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ANALYSIS

The economic value of a forested catchment with timber, water and carbon sequestration benefits

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Abstract

This paper examines the optimal management strategy for a forested catchment that yields timber, water and carbon sequestration benefits. The Faustmann multiple rotation model is extended to allow for the maximisation of the net present value of these timber and non-timber benefits. The model is applied to the Thomson Catchment in Central Gippsland, Victoria. Carbon sequestration benefits are modelled via total stand biomass accumulation. The cost of carbon release back into the atmosphere upon logging is estimated as a function of rotation age using an adjusted pulpwood/sawlog ratio. The allowance for both non-timber benefits is found to lengthen the optimal rotation, in a large range of cases to infinity. © 2001 Elsevier Science B.V. All rights reserved.

1. Introduction

This paper examines the optimal management strategy for a forested catchment that yields timber, water and carbon sequestration benefits. Carbon sequestration, as a result of photosynthesis, involves the uptake and conversion of atmospheric CO_2 into cellulose and other organic compounds, such as wood. By sequestering atmospheric CO_2, trees convert anthropogenic and natural greenhouse gases into carbon, which is stored in their biomass and released when the tree or its products decay: for a broad-ranging discussion of carbon sequestration, see Cannell (1999).

The model is applied to the Thomson Water Catchment in Central Gippsland, Victoria, which contains extensive native forests. The Thomson Catchment is a forested area of 48 000 ha draining into the Thomson Dam, one of the major water reservoirs for Melbourne (Vertessy et al., 1994). Roughly a third of the Thomson Catchment is covered by Ash species which are valued for their high-quality timber as well as playing a crucial part in the catchment's hydrology cycle.

The quality and quantity of water flowing from the catchment are maximised for old-growth forests. However, optimal exploitation of the timber resource requires harvesting at regular inter-

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vals. Therefore, the socially optimal rotation between planting and harvesting is likely to diverge from the rotation that would be privately optimal if only timber benefits were maximised. While other environmental benefits such as biodiversity conservation cease to exist after clear-felling, forest managers can influence the cost of carbon release back into the atmosphere by choosing the age of the tree cut and, as a result, the likely end-use of the timber.

There are other environmental benefits, e.g., biodiversity conservation, water purification and soil stabilisation, in addition to various recreational benefits; for a general discussion of costs and benefits in relation to forests, see Pearce (1994). These benefits are not considered here, largely because of the difficulty of obtaining suitable values. Furthermore, the effects of, e.g., nutrient depletion or soil compaction arising from harvesting, are not examined. However, it is expected that consideration of such factors would unambiguously increase the socially optimal rotation length since environmental and amenity values are likely to be positively related to tree age.

In 1998 the Kyoto Protocol to the United Nations Framework Convention on Climate Change opened the opportunity to trade greenhouse gas emissions for increased sequestration of CO_2 by forests. While an established catchment like the Thomson would not qualify for carbon credits under the Kyoto protocol, the debate nevertheless stimulated independent studies of the traded value of a tonne of carbon.

Victoria's catchments are areas of public land that are managed by the state through Melbourne Water. The Thomson Catchment is part of the Central Gippsland Forest Management Area and is managed on a sustainable yield basis allowing for 80-yr rotations. The current management strategy does not take explicit account of non-timber values. However, in 1992 the Department of Conservation and Environment, together with Melbourne Water, commissioned an evaluation of the economic values of wood and water for the Thomson Catchment. The resulting report simulated the expected present values of timber and water yields for eight management options; see Read et al. (1992). Clarke (1994) used the data from the report and found that logging of the Thomson is not socially optimal. His findings were contradicted by Ferguson (1995), who argued that logging is optimal until 2022 on the grounds that the water values used by Clarke were too high and that appropriate policies could reduce water losses in future rotations. Ferguson (1995) based water values on marginal cost considerations rather than tap values; see also Ferguson (1996).

The effects of carbon subsidies and taxes on the optimal rotation age of a forest plantation were examined by van Kooten et al. (1995). They found that for the forest regions of northern Alberta and British Columbia, rotation ages are only marginally longer if the benefits from carbon uptake are taken into account.

The model developed here is based on the Faustmann multiple rotation model, extended to include water and carbon sequestration and allowing for the costs of regeneration and replanting. Unlike van Kooten et al. (1995), the instantaneous cost of carbon release back into the atmosphere upon logging is modelled as a function of rotation age since this affects the quality of the timber and therefore its use. For a transition matrix approach to carbon sequestration in the context of tropical forests, with regeneration uncertainty, see Reddy and Price (1999).

The formal model is developed in Section 2. The specification of various functional forms and parameter estimates for the Thomson Catchment are presented in Section 3. Section 4 examines the implications for optimal rotation length. The management of an existing stand, in contrast with an optimal rotation plan, is also discussed. Conclusions are in Section 5.

2. The formal model

This section presents the basic model of optimal rotation from the widely used Faustmann (1849) analysis, and extends it to include water and carbon sequestration benefits. For discussions of the Faustmann approach, see, e.g., Hartman (1976) and Hanley et al. (1997). The model is limited to a homogeneous forest, though in practice the species composition is heterogenous. The use of harvesting for fire protection is ignored here. Furthermore, silviculture practices are not modelled, but Hanley et al. (1997) suggest that their inclusion in this framework is unlikely to be feasible. For a linear programming approach for forestry management, see, e.g., Buongiorno and Gilles (1987).

