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Optimal management of a flammable forest providing timber and carbon sequestration benefits: an Australian case study*

Daniel Spring, John Kennedy and Ralph Mac Nally†

In deciding to keep or fell a forest stand given its age, the risk of loss of timber through wildfire is an important consideration. If trees also have value from sequestration of carbon, another effect of fire is the unplanned loss of stored carbon. Factors affecting the decision to keep or fell trees, and how much to spend on fire protection, are investigated using stochastic dynamic programming, using carbon sequestration in stands of mountain ash in Victoria as a case study. The effect of treating sawlogs as a permanent carbon sink after harvesting is explored.

Key words: Forest management, timber, carbon, dynamic, programming.

1. Introduction and background

The need for countries to meet targets for reductions in net carbon emissions, as stipulated under the Kyoto Protocol, has focused attention on forests as potential carbon sinks. Carbon-offset schemes have been introduced, in which carbon sequestered by forests is set against carbon emissions in determining the net emissions of a country or firm. They provide both a temporary increase in carbon storage (Hoehn and Solberg 1994) and increased production of sawlogs, which typically retain their carbon long after harvesting, in the form of durable timber products (whereas much of the carbon stored in lower grade logs, referred to as pulplogs, is released soon after harvesting, in the manufacture and decay of paper products). Under such offset schemes, forest owners have incentives to establish new forests, avoid clearing existing forests, or delay harvesting in forests currently managed for timber production.

It has been argued that extending the rotation is a pragmatic option for sequestering carbon (Gong and Kristrom, 2003). However, if the forest can be destroyed by wildfire, the cost of the fire is not just in lost timber but also in the release of stored carbon. This puts a brake on the optimal extension of the rotation.

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It is important to point out that introducing the risk of timber loss through fire changes the simple nature of the optimal harvesting strategy for the case of fixed prices, costs, growth functions and fire probability distributions over infinite time. This is the case addressed in the present study. Without fire risk, the age at which trees should be cut to maximise returns from harvested timber and stored carbon can be determined. The optimal cutting age is also termed the 'optimal rotation period'. The optimal rotation period is the same for all decision stages.

With fire risk, the optimal harvesting strategy can only be given in terms of whether trees of a particular age should be harvested or not. If fire can destroy trees at any age, there is no fixed optimal rotation period. (Jacobs 1967, p. 99, gives a cogent explanation of why, quite generally, if the change in state of a system from one decision stage to the next depends not only on the decision but also on stochastic factors, the optimal policy is a feedback policy, in the sense of being state-dependent.) However, the optimal harvesting policy with fire risk does determine an optimal maximum tree age, or optimal planned harvest age, which holds for all decision stages beyond the first. (Trees older than the optimal planned harvest age at the first decision stage will be cut.) The optimal planned harvest age is only realised if no fire has destroyed the trees at earlier ages. For the purposes of the current study, it is useful to summarise optimal cutting policies in terms of optimal 'planned harvest ages' as an upper limit on 'rotation periods' of management interest, and to determine how planned harvest age is affected by the price of carbon and other parameters. However, it must be recognised that planned harvest age as defined here is not a decision variable for the problem with stochastic fire. Optimal decisions can only be specified as contingent on tree age at the time of the decision.

Another important decision variable in the management of a forest stand threatened with extinction by fire, besides age-dependent cutting, is the level of fire protection. The value of a stand of even-aged trees increases with age because of increases in the volume of merchantable timber, in the proportion of the timber of sawlog grade and in the carbon stored. As the stand becomes more valuable with age, so the losses from fire become greater, and expenditure on additional fire protection is likely to increase expected returns. A stochastic dynamic problem is formulated and solved to determine age-dependent policies for both cutting and fire protection, which maximise the expected present value of returns across infinite years from timber production and carbon storage.

