

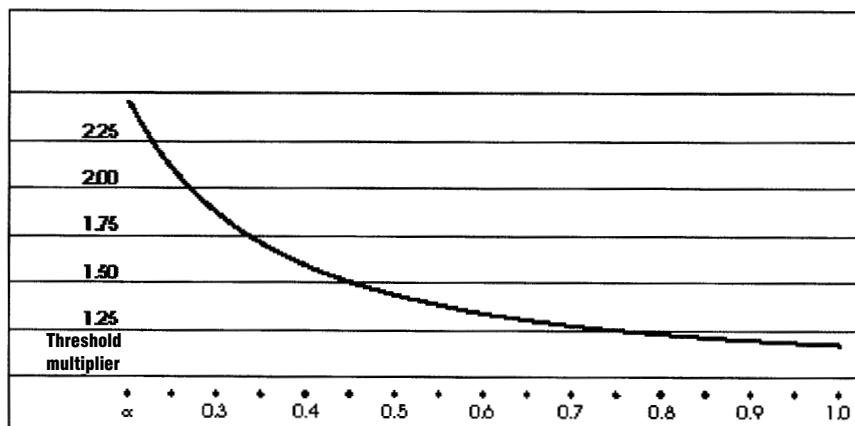


Figure 2 Sensitivity to α

study, is the most conservative choice available under the current assumptions about the functional form of the amenity value function, as this produces the lowest threshold multiplier. The intuition behind this result is that diminishing marginal value implies that initial increases in social benefits from unit increases in biomass are worth more than biomass growth in subsequent years. This effect is enhanced the larger the discount rate is.

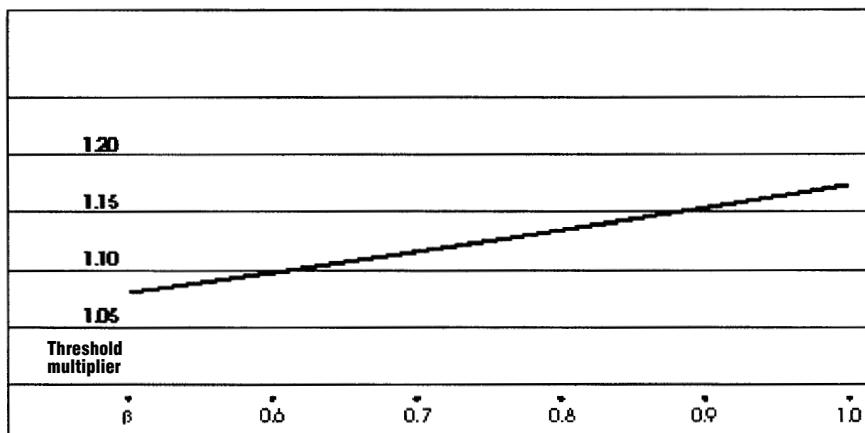


Figure 3 Sensitivity to β

Sensitivity to the success of rehabilitation

The threshold multiplier increases with β from a value of unity when $\beta = 0$ (no rehabilitation) to 1.17 when $\beta = 1$ (completely successful rehabilitation). As can be seen from figure 3, the threshold multiplier is relatively insensitive to changes in β for a large range of possible values of β (it lies between 1.08 and 1.17 for values of β ranging from 0.5 to 1). However, as can be seen from equation 7, the sensitivity of the threshold to β would increase if α is set to a value less than 1.

Sensitivity to the growth rate of the environmental index

It is apparent that the choice of growth rate has a significant effect on the threshold multiplier (figure 4). However, as this growth rate is generally estimated from available data, it is possible to report the range of values of the threshold multiplier associated with the variance in the estimate of the growth rate. In this example, for a growth rate of 0.1 (which implies 50 per cent regeneration after 46 years and 90 per cent regeneration after almost 70 years), the threshold multiplier is 1.12, while for a growth rate of 0.15 (which implies 50 per cent regeneration after 30 years and full regeneration after around 70 years), the threshold multiplier is 1.26.