2.1. Timber and water benefits

Let T denote the forest rotation length, and $V(T)$ the timber value of the forest stand at time T. The water catchment involves a flow of associated benefits, $w(t)$, over the period $t=1,\ldots,T$. If r denotes the real discount rate, the present value of water benefits, $W(T)$, at the start of the rotation is

$$W(T)=\int_0^T w(t)\,\mathrm{e}^{-rt}\,\mathrm{d}t. \tag{1}$$

If the cost of planting seedlings at the start of each rotation is S, the present value of the first and future rotations, $P_0(T)$, is given by

$$P_0(T)=-S+\sum_{j=1}^{\infty}\{V(T)-S+W(T)\}\,\mathrm{e}^{-jrT}. \tag{2}$$

This can be further simplified, using

$$\sum_{j=0}^{\infty}\mathrm{e}^{-jrT}=(1-\mathrm{e}^{-rT})^{-1},$$

to give

$$P_0(T)=-V(T)+\frac{1}{1-\mathrm{e}^{-rT}}\{V(T)-S+W(T)\}. \tag{3}$$

The optimal rotation length is the value of T for which $\mathrm{d}P_0(T)/\mathrm{d}T=0$ and, using $W'(T)=w(T)\,\mathrm{e}^{-rT}$, is given by the root of the following equation:

$$\frac{V'(T)}{V(T)-S}-\frac{r}{1-\mathrm{e}^{-rT}}=\frac{1}{V(T)-S}\left\{\frac{r}{1-\mathrm{e}^{-rT}}\,W(T)-w(T)\right\}. \tag{4}$$

It is convenient to write the left- and right-hand sides, respectively, of Eq. (4) as F_1 and F_2, so that (4) becomes

$$F_1=F_2. \tag{5}$$

In the absence of a water catchment, the right-hand side of Eq. (4) is zero and the resulting equation is the Faustmann condition. If $V(T)$ is increasing and concave, for a given value of r, the left-hand side of Eq. (4) decreases as T increases. The shapes of the various functions are discussed in Section 4, where it is shown that allowance for water benefits involves an increase in the optimal rotation length.

2.2. Net carbon sequestration

The present value in Eq. (2) and the first-order condition in Eq. (4) can be extended to allow for further flow benefits and further benefits or costs of logging. Thus, if there is a flow of carbon sequestration benefits, $k(t)$, over the length of each rotation from $t=1,\ldots,T$, the present value, $K(T)$, is given by

$$K(T)=\int_0^T k(t)\,\mathrm{e}^{-rt}\,\mathrm{d}t. \tag{6}$$

Hence, the term $W(T)$ is replaced by $W(T)+K(T)$ and $w(T)$ is replaced by $w(T)+k(T)$.

Logging at the end of each rotation involves carbon release, valued at $C(T)$. In reality the release of carbon occurs over long periods and depends on the life cycle of the wood products. Some timber is burned and the carbon release is therefore instantaneous while other uses involve long-term storage in timber constructions and furniture. Previous models of net carbon sequestration specified its release as either a constant proportion of the total amount sequestered, as in van Kooten et al. (1995), or concentrated on the product life after the timber is harvested, as in Maclaren (1996), Kadekodi and Ravindranath (1997) and Price et al. (1997). The former treatment ignores the fact that the quality and age of the timber harvested largely determine its end-use and, as a result, the rate at which carbon is released.

The question arises of how to model the instantaneous release of carbon as a function of rotation length, without having to incorporate explicitly the life span of wood products. The approach used here involves specifying the instantaneous carbon release as a function of rotation age. This is because the proportion of the timber yield in the form of pulpwood, rather than high-grade sawlogs, depends on the rotation age. A large proportion of pulpwood is used for short-lived wood products such as paper or firewood. Hence, the ratio of pulpwood to sawlog, adjusted for non-typical product life, acts as a proxy for the proportional instantaneous release of sequestered carbon into the atmosphere.

Define the function $Z(T)$ as the proportion released of the total value of carbon sequestered over the length of the rotation. Hence $C(T)$ is expressed as

$$C(T) = Z(T)K(T). \tag{7}$$

In this case it is appropriate to extend Eq. (3) by writing the present value as

$$\begin{aligned} P_0(T) = & -V(T) \\ & + \frac{1}{1-\mathrm{e}^{-rT}}\{V(T) - S + W(T) + K(T)\} \\ & - \frac{\mathrm{e}^{-rT}}{1-\mathrm{e}^{-rT}} Z(T)K(T). \end{aligned} \tag{8}$$

It can be shown that the allowance for carbon sequestration and release involves adding a term, F_3, to the first-order condition in Eq. (5), where

$$\begin{aligned} F_3 = & \left\{\frac{1}{V(T)-S}\right\} \\ & \left[\frac{rK(T)}{1-\mathrm{e}^{-rT}}\{1 - Z(T)\} \right. \\ & \left. + k(T)\{Z(T)\,\mathrm{e}^{-rT} - 1\} + Z'(T)K(T)\right]. \end{aligned} \tag{9}$$

The augmented first-order condition for the determination of the optimal rotation length is therefore

$$F_1 = F_2 + F_3. \tag{10}$$

If F_2 and F_3 are both negative, the allowance for water and carbon has the effect of increasing the rotation period. The values of these terms depend in complex ways on the precise nature of the functions, $V(T)$, $w(t)$, $k(t)$, and $Z(T)$. These are examined in the following section.

3. Functional forms

This section presents the specifications and estimates of the functions introduced above for the Thomson Catchment. The analysis is limited to Alpine Ash, for which functional forms are available, rather than incorporating a wider cross-section of the vegetation in the Thomson. However, Alpine Ash is the most prominent and most valuable species in terms of water and timber yield and quality. In addition, its commercial value makes the Ash stand strategically important. Indeed, the most important values for other species are related to amenity and biodiversity characteristics, rather than commercial values. These are non-decreasing over time.