The profitability of cutting some proportion of trees at early ages to promote the growth of remaining trees and carbon sequestration, or thinning, is another option to be considered. Although thinning is not included as a decision variable in the optimising model, results from the optimising model are compared with and without a recommended thinning schedule under sensitivity analysis in section 4.3.

The type of carbon-offset program we consider is one in which revenues are earned in each year, additional carbon is locked up through tree growth and penalties are charged for carbon releases caused by logging and fire. For every tonne of carbon sequestered in a live tree in a year, a payment p_c is received, which would be appropriate if the carbon were locked up for all future years. The payment received is effectively the present value of the annual benefits of a tonne of carbon sequestered across infinite

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years. Carbon that is subsequently released from the timber, after being burnt or felled, is charged at the rate equal to the original payment rate. This system is similar to the 'ideal accounting system' described by Cacho *et al.* (2003). However, it differs in that the carbon in felled sawlog timber is assumed, as an approximation, to continue to be locked up indefinitely, and is therefore not subject to a carbon-release charge. Sensitivity analysis is conducted to test the effect of this assumption compared with the assumption that the carbon in sawlogs is released immediately after felling. Our case study focuses on the mountain ash forests of south-eastern Australia's Central Highlands region, which are managed by the Victorian Department of Sustainability and Environment (DSE). These forests provide high quality timber but are prone to large wildfires, which kill all or most trees in the burnt stands (Gill 1981). Burnt stands typically are salvage-logged, using clearfell-harvesting followed by aerial reseeding and controlled fire to stimulate regeneration (Lutze *et al.* 1999).

2. Model formulation

Because decisions are sequential and subject to uncertainty, stochastic dynamic programing (SDP) is used to formulate and solve the problem. A decision is made at the beginning of each year on whether to cut all trees in an even-aged stand. Because trees can be lost to fire, with probabilities inversely related to expenditure on fire protection, a decision is also made on the level of fire protection. The objective is to determine, for each possible tree age at each decision stage, the decision combination that results in the maximum present value of expected net returns from timber production and carbon sequestration over infinite stages.

Obtaining the infinite-stage optimal policy relies on the assumption that all stage-return and state-transition functions are the same for all decision stages (Kennedy 1986). Optimal policies are identified for alternative estimates of uncertain parameter values: the price of carbon, the discount rate, the proportion of timber destroyed in a fire event and the cost of reducing fire risk.

The state variable is x, the age of trees in a 1 ha stand. There are 121 age classes, spanning tree ages from 0 to 120 years ($x = 1, \ldots, 121$). The decision variables are a, fire protection expenditure (one of three possible levels) and the keep/fell decision d, set to 0 for 'keep' and 1 for 'fell'. Thus, the optimal decision combination is selected from six possible combinations for a and d. Both decisions are implemented at the start of the stage, knowing the current age of trees in the stand. Any fire occurs just before the end of the stage, immediately followed by salvage-logging of burnt trees. The sequence and timing of events and decisions in the SDP problem are shown in Figure 1.

Tree age is zero at the start of a stage if trees are felled at the start of the stage, or if a fire occurred at the end of the previous stage. In either case, regeneration costs are incurred. After any felling at the start of the stage, a payment is received for carbon sequestered during the stage. Felling yields an immediate timber revenue and incurs a carbon-release charge, both dependent on tree age.

If fire occurs at the end of the stage, timber revenues are obtained from salvaging and a cost is incurred for the carbon released by the fire and subsequent salvage-logging.