Sensitivity to the discount rate

It is apparent that the choice of discount rate has an important bearing on the threshold multiplier. At $r = 0.05$ the threshold multiplier is 1.23; however, as r is increased to 0.1 and 0.15, the threshold multiplier falls to

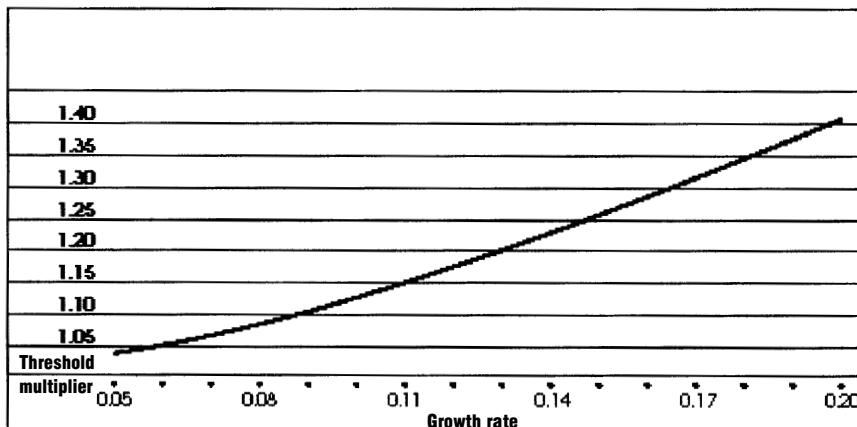


Figure 4 Sensitivity to growth rate

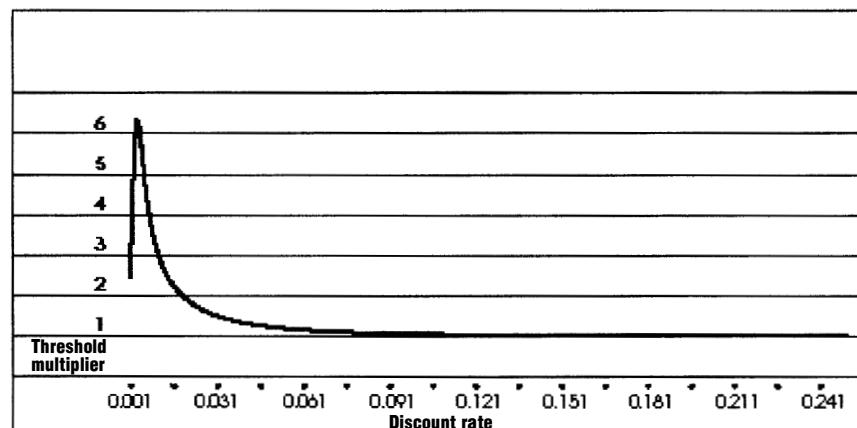


Figure 5 Sensitivity to discount rate

1.06 and 1.03 respectively (figure 5). It can be seen that, for most values of r (in this case $r > 0.003$), the threshold multiplier decreases as r increases. At $r = 0$, the threshold multiplier is undefined.

To understand the intuition behind these results, it is necessary to consider the economic interpretation of Y . By examining equation 4, it can be seen that Y is the present value of a perpetuity which starts close to zero, but then grows logically (given the specification in equation 2) to one dollar. As can be seen from figure 5, for discount rates greater than 0.003, $\frac{\partial s}{\partial r} < 0$. The

intuition behind this result is that as the discount rate increases, the present value of the (threshold) regeneration benefits falls by proportionately more than the present value of the (threshold) pristine benefits. Given that under the threshold condition the difference between these two values must equal the net mining benefits, this implies that the present value of amenity benefits (and hence the threshold multiplier, s) must fall.⁵

Conversely, for very low discount rates (under the base case, $r < 0.003$), as r increases, the present value of pristine benefits falls by proportionately more than the present value of regeneration benefits. From equation 10, it can be seen that the point where $\frac{\partial s}{\partial r} = 0$ is also a function of the logistic parameter, g , through Y . As g (the instantaneous rate of growth) increases, it can be shown that the turning point shifts to higher discount rates. However, even when the growth rate is set to very high levels ($g = 100$ per cent), the turning point still occurs at a quite low r (approximately 0.005). Given this, it is likely that only $\frac{\partial s}{\partial r} < 0$ should be viewed as meaningful within the normal range of discount rates. Indeed, it can be shown that in the case where environmental regeneration is linear and perfect, $\frac{\partial s}{\partial r} < 0 \forall r$, and that there exists a defined threshold annual amenity value when $r = 0$, unlike the logistic case described above.