Data on timber and water yields and values were taken from Read et al. (1992). Data relating to the carbon sequestration and carbon release properties of the Thomson Catchment were collected from a variety of sources, including Grierson et al. (1992), Byron and Coleman (1999) and unpublished government reports, along with discussions with employees at the Australian Greenhouse Gas Office and the Department of Natural Resources and Environment. All values reported here are expressed in Australian dollars.

3.1. Timber benefits

The timber value, $V(T)$, equals the value of timber per unit multiplied by the amount of saleable timber, as given by a timber growth function. The volume of saleable timber increases with time but at a decreasing rate. A forest stand yields positive returns from harvesting only after reaching a minimum age. The timber growth function depends on the species as well as the location; see Grierson et al. (1992) and Kirschbaum (1995).

The timber yield function used here is taken from Clarke (1994) and is the revised yield function used by Read et al. (1994) to represent the sawlog yields for the Thomson Catchment. On this revised function, see also the discussion in Ferguson (1995, p. 142). A generic functional form for the yield curve was proposed by Chikumbo et al. (1999).

The returns from pulpwood are ignored because the principal income from timber is likely to come from sawlogs that are graded C and above. If $V(T)$ is measured in dollars per cubic metre and if p_f denotes the price of timber (adjusted for the sawlog grade distribution), then

$$V(T) = p_f\{-2231.3 + 961.8 \log T - 88.48(\log T)^2\}. \tag{11}$$

The price is assumed to be constant, on the assumption that the yield is a small proportion of the total supply.

Timber is valued in the year of harvest as standing timber. The Victorian Government administers this valuation system, known as a royalty system. However, royalties undervalue the timber resource and it is desirbable to use values closer to market prices; see Sinden and Thampapillai (1995). One approach is to add the prices paid for long-term harvesting rights to the royalties. This is the preferred approach of the Australian Bureau of Agricultural Economics (ABARE) and was adopted by Read et al. (1992). In Victoria, the long-term harvesting rights are auctioned. O'Regan and Bhati (1991) estimate transferable long-term harvesting rights to be 33% and 41% above royalty for A/B grade and C grade logs, respectively. With an assumed grade distribution of 34% and 66%, respectively, of A/B and C grade sawlogs, the value is $p_f = 55$.

3.2. Water yield and value

The water benefits function, $w(t)$, consists of the net dollar value of annual water yield as a function of stand age, t. Annual yield is measured in terms of Ml/ha. The water yield function, $y(t)$, obviously depends on many variables, but the following analysis is based on the equation estimated by Kuczera (1985), using observations of changes in the water yield as a function of regeneration age after bush fires. Its applicability to water yield predictions of Ash forests regenerating after being clear felled is generally accepted; see Read et al. (1992, 1994), Clarke (1994), Vertessy et al. (1994), Ferguson (1995, 1996), and Vertessy et al. (1996). It takes the following form. For $t \leqslant 2$, $y(t) = 11.9$, and $t > 2$:

$$y(t) = 11.9 - (6.1)(0.039)(t-2) \exp\{1 - 0.039(t-2)\}. \tag{12}$$

Here the yield of a mature forest is 11.9 Ml/ha and the maximum yield reduction below that for a mature forest is 6.1.

The shape of the water benefits curve can be explained as follows. After clear felling, the stand is covered with very young trees which absorb only small quantities of water. As the trees grow, their water usage increases without a decline in stand density. Thus substantial amounts of water are lost through evapotranspiration. As leaf coverage increases, shading leads to a natural thinning of the stand, which reduces water usage and translates into higher water yields; see Vertessy et al. (1998). The curve is illustrated in Fig. 1.

Water quality is an important factor in determining its value. Logging has an adverse impact on quality, mainly through increased turbidity of water in the catchment. The severity depends on the logging practices, such as road location and design, and the width of buffer zones. Water quality is highly erratic for the first five to eight years after logging. Water quality effects are allowed for here by assuming that the water resource is unavailable (the value is zero) for the first five years after logging because the high capital cost of purification is likely to outweigh the costs of foregoing the resource. Ash-type stands are situated in the wettest areas of the catchment. About 80% of the total run-off filters

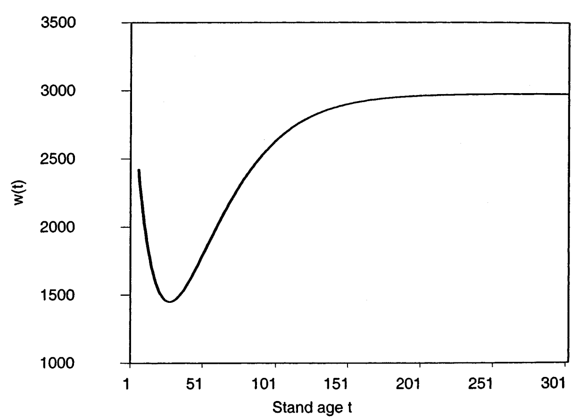

Fig. 1. Water yield and stand age.

through these stands. As a result, they are strategically important areas to consider when deciding on a catchment management strategy; see Vertessy et al. (1998). After 5 years, the value of water per Ml per year is $p_w = 250$ for the base case: this value is a lower bound estimate of the costs of a Ml of water to Melbourne Water.

The multi-rotational model requires that the water benefits are modelled as a flow benefit, so that discounted accumulated water yields over the years from the start until the end of each rotation are required. Clarke (1994) derived a continuous integral term (using the mathematical software package DERIVE) for a given rate of interest, for the dual interval equations. He did not allow for the water quality in the early years after logging; this can, in some cases, cause the optimal rotation length to fall as the water value increases. The present study uses discrete rather than continuous discounting, which considerably simplifies present value calculations and in particular allows sensitivity analyses to be carried out with respect to the discount rate. Further calculations showed that there was no significant difference between continuous and discrete discounting.