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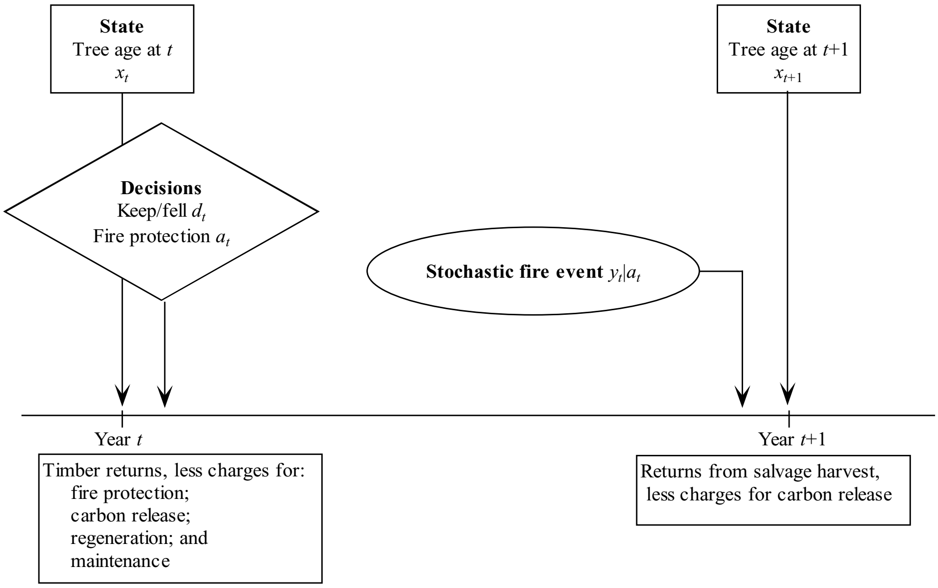

Figure 1 Forest event time line for stage starting at time t.

Any sawlogs that are salvaged from the burnt stand do not incur a carbon-release charge, reflecting our assumption that carbon in sawlogs remains sequestered after the logs are processed into timber products.

The fire event, denoted by y, is set to 0 if fire does not occur and 1 if it does. It is assumed that if a fire occurs, it burns through the entire stand, but does not consume all of the timber. The probability of the fire event is a function of the expenditure on fire protection, denoted $\Pr\{y|a\}$, and is subject to the requirement that $\Pr\{y = 0|a\} + \Pr\{y = 1|a\} = 1$ for all a.

2.1 Age state transformation function

As there is no change in sawlog or pulplog volumes beyond a tree age of 120 years, trees in the SDP formulation that are aged 120 years at the start of the stage remain at that age if they are not burnt or logged. The tree-age index at the end of year t before any fire event (x_F) is specified as follows: if at the start of the year the stand is logged ($d = 1$), tree age at the end of the year will be 1 year ($x_F = 2$), and if kept ($d = 0$), tree age will either increase by 1 year or remain at 120 years, or:

$$x_F\{x, d\} = \begin{cases} x + 1 & \text{if } x < 121, \quad d = 0 \quad \text{(keep)} \\ 121 & \text{if } x = 121, \quad d = 0 \quad \text{(keep)} \\ 2 & \text{if } d = 1 \quad \text{(fell).} \end{cases} \tag{1}$$

If a fire does occur at the end of the year ($y = 1$), salvage operations and replanting occur immediately, and tree age is zero ($x = 1$) at the start of year $t + 1$. The

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age transformation function giving tree-age index at the start of the following year is thus:

$$x_{\mathrm{T}}\{x, d, y\} = \begin{cases} x_{\mathrm{F}} & \text{if } y = 0 \quad \text{(no fire)} \\ 1 & \text{otherwise.} \end{cases} \tag{2}$$

2.2 Timber revenue and cost functions

If the stand is burnt just before the end of year t, it is immediately salvage-logged, yielding a proportion, θ, of the merchantable volumes that would have been available had the stand not been burnt. The combination of x, d and y determines the total volume of merchantable timber harvested over the year. It consists of the planned volume of timber cut at the beginning of the year $\sum_{f=\mathrm{s,r}} q_f\{x, d\}$ (subscript f refers to the grade of timber, equal to 's' for sawlog grade and 'r' for pulplog or residual grade) plus the volume of salvaged timber $\sum_{f=\mathrm{s,r}} \theta v_f\{x_{\mathrm{F}}\}$ if fire does occur at the end of the year ($v_f\{x\}$ is the volume of merchantable timber of grade f available dependent on tree age). The resulting present value of timber returns in a year is:

$$R_{\mathrm{w}}\{x, d, y\} = \sum_{f=\mathrm{s,r}} p_f(q_f\{x, d\} + y\theta\alpha v_f\{x_{\mathrm{F}}\}), \tag{3}$$

where

$$q_f\{x, d\} = \begin{cases} v_f\{x\} & \text{if } d = 1 \quad \text{(fell)} \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

and p_{s} is the price of sawlogs, p_{r} is the price of residual timber and α is the discount factor dependent on the annual rate of discount i, equal to $1/(1+i)$.

A regeneration cost, b, is incurred at the beginning of the decision stage if the stand is bare at the start of the stage; that is, aged zero ($x = 1$). The stand is bare if fire occurred at the end of the previous stage or the decision to log is taken at the start of the stage. The regeneration cost function is:

$$g\{x, d\} = \begin{cases} b & \text{if } x = 1 \quad \text{or} \quad d = 1 \\ 0 & \text{otherwise.} \end{cases} \tag{5}$$

2.3 Carbon revenue and charge functions

If the stand is logged at the start of a year, emission costs are incurred at the carbon price rate of p_{c} on the carbon released from residual grade timber and non-merchantable biomass. If a fire occurs at the end of a year, emission costs are also incurred at the same rate on the carbon released from all residual grade timber and non-merchantable biomass, and from the proportion $(1-\theta)$ of sawlog-grade timber that is burnt. Offsetting these costs is revenue received at the start of the year for carbon stored over the year, which depends on tree age immediately after the keep/fell decision is implemented.

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Net returns each year from carbon sequestration are therefore:

$$R_c\{x,d,y\} = \begin{cases} p_c\left[q_c\{x\} - y\alpha\left((1-\theta)v_s\{x_F\} + \sum_{f=r,n} v_f\{x_F\}\right)\delta\{x_F\}\right]\beta & \text{if } d=0 \\ p_c\left[q_c\{1\} - \sum_{f=r,n} v_f\{x\}\delta\{x\} - y\alpha\left((1-\theta)v_s\{2\} + \sum_{f=r,n} v_f\{2\}\right)\delta\{2\}\right]\beta & \text{otherwise,} \end{cases} \tag{6}$$

where $q_c\{x\}$ is the dry-weight timber in tonnes of the stand which locks up carbon over the year:

$$q_c\{x\} = \sum_{f=s,r,n} (v_f\{x+1\}\delta\{x+1\} - v_f\{x\}\delta\{x\}), \tag{7}$$

where $v_s\{x\}$ and $v_r\{x\}$ are sawlog and pulplog volumes as defined above and $v_n\{x\}$ is the volume of non-merchantable timber at age x on the stand in cubic metres, $\delta\{x\}$ (also known as 'basic density') is timber dry weight in tonnes per cubic metre of green weight wood and β is carbon in tonnes per tonne of dry-weight timber.

2.4 Solution method

The objective is to find the settings of a_t and d_t, for $t = 1, 2, \ldots$ which result in maximum expected present value of stage returns over infinite stages, or:

$$\max \underset{\substack{y_t|a_t \\ t=1,2,\ldots}}{E} \left[\sum_{t=1}^{\infty} \alpha^t (R_w\{x_t,d_t,y_t\} + R_c\{x_t,d_t,y_t\} - g\{x_t,d_t\} - a_t - m_t)\right] \tag{8}$$

$$\text{subject to} \quad x_{t+1} = x_T\{x_t,d_t,y_t\} \quad \text{and } x_1 \text{ given,}$$

where m_t is the annual stand maintenance cost.