4. Some issues in application

The preceding analysis demonstrates that, under certain circumstances, including regeneration can have a significant effect on the threshold amenity value required for mining to be considered suboptimal. Despite the potential importance of including this effect, there are some issues concerning the practical application of the concept which remain to be considered. Some, however, such as the choice of discount rate, are endemic to environmental benefit-cost analysis and will not be detailed here. The critical relationships underlying the model are the environmental quality regeneration function and the environmental value function. Although the issues concerning these two functions are closely related, they are dealt with separately below in order to differentiate problems of physical measurement from problems of economic valuation.

⁵ From equation 10 it can be seen that if $\alpha = \beta = 1$, $\frac{\partial s}{\partial r} = (Y'(r).r + Y)(1 - Yr)^{-2}$. From the numerical solutions to Y it was found that $(1 - Yr)^{-2} > 0 \forall r$, where $0 < r \leq 1$. Therefore if

$$\frac{\partial s}{\partial r} < 0 \Rightarrow \frac{\partial \ln Y}{\partial r} > \frac{\partial \ln \frac{1}{r}}{\partial r}.$$

4.1 The choice of environmental indexes

In the preceding model it was assumed that the environmental index effectively captured all of the relevant use and non-use benefits. As a first order approximation, the index was derived from data on the regrowth of above ground cellulose biomass on rehabilitated minesites. In some cases, it could be expected that an index based on attributes such as species diversity and forest complexity would be more representative of certain use and non-use values derived from the area. It must be noted, however, that this type of index is unlikely to be successful in aggregating those characteristics of the forest from which all benefits are derived. Some physical benefits, such as the water-generative capacity of the area, may not be related in a positive and linear fashion to an index based on such attributes alone. Where these effects are likely to be significant, separate indexes which account for divergent growth rates of different aspects of environmental quality could be used. Correspondingly, however, separate value functions would be required.

4.2 The choice of amenity value functions

As with the environmental index, an important issue concerning the value function is the nature of amenity benefits the specified form includes and excludes. Although it seems likely that many aesthetic and recreational values could be related to some index of environmental quality, it is possible to think of some values which may not be well related to such an index. These include benefits which do not 'grow back' following regeneration of the forest, even over long time periods. For example, there may be some use and non-use values attached to a forest simply because people are aware that the trees pre-date European settlement (see Randall 1991 for a taxonomy of resource values).

However, the interpretation of the threshold value changes in such circumstances where these types of values are likely to be significant and cannot be estimated. The minimum environmental cost required for mining to be suboptimal in this case will be equal to the threshold value (as described here) less the values not accounted for in the specified amenity value function and environmental index. Without first estimating these values there would be no way to estimate the minimum economic value of the mining project necessary for benefits to be greater than costs. On the other hand, if irreversible benefits, such as the existence value of pre-European forest, could be estimated, this could then be subtracted from the threshold and included in the analysis. In this case, the threshold expression (equation 1) would be written:

$$M - X + \int_0^{\infty} a_t e^{-rt} dt = \int_0^{\infty} a_p e^{-rt} dt + \int_0^{\infty} a_e e^{-rt} dt, \quad (11)$$

where a_e = 'irreversible' annual benefits which do not grow back following mining. As such, the annual threshold value, a_p , may now be written as:

$$a^p = \frac{M - X - \frac{a_e}{r}}{\frac{1}{r} - \beta^x Y} \quad (12)$$

It should be noted that including the effects of environmental regeneration could still be an important factor in the overall analysis, even if these types of values cannot be estimated.

Aside from these aggregation issues, there is also the issue of the actual form of the aggregate environmental valuation function. In the model presented it was assumed that the function took a particular form (equation 3), with the only parameter requiring specification being α , which determines the rate at which marginal benefits diminish. However, it could be expected that the valuation function could take a variety of forms, depending on the nature of benefits associated with the forest. For example, it may be the case that, at least initially, marginal aesthetic and recreational values increase with respect to increases in environmental quality. In the long run, however, it could be expected that, as the forest matures, marginal benefits would decline. This would imply a functional form similar to the logistic function assumed for the environmental index.