3.3. Carbon sequestration and stand age

Photosynthesis involves the absorption of atmospheric CO_2 and its conversion into cellulose and other organic compounds such as wood. Carbon constitutes a substantial proportion, depending on changes in soil and other characteristics, of the accumulated dry weight biomass; see Cannell (1999). Estimates of biomass changes as a function of stand age, type and region exist for Victoria's native forests.

The forest soil also stores a significant proportion of the total amount of carbon absorbed from the atmosphere, though less is known about this aspect; see Cannell (1999). Estimates range between 44 and 268 tonne of C per ha, depending on vegetation, altitude and climate factors, soil nutrient levels and the level of complexity of forest floor ecosystems; see Tate et al. (1995), Vesterdal et al. (1995), and Pennock and von Kessel (1997). Similarly, little is known about the effects of logging on soil carbon storage. Most studies conclude that soil carbon storage decreases after disturbance and is slow to recover; see Rab (1994), Black and Harden (1995), and Nakane and Lee (1995). In view of the uncertainty regarding carbon storage in forest soils, this study is limited to above-ground sequestration.

Carbon sequestration benefits, $k(t)$, are modelled here as the annual rate of carbon sequestered (mean annual increment) multiplied by its value per unit of carbon. The mean annual carbon increment is highest as seedlings are planted. It falls to zero after about 100 years. This has led to some confusion, whereby some commentators have advocated a conversion of old forests to young forests so that short-term carbon sequestration is maximised. However, the full potential of carbon sequestration is realised only when the stand has reached its maximum total biomass. The conversion to young forests would lead to a significant initial loss of stored carbon; see Kirschbaum (1995) and Harmon et al. (1990). Maclaren (1996) found that the age-class structure of a forest is among the most important factors determining whether the forest constitutes a net carbon sink or source. The amount of carbon stored per hectare of plantation in perpetuity is smaller, the shorter the rotation.

The annual amount of carbon sequestered is directly related to the annual increase in biomass. Grierson et al. (1992) estimated the dry weight biomass accumulation for native species in Victoria as a function of stand age. For this study the biomass function specified for Alpine Ash because it is the most prominent (more than 60%) among the three Ash species present. Grierson et al.'s biomass function for Alpine Ash is

$$B_t = 9.94 + 9.63t - 0.0516t^2. \tag{13}$$

This quadratic function was estimated for a data range limited to the first 100 years of stand age. However, biomass is expected to stabilise once the maximum has been reached; see Kirschbaum (1995). Hence, in this study the annual increase in biomass, given by the first derivative of Eq. (13), is replaced by zero as soon as the maximum is reached.

Grierson et al. (1992) found that native Ash forests have high carbon densities of up to 400 tonne/ha, which are sometimes greater than those for tropical forests. Approximately 50% of the annual increase is in the form of carbon; see Grierson et al. (1992) and Dobes et al. (1998).

Efforts to value a tonne of carbon have resulted in a vast array of estimates ranging from as little as US$3.93 to US$250; see Sedjo et al. (1995) and Byron and Coleman (1999). Methods of arriving at these estimates include carbon tax equivalence studies, as in Solberg (1998), as well as imputing a shadow price by asking how much it would cost to sequester the same amount of carbon using human technology; see Pearce and Brown (1994).

A benchmark value of $p_c = 110$ per tonne of carbon is used in this study and has also been adopted in an unpublished government report. This value represents a middle value of previous estimates and is therefore to some extent arbitrary. For this reason, sensitivity tests are conducted on carbon values ranging from \$20 to \$300 per tonne of carbon. Instead of using a constant value, it might be suggested that the value of carbon sequestration to society is affected by climate change and therefore varies over time; on the costs of climate change, see Fankhauser (1995) and the debate between Demeritt and Rothman (1999) and Fankhauser and Tol (1999). Allowing the value to increase over time is likely to raise the rotation length, and therefore strengthen the main conclusions below.

3.4. Carbon release and stand age

The timber harvested from forests managed under short rotations is used as either firewood or for short-lived products such as paper. As a result, all the carbon sequestered over the length of the rotation is assumed to be released instantaneously. With longer rotation length the quality of the timber improves, so that higher proportions of the timber can be used as sawlogs and the cost of instantaneous carbon release decreases. As the forest reaches maturity and becomes over-mature, the trees develop hollows and become less valuable in terms of high-grade timber production. Old-growth forests and young forests yield proportionately less high-quality timber than forests that are managed at rotations of between 80 and 170 years. Such rotations also minimise the instantaneous cost of carbon release; on the speed of carbon release, see Kirschbaum (1995). Van Kooten et al. (1995) assumed that a constant fraction of the harvested timber, independent of the age of the wood that is harvested, remains in long-term storage. However, a much higher proportion is likely to be used in short-term products for very young forests as well as over-mature forests.

It is necessary to model the cost of carbon release upon logging as a function of the rotation age. The ratio of pulpwood to total timber harvested seems to fit this requirement. However, as not all carbon stored in sawlogs is preserved in long-lived timber uses, it is necessary to refine the ratio of pulpwood to sawlogs accordingly. Adjustments to the data on the ratio of pulpwood to sawlogs (taken from Read et al. (1992)) were based on estimates suggesting that 100% of pulpwood and 80%, 60% and 50% of A, B and C logs, respectively, are used for long-lived wood products. Furthermore, it was assumed that the carbon stored in short-lived products is released instantly while the carbon stored in long-lived products is never released.