Because it is assumed that all functions and parameters determining expected stage return, and the state transition function, are the same for all stages, the optimal settings of a_t and d_t, conditional on the age index x_t, are the same for all t, written as $a^*\{x\}$ and $d^*\{x\}$. The optimal decision functions can be found as the solution to the problem:

$$V\{x\} = \max_{a,d} \sum_{y=0}^{1} \Pr\{y|a\}(R_w\{x,d,y\} + R_c\{x,d,y\} \\ -g\{x,d\} - a - m + \alpha V\{x_T\{x,d,y\}\}), \tag{9}$$

where $V\{x\}$ is the expected present value of stage returns from applying the optimal policy $a^*\{x\}$ and $d^*\{x\}$ across infinite stages, starting at the current stage with tree-age index x. Stage subscripts t have been dropped because the problem holds for all t. The maximand is the expected current stage return from applying $a^*\{x\}$ and $d^*\{x\}$, plus the

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expected present value of continuing to apply the optimal policy starting at the next stage with $x = x_T$. The function $V\{x\}$ appears on both sides of the equation, because the return horizon for $V\{x\}$ is the same, namely infinite.

Equation (9) is solved numerically by policy or value iteration (Kennedy 1986) for all tree ages from 0 to 120 years, and the optimal fire protection and cutting policy $a^*\{x\}$ and $d^*\{x\}$ recorded for all tree ages. Use is made of the general-purpose dynamic programing (GPDP) Windows-based software package,[1] an advanced integrated version of programs initially presented in Kennedy (1986).

3. Case study parameter values

3.1 Timber yields and carbon storage

We used the mountain ash stand simulation model, STANDSIM (Coleman 1989), to estimate sawlog and pulplog wood volumes at different stand ages, as well as non-merchantable wood volume (calculated as total volume net of merchantable volume). In the STANDSIM simulations, initial stand density was set at 10 000 stems, the minimum small-end diameter for sawlogs at 25 cm and the minimum small-end diameter for pulplogs at 10 cm. We followed Grierson *et al.* (1992) in assuming that organic matter contains 50 per cent carbon by weight and set β in Equations (6) and (7) at 0.5. Basic density as a function of age $\delta\{x\}$ in Equations (6) and (7) was estimated by fitting the following equation to the values of δ reported for selected ages in Clark (1991, Table 8.7):

$$\delta\{x\} = -0.0000082x^2 + 0.0021735x + 0.40685. \tag{10}$$

Timber volumes and carbon storage as a function of stand age are shown in Figure 2. Figure 2 illustrates the growth in sawlog volume as a proportion of total wood volume over a significant range of tree ages. Non-merchantable wood volume initially increases until trees become old enough to provide merchantable timber (20 years) and then declines between the ages of 20 and 40 years when much of the timber becomes merchantable. The eventual increase in non-merchantable timber reflects growth in the higher parts of trees, above the merchantable component of the stems.

3.2 Carbon release

As a first approximation, we assumed that carbon in harvested sawlogs is retained forever, and that other above-ground carbon (in pulpwood and non-merchantable biomass) is released at harvest time. Below-ground carbon, in tree roots and soil, is assumed unchanged by harvesting. Bauhus *et al.* (2003) found there is relatively little loss of soil carbon arising from timber harvesting in mountain ash forest.

Fire kills all or most trees in the stand. Any unburnt trees are harvested before regenerating the stand to prevent those trees hindering the salvage operation (M. Leonard, pers. comm., 2003). In addition to the timber obtained from unburnt trees, a proportion

[1] GPDP routines and manual can be freely downloaded from: http://www.business.latrobe.edu.au/staffhp/jkennedy/index.htm