Despite these uncertainties, it could be expected that there will be fewer restrictions in estimating the general functional form of environmental valuation functions (as required in the threshold approach), than in estimating an exact point on such a schedule for a specific level of environmental quality (as required in a full benefit-cost analysis). Further work on the nature of cardinal environmental value functional forms, perhaps derived from revealed preference and contingent rating studies, may shed more light on this issue. The applicability of the contingent ranking approach has not yet been fully established, yet it could be useful for this purpose and appears theoretically valid (Commonwealth Department of Environment, Sport and Territories 1995). In addition, Mackenzie (1993) finds the contingent rating method was informationally more efficient than standard contingent valuation.

4.3 Disaggregating the threshold analysis and other extensions

To a large extent the issues identified above are associated with the aggregation of non-mining benefits into one index of environmental quality and one function of environmental value. In the threshold model presented,

the only benefits which were assumed quantifiable were the potential mining benefits. In some cases, however, it may be possible to measure certain non-market benefits associated with forest use. For example, it may be possible to estimate the value of recreational demand for the forest in its current state using the travel cost method, and then this could be used to calculate the net reduction in recreational benefits associated with mining.

The effect of separately identifying the recreational benefits and netting them out would be to lower the threshold value, as some of the environmental costs would now be quantified. It is expected that this would make the interpretation of the resultant threshold value easier for two reasons. First, the value would now pertain to a smaller subset of the non-market values (possibly only non-use values), and therefore have greater decision-making practicability. Second, the index and valuation functions would be less aggregated, and therefore potentially more accurate. A further possible extension to the model presented here is to incorporate some uncertainty into the whole valuation procedure. This could be achieved by making β (the rehabilitation success rate) a random variable. The distribution for β could be obtained from data on the success of rehabilitation of ecosystems elsewhere following mining.

It should be noted that the approach presented here may also have applications in examining questions of environmental disturbance and rehabilitation for other activities within areas of potential conservation value. For example, evaluating the benefits of a proposed waste dump, where after a period of use the area would be backfilled and rehabilitated. In this case, however, equation 1 would need altering to reflect the delay between disturbance (when the waste dump is established) and rehabilitation (when the waste dump is full). This is unlike the case of bauxite mining, where clearing, mining and rehabilitation happen within a short period of time.

5. Conclusions

When considering the economic benefits of a proposed mining activity against the environmental costs of that activity, a threshold approach is often adopted, where the net economic benefits of mining are taken to represent the minimum environmental costs that are required for mining to be suboptimal. It has been shown that for mining operations which cover large areas of land, and therefore have environmental impacts which are largely contained onsite, the inclusion of environmental regeneration following minesite rehabilitation can have a significant impact on the threshold value.

The example of bauxite mining and rehabilitation developed here found that the threshold value is 17 per cent higher (under base case assumptions) when environmental regeneration is included in the analysis. The results are

sensitive to the rate of environmental regrowth, the discount rate and the functional form of the amenity value function for non-market forest goods. The dynamics of regeneration has a crucial bearing on the economic value of regrowth, with the benefits from regeneration after 60 years not affecting the threshold value significantly.

The threshold approach was used as the vehicle to incorporate environmental regeneration for two main reasons. First, it is often the case that non-market values are unavailable. Second, the threshold approach enables environmental regrowth to be incorporated into the analysis without having to estimate actual dollar values for different levels of amenity. The importance of including regenerative effects discussed here also applies in situations where non-market benefits are estimated.

As with all environmental valuation techniques, there are a number of issues which emerge in the practical application of this method. Among those is the aggregation of environmental values. Certain types of benefits (such as the preservation of old growth forest) would not be captured in this analysis because they will not grow back in proportion to biological regeneration of the forest. The inclusion of these types of benefits changes the interpretation of the threshold value calculated here. However, the inclusion of environmental regeneration is still an important aspect of the analysis.

If an area is expected to provide benefits for aesthetic and recreational purposes which can be related to the environmental quality of the forest, then it is important that changes in these values as the forest regenerates are considered when examining land use alternatives. A valuation of mining benefits alone is misleading when viewed as a threshold, because it is often compared (directly or by implication) with the perceived current non-market value of the resource, and not the change in non-market value of the resource that would occur following mining and rehabilitation. The inclusion of the regeneration of environmental values results in a threshold value which is directly comparable to what the perceived or estimated current non-market value of the resource in question is, and therefore has the potential to enable better land use decisions.

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