An instantaneous carbon release function was calibrated from 12 observations of the pulpwood/sawlog ratio adjusted for the carbon release properties. The function is quadratic and has the following form:

$$Z(T) = \underset{(16.76)}{1.05965} - \underset{(-3.57)}{0.005063T} + \underset{(3.26)}{0.0000168T^2}, \tag{14}$$

where $R^2 = 0.62$ and estimated t statistics are given in brackets. To make the function more realistic, its value was assumed to equal unity until year 13. Further, the maximum amount of carbon released instantaneously when overmature forests are logged was assumed to be 85%. The cost of carbon released instantaneously is assumed to be the same as the benefit from sequestration, and is therefore set at \$110 per tonne for the base case. The function $Z(T)$, the proportion

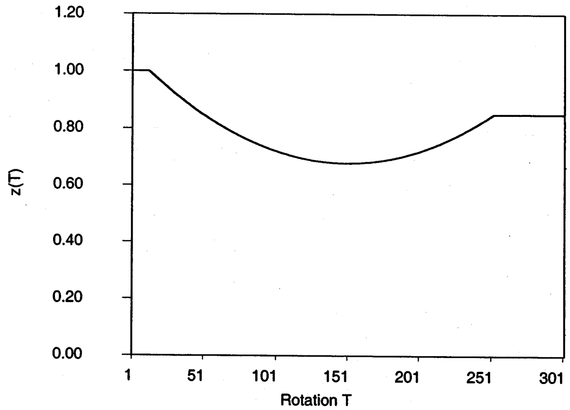

Fig. 2. Carbon release as a function of rotation.

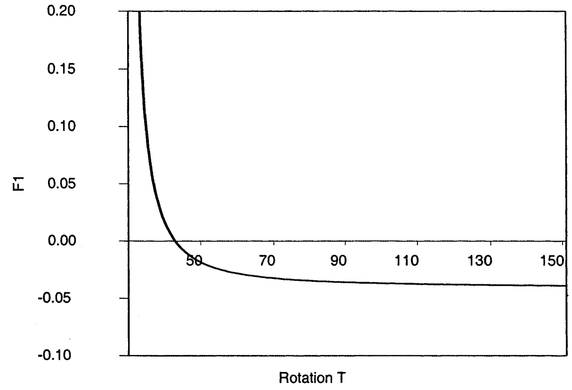

Fig. 3. Timber benefits: F_1.

released of the total value of carbon sequestered over the length of the rotation, is shown in Fig. 2.

4. Optimal rotation length

4.1. The first-order conditions

An initial insight into the determination of optimal rotation length can be obtained by considering the three functions, F_1, F_2 and F_3 derived above, using the specifications discussed in the previous section. In addition, the cost, S, of regenerating 1 ha is set at \$607, which includes the cost of seed and site preparation. This cost was ignored by Clarke (1994).

For the 'benchmark' or base case, the following values are used: $r = 0.04$, $p_f = \$55$, $p_w = \$250$, and $p_c = \$110$. The two functions relating to timber and water are shown in Figs. 3 and 4. Fig. 3 shows that, allowing for the timber values of S shifts the profile upwards, thereby lengthening the optimal rotation. However, higher timber values and a higher discount rate would shift the profile downwards and lower the rotation length.

Fig. 4 shows that, in this benchmark case, the allowance for only water benefits implies that the forest should never be cut; there is no solution to the equation $F_2 = 0$. A reduction in the value of water has the effect of shifting the profile upwards. Fig. 5 shows that the effect of adding water to timber values also implies an infinite rotation length. A substantial reduction in the value of water is required to shift the F_2 upwards such that a feasible root exists for the equation $F_1 - F_2 = 0$; see the sensitivity analysis reported below.

Allowing for carbon sequestration benefits gives F_3 shown in Fig. 6; these benefits alone imply an optimal rotation of about 75 years. An increase in the extent of carbon release when cutting causes the schedule to shift downwards, thereby increasing optimal rotation length. Allowing for timber and carbon gives the profile for $F_1 - F_3$ shown in Fig. 7, which indicates a slight increase in the optimal rotation length compared with the use of timber values only. Obviously, allowance for all three factors leads to an infinite rotation length, dominated by the effect of water values in this

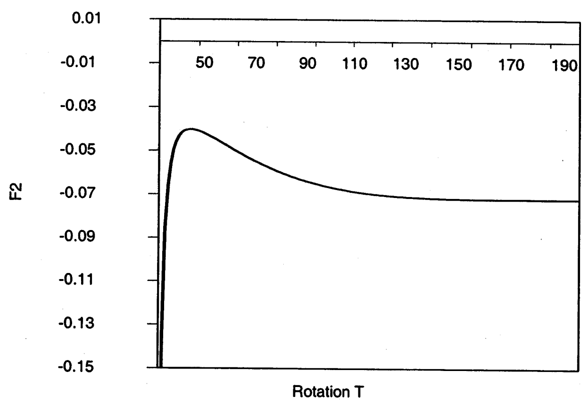

Fig. 4. Water benefits: F_2.

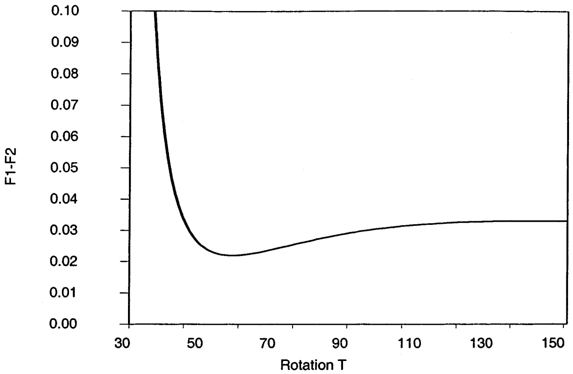

Fig. 5. Timber and water: F_1-F_2.

benchmark case. All the schedules become relatively flat beyond a certain length of rotation. If these ranges were relevant, very small changes in conditions (causing vertical shifts) would have substantial effects on optimal rotations.