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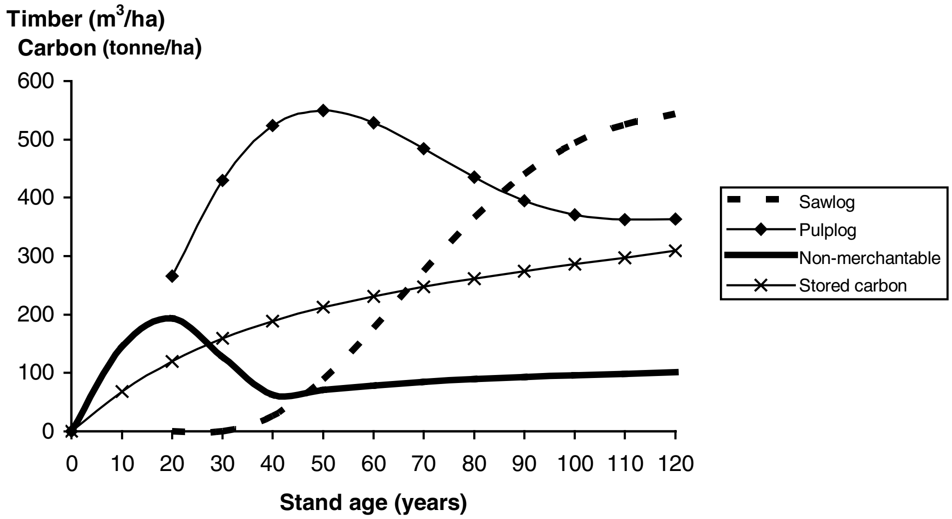

Figure 2 Timber volumes and carbon storage as the stand matures.

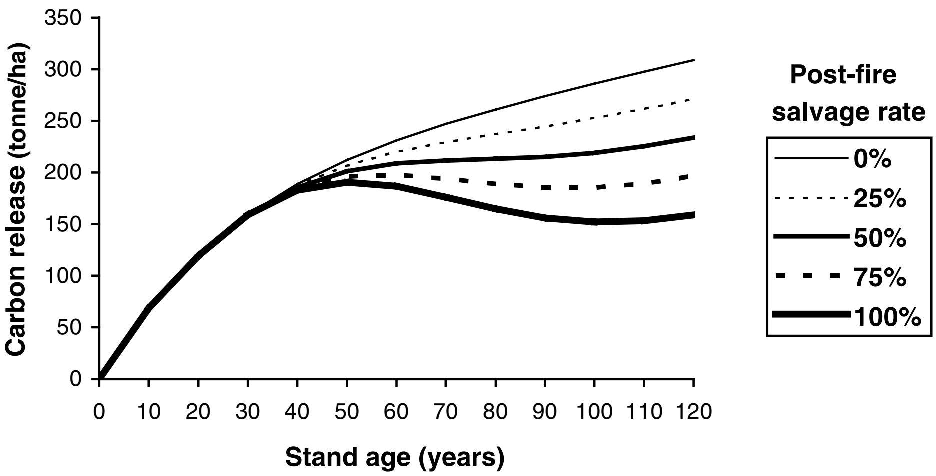

Figure 3 Carbon release after fire by stand age and post-fire salvage rate.

of the timber in burnt trees is salvaged, with the salvage proportion depending on the intensity of the fire (Loane and Gould 1986). As simplifications in the model it is assumed that following any fire, all salvage operations and replanting are completed by the start of the following year, and that the salvage proportion θ applies to all merchantable timber extant before the fire. Based on a range of salvage proportions obtained for mountain ash forest (M. Leonard, pers. comm., 2003), the baseline rate in this analysis is 50 per cent, with sensitivity analysis conducted for rates of 25 and 75 per cent. Given our assumption that salvaged sawlog-grade timber does not incur a carbon-release charge, the size of the salvage proportion affects the charge on carbon released following a fire. Fire-induced carbon emissions under timber salvage proportions from 0 to 100 per cent are illustrated in Figure 3.

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The age profile of carbon release caused by fire for $\theta = 100$ per cent is also the profile for carbon release by age when the stand is harvested in the absence of fire. Thus, it can be seen from Figure 3 that carbon emissions after cutting decrease as the harvesting age increases from 50 to 100 years. This is because of the higher proportion of standing timber that is in the form of sawlogs.

Figure 3 shows that for stand ages of 50–90 years, carbon release at harvest falls with age under salvage rates of 75 and 100 per cent. There is a potential gain, in terms of reduced carbon emission charges, from extending the planned harvest age. However, doing so increases the risk that a proportion of sawlogs will be destroyed by fire before planned felling.

3.3 Fire protection expenditures

The data used in the study are based on the work of Brigham (1997), who considered the following protection strategies: fire detection using lookout towers; fire response using alternative levels of manpower in readiness for fighting an outbreak; fire protection by burning off strategic corridors every 3 years; and education to reduce fires initiated by people. Annualised costs were calculated for each strategy from estimated capital and annual costs. Rough estimates of the impact of the strategies on fire risk, alone and in combination, were obtained from staff at the Alexandra office of the DSE.

Three points on the efficient frontier of the set of 12 fire-probability/protection-expenditure points based on the Brigham study were selected as the basis of three fire protection programs in our study (Table 1). The first program is the null program of no protection, chosen because there has been a longer period of observation of fires under this program than any other. Brigham (1997, p. 35) gives a probability of a destructive fire spreading through a particular hectare of mountain ash forest, without any detection or suppression activity, to be 1 year out of 30. This estimate was made in consultation with DSE staff on the basis of historical data before 1940 when no state-owned fire agency was used to prevent or suppress an outbreak of fire.

The second program is the combination of towers and home standby. The third program is the combination of towers, depot standby, education and burnoff. Changes have been made to the original estimates in Brigham (1997) by adding the cost of fire access roads (D. Young, pers. comm., 2003) and increasing the cost of the burnoff strategy to reflect the higher density of trees in an all-mountain-ash stand than in the mixed-species stands considered by Brigham (G. McCarthy, pers. comm., 2003).

Table 1 Probability of fire by annualised protection expenditure

	Fire protection program		
	1	2	3
Annualised protection expenditure, a \$A/ha per year[†] (discount rate 4% p.a.)[‡]	0.00	11.27	39.75
Probability stand destroyed in a year $\Pr\{y = 1 \mid a\}$	0.0333	0.0064	0.0032

[†]Expenditures are Consumer Price Index adjusted to 2002 \$A values (Australian Bureau of Statistics 2002); [‡]corresponding expenditures for discount rate 1 per cent p.a. are 0.00, 11.23 and 38.10; and for discount rate of 10 per cent p.a. are 0.00, 11.38 and 43.16.

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Table 2 Model parameters

Parameter	Symbol	Value†
Area of stand (ha)		1
Sawlog price ($A/m^3)	p_s	51.00
Residual log price ($A/m^3)	p_r	12.60
Salvage rate of burnt timber (sawlogs and pulplogs)	θ	0.50, 0.25, 0.75
Ratio of carbon weight in timber to dry-weight biomass of timber‡	β	0.50
Costs:		
Maintenance ($A/ha per year)§	m	86
Regeneration – 1000 seedlings per ha ($A/ha)	c	1622
Fire protection expenditure ($A/ha per year)	a	see Table 1
Annual rate of discount (%)	i	4, 1, 10

†For parameters with more than one value (θ and i), the first value is the baseline value and the others are for sensitivity analysis; ‡Grierson *et al.* (1992); §prices are in real terms expressed in Australian dollars (2002).

Because of the subjective element in the fire probabilities, sensitivity analysis is conducted using protection expenditures at double and half the rates shown in Table 1 for the three programs at the baseline discount rate of 4 per cent per annum.

Remaining parameter values are set out in Table 2.

3.4 Timber prices

The sawlog price is a weighted-average price based on the royalties received from the most recent timber sales in the study region, which are: $A64/m^3 for grade B sawlogs, $A50/m^3 for grade C sawlogs and $A27/m^3 for grade D sawlogs (M. Woodman, pers. comm., 2003). Approximately 40 per cent of the sawlogs harvested are grade B, 40 per cent are grade C and the remaining 20 per cent are grade D (M. Woodman, pers. comm., 2003). The weighted-average sawlog price, p_s, is $A51/m^3. The price of pulpwood is approximately $A12.60/m^3 (M. Woodman, pers. comm., 2003).