4.2. Sensitivity analyses

Consider the sensitivity of the results of the previous subsection to changes in the components of the benchmark case. In carrying out the sensitivity analyses, a rotation of 300 years is treated as corresponding to 'infinity', or 'never cutting', as shown in the benchmark case of the first row of Table 1. This table reports, for given values of other variables, critical values of the interest rate, water and timber values for which logging is optimal. In addition, values are shown which generate the current policy of 80-years rotations.

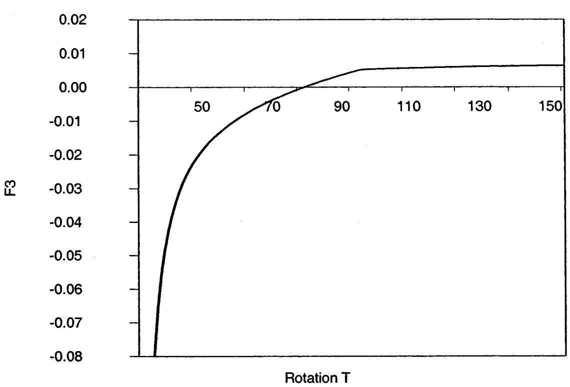

Fig. 6. Net carbon sequestration: F_3.

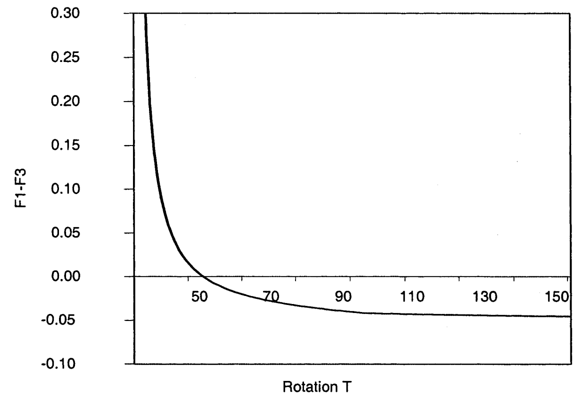

Fig. 7. Timber and carbon: F_1-F_3.

Table 1 shows that increasing the discount rate causes the optimal rotation length to fall, and as the interest rate reaches 0.0425, logging becomes optimal at 81 years. The flatness of the relevant profiles leads to considerable sensitivity in the optimal value of T, with little effect on the net present values.

For fixed values of the other benchmark assumptions, it is found that a critical water value of less than \$160 is required for logging to become optimal, which is similar to the value obtained by Clarke (1994). A timber value of at least \$95 is required for logging to be optimal. All sensible carbon values are associated with an infinitely long optimal value of T, in view of the dominance of water in the benchmark case; however, other configurations can introduce a greater role for carbon benefits. Further sensitivity analyses are reported in Tables 2–4. The range of

Table 1
Sensitivity to timber and water values

	Optimal T
Benchmark case	
$r=0.04$, $p_f=\$55$, $p_w=\$250$, $p_c=\$110$	300
Discount rate	
Critical $r=0.0425$, $r=0.0425$	81
Water value	
Critical $p_w=\$160$, $p_w=\$100$	81
Timber value	
Critical $p_f=\$95$, $p_f=\$100$	81

Table 2
Optimal rotation length with interest rate variations

Interest rate	$P_0(T)$: T, W, C	Optimal T
0.0100	232 436.50	300
0.0400	46 501.75	300
0.0700	24 285.82	300
0.0750	22 373.85	300
0.0775	21 512.70	136–300
0.0780	21 347.25	131–300
0.0790	21 022.82	91
0.0800	20 706.79	89
0.0825	19 950.92	81
0.0850	19 240.39	77
0.1000	15 734.01	61
0.1500	9168.78	49

values shown in Table 2 reflects the flatness of the profiles over the relevant range. These sensitivity analyses demonstrate greater robustness of the no-logging result, compared with those in Clarke (1994).

4.3. Management of the Thomson Catchment

The above optimal rotations were derived under the assumption that trees are 0-years old at the beginning of the multiple rotations. The case of the forest in question being already established, but younger than the optimal rotation age, can be examined as follows. The basic condition is that the Thomson should not be logged if the present value of not logging exceeds the present value of logging under the status quo arrangement. Hence, the following inequality must hold:

$$\int_{80}^{\infty} w(t)\,\mathrm{e}^{-rt}\,\mathrm{d}t + \int_{80}^{\infty} k(t)\,\mathrm{e}^{-rt}\,\mathrm{d}t > \mathrm{e}^{-r(80-60)}[V(80) - Z(80) - C] + P_{60}(80). \quad (15)$$

The water and carbon sequestration benefits until the end of the rotation cancel, so that the net former benefits consist of the discounted water benefits from year 80 to infinity plus the maximum amount of carbon stored. The latter equals the value of the stand's timber resource at the end of the rotation minus the instantaneous cost of carbon release, minus the regeneration costs discounted for 20 years, plus the net present value of all future rotations.

The values of the terms in Eq. (15) are as follows: $\int_{80}^{\infty} w(t)\,\mathrm{e}^{-rt}\,\mathrm{d}t = \$65\,469$, $\int_{80}^{\infty} k(t)\,\mathrm{e}^{-rt}\,\mathrm{d}t = \$9647$, $V(80) = \$15\,640$, $z(80) = \$7338$, $P_{60}(80) = \$20\,989$.

The left-hand side of Eq. (15) is \$75 116, while the right-hand side is \$24 501. This shows that the decision not to log the Thomson Catchment more than doubles its net present value under the status quo. Thus, given that the Thomson Catchment is already an established forest, its net present value is maximised by taking advantage of the high water yield and carbon stock, rather than forgoing these to earn the profits from its timber resource.

5. Conclusions

This paper has examined the socially optimal management strategy for a forested catchment, the Thomson Catchment in Central Gippsland, Victoria. This yields timber, water and carbon sequestration benefits. The Faustmann multiple

Table 3
Optimal rotation length with variations in water values

Water value (\$)	$P_0(T)$: T, W	Optimal T	$P_0(T)$: T, W, C	Optimal T
100	14 694.60	54	26 835.82	66
135	19 622.99	161	29 346.29	81
150	21 870.21	300	34 115.14	91
160	23 368.68	300	35 583.93	131
200	29 362.57	300	41 575.94	300
250	36 854.92	300	46 501.75	300
800	119 270.81	300	131 484.18	300

Table 4
Optimal rotation length with variations in carbon values

Carbon value ($)	$P_0(T)$: T, C	Optimal T	$P_0(T)$: T, W, C	Optimal T
25	3057.99	47	39 047.38	300
70	6893.72	50	42 993.81	300
110	10 334.42	52	46 501.75	300
366	32 701.13	64	68 952.55	300
500	44 503.19	67	80 704.15	300

rotation model was extended to allow for maximisation of the net present value of timber and non-timber benefits. Carbon sequestration benefits were modelled via total stand biomass accumulation. The cost of carbon release back into the atmosphere upon logging was estimated as a function of rotation age using a ratio of pulpwood to sawlogs. In the benchmark case, allowance for both of the non-timber benefits was found to lengthen the optimal rotation to infinity. Sensitivity analyses were carried out to determine values for which the current management plan of 80-years rotations is optimal, and for which finite rotations become optimal.

The profiles relating to the first-order conditions were relatively flat for higher values of the rotation length. For example, in the benchmark case of a 4% discount rate, the present value of benefits increases sharply for rotation lengths of up to about 40 years. The cost of logging prematurely in each rotation is high over this range. After this point the present value schedule becomes relatively flat. Hence it might be argued that as long as the rotations are long enough to avoid the costs of premature logging, it does not matter what rotation is used. As the Thomson Catchment is managed on an 80-years rotation, these results could be viewed as providing some support for the present logging policy.

However, only two of many additional benefits accruing from the Thomson Catchment were included in the analysis. There are other environmental benefits, e.g., biodiversity conservation, water purification and soil stabilisation. While it is very difficult to attach values to these further benefits, it is suggested that they are likely to increase the optimal rotation length and therefore strengthen the main conclusion. Similarly, this analysis excluded the catchment's amenity value. These extra non-timber values are likely to increase with forest age, following a similar pattern to carbon sequestration benefits. Their inclusion would again be expected to reinforce the no-logging result. Furthermore, when consideration is given to the current age of the Thomson Catchment, it was found that the decision not to log it more than doubles its net present value compared with the current plan.

In terms of forest management, it is likely that the issue of water quality and quantity is likely to become even more important in the future, in view of projected increases in demand and the limited scope for increasing dam capacities. The analysis suggests that the value of the forest as a carbon sequester lies in its maximum value of carbon sequestration rather than in the rate of sequestration, so that rotations are unambiguously increased. It has also been seen that the current stand age is an important determining factor in forest management. Allowing for this substantially increases the net present value resulting from a no-logging decision compared with current rotations.

It would be useful, given the appropriate data, to extend the method to allow not only for a wider range of costs and benefits, but also for alternative types of management strategy. For example, Church and Richards (1999) argue that the debate on native forest harvesting should place emphasis on devising sustainable policies. Worrell and Hampson (1997) consider the management of forest soils and argue that data limitations make it difficult to distinguish sustainable from unsustainable practices. The finding that socially optimal rotation lengths are considerably greater than privately optimal lengths also raises important policy design questions.

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References

Black, T.A., Harden, J.W., 1995. Effect of timber harvest on soil carbon storage at Blodgett Experimental Forest, California. Canadian Journal of Forest Research 57, 1385–1396.

Buongiorno, J., Gilles, J.K., 1987. Forest Management and Economics: A Primer in Quantitative Methods. Macmillan, New York.

Byron, N., Coleman, A., 1999. Kyoto forests: prospective providers of carbon-sequestration services? Sydney, Second Australasian Emissions Trading Industry Forum.

Chikumbo, O., Kotze, H., Hamilton, F., 1999. Development of a generic yield curve. Australian Forestry 61, 127–136.

Cannell, M.G.R., 1999. Growing trees to sequester carbon in the UK: answers to some questions. Forestry 72, 237–247.

Church, R., Richards, M.T., 1999. Native forest harvesting in Australia: an ecological economics approach to the question. Australian Forestry 61, 137–140.

Clarke, H.R., 1994. Forest rotation and streamflow benefits. Australian Forestry 57, 37–44.

Demeritt, D., Rothman, D., 1999. Figuring the costs of climate change: an assessment and critique. Environment and Planning 31, 389–408.

Dobes, L., Enting, I., Mitchell, C., 1998. Accounting for the carbon sinks: the problem of time. In: Trading Greenhouse Emissions: Some Australian Perspectives. Bureau of Transport Economics, Canberra.

Fankhauser, S., 1995. Valuing Climate Change. Earthscan, London.

Fankhauser, S., Tol, R.S.J., 1999. Figuring the costs of climate change: a reply. Environment and Planning 31, 409–411.

Faustmann, M., 1849. On the determination of the value which forest land and immature stands pose for forestry. In: Gane, M. (Ed.), Martin Faustmann and the Evolution of Discounted Cash Flow. Oxford Institute, Oxford.

Ferguson, I.S., 1995. Timber production and streamflow benefits: a contrary analysis of options. Australian Forestry 58, 142–146.

Ferguson, I.S., 1996. Sustainable Forest Management. Oxford University Press, Oxford.

Grierson, P.F., Adams, M.A., Attiwill, P.M., 1992. Estimates of carbon storage in the above-ground biomass of Victoria's forests. Australian Journal of Botany 40, 631–640.

Hanley, N., Shogren, J.F., White, B., 1997. The economics of forestry exploitation. In: Hanley, N., Shogren, J.F. (Eds.), Environmental Economics in Theory and Practice. Macmillan, London, pp. 335–354.

Harmon, M.E., Ferrell, W.K., Franklin, J.F., 1990. Effects on carbon storage of conversion of old-growth forests to young forests. Science 247, 699–702.

Hartman, R., 1976. The harvesting decision when a standing forest has value. Economic Inquiry 14, 52–58.

Kadekodi, G.K., Ravindranath, N.H., 1997. Macroeconomic analysis of forestry options on carbon sequestration on India. Ecological Economics 23, 201–223.

Kirschbaum, M., 1995. The carbon squestration potential of tree plantations in Australia. In: Eldrige, K.G., Crowe, M.P., Old, K.M. (Eds.), Forestry and Forest Products. CSIRO, Canberra.

Kuczera, G., 1985. Prediction of water yield reductions following a bushfire in Ash-mixed species Eucalypt forest. Melbourne and Metropolitan Board of Works Report no. MMBW-W-0014.

Maclaren, J.P., 1996. Plantation forestry: its role as a carbon sink. In: Bouma, W.J., Pearman, G.I., Manning, M.R. (Eds.), Greenhouse: Coping With Climate Change. CSIRO, Canberra.

Nakane, K., Lee, N.J., 1995. Simulation of soil carbon cycling and carbon balance following clear-cutting in a mid-temperate forest and contribution to the sink of atmospheric CO_2. Vegetatio 121, 147–156.

O'Regan, M., Bhati, U.N., 1991. Report pricing and allocation of logs in Australia. ABARE Discussion Paper, 91-7.

Pearce, D.W., 1994. Assessing the social rate of return from investment in temperate zone forestry. In: Layard, R., Glaister, S. (Eds.), Cost-Benefit Analysis. Cambridge University Press, Cambridge.

Pearce, D.W., Brown, K., 1994. Saving the world's tropical forests. In: Brown, K. (Ed.), The Causes of Tropical Deforestation. CSERGE, London.

Pennock, D.J., von Kessel, C., 1997. Effect of agriculture and of clear-cut forest harvest on landscape-scale soil organic carbon storage in Saskatchewan. Canadian Journal of Soil Science 77, 211–218.

Price, D.T., Halliwell, D.H., Apps, M.J., Kurz, W.A., Curry, S.R., 1997. Comprehensive assessment of carbon stocks and fluxes in a Boreal-Cordilleran forest management unit. Canadian Journal of Forest Research 27, 2005–2016.

Rab, M.A., 1994. Changes in physical properties of a soil associated with logging of Eucalyptus regnans forest in southeastern Australia. Forest Ecology and Management 70, 215–229.

Read, S., et al., 1992. Evaluation of the Economic Values of Wood and Water for the Thomson Catchment. Consultancy Report, Melbourne.

Read, S., et al., 1994. Phase Two of the Study into the Economic Evaluation of Wood and Water for the Thomson Catchment. Consultancy Report, Melbourne.

Reddy, S.R.C., Price, C., 1999. Carbon sequestration and conservation of tropical forests under uncertainty. Journal of Agricultural Economics 50, 17–35.

Sedjo, R.A., Wisniewski, J., Sample, A.V., Kinsman, J.D., 1995. The economics of managing carbon via forestry: assessment of existing studies. Environmental and Resource Economics 6, 139–165.

Sinden, J.A., Thampapillai, 1995. Introduction to Benefit-Cost Analysis. Longman, London.

Solberg, B., 1998. Economic aspects of forestry and climate change. Commonwealth Forestry Review 77, 229–233.

Tate, K.R., Pashotam, A., Ross, D.J., 1995. Soil carbon storage and turnover in temperate forests and grasslands – a New Zealand perspective. Journal of Biogeography 22, 695–700.

van Kooten, G.C., Binkley, C.S., Delcourt, G., 1995. Effect of carbon taxes and subsidies on optimal forest rotation age and supply of carbon services. American Journal of Agricultural Economics 77, 365–374.

Vertessy, R., Benyon, R., Haydon, S., 1994. Melbourne's forest catchments: Effect of age on water yield. Water (April), 17–20.

Vertessy, R., Hatton, T.J., Benyon, R.G., Dawes, W.R., 1996. Long-term growth and water balance prediction for a Mountain Ash (Eucalyptus Regnans) forest catchment subject to clearfelling and regeneration. Tree Physiology 16, 221–232.

Vertessy, R., Watson, F., O'Sullivan, 1998. Report Predicting Water Yield From Mountain Ash Forest Catchments. Industry Report, Victoria.

Vesterdal, L., Dalsgaard, M., Felby, C., Raulund-Rasmussen, K., Jorgensen, B.B, 1995. Effects of thinning and soil properties on accumulation of carbon, nitrogen and phosphorous in the forest floor of Norway spruce stand. Forest Ecology and Management 77, 1–10.

Worrell, R., Hampson, A., 1997. The influence of some forest operations on the sustainable management of forest soils—a review. Forestry 70, 61–85.