4. Optimal policies

Optimal decisions on cutting and fire protection by age of tree are reported for the baseline parameters given in Table 2. Because of uncertainty over the price of carbon, baseline optimal policies are given for a wide range of prices. For a carbon price of $A20/tonne, the expected present values by tree age of implementing the optimal baseline policy are compared in section 4.2 with those which would be obtained by implementing the optimal policy for the case of no risk of fire. The sensitivity of results to alternative parameter values and model assumptions is investigated in section 4.3.

4.1 Optimal policies for baseline parameter values

Figure 4 shows the optimal Dynamic Programming (DP) policies obtained for a range of carbon prices. The optimal DP policy details the optimal combination of fire protection and cutting decisions dependent on tree age. For example, the optimal policy

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Table 3 Optimal age-dependent policy for carbon price of $A60/tonne

Current tree age (years)	x	Optimal decision combination for current year	
		$a^*\{x\}$	$d^*\{x\}$
0–54	1–55	Fire protection program 2	No cut
55–67	56–68	Fire protection program 3	No cut
68–120	69–121	Fire protection program 2	Cut and replant

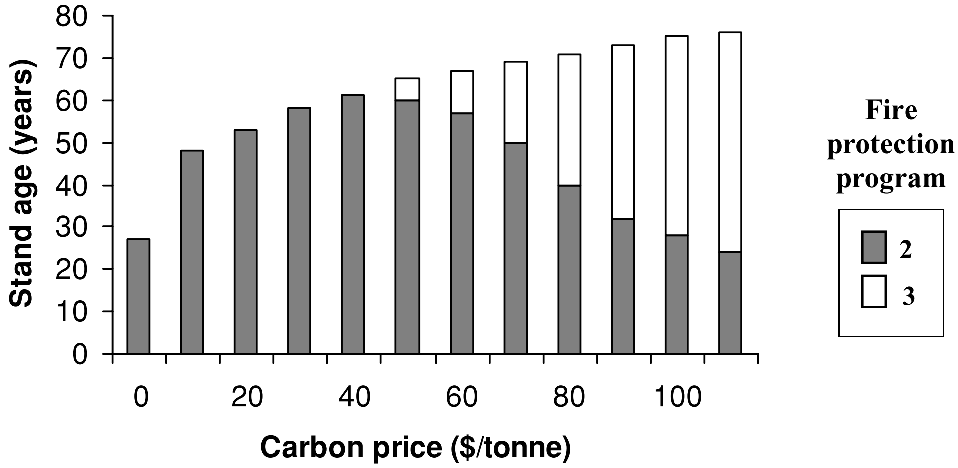

Figure 4 Optimal planned harvest age and fire protection by carbon price.

for a carbon price of $A60/tonne is to keep all trees currently aged below 68 years (the height of the bar = planned harvest age − 1 year), and cut all trees currently 68 or older. The optimal level of protection for trees currently at all ages below planned harvest age is given by the shading of the bar. Thus, for current ages less than 55 years, protection program 2 is optimal for the current year and protection program 3 otherwise. This derivation of the optimal policy for a carbon price of $A60/tonne from Figure 4 is summarised in Table 3 and applies to the derivation of optimal policies from subsequent figures.

Note that because fire is possible in any year, annual implementation of the optimal policy can result in trees in the stand not reaching the planned harvest age.

The planned harvest age increases at a declining rate as carbon price increases. In the absence of the carbon-offset scheme (carbon price of zero), fire protection program 2 is optimal (costing $A11.27/ha) whatever the stand age. The same applies to carbon-offset schemes for carbon prices up to $A40/tonne. Further increases in carbon price result in protection program 3 (costing $A39.75/ha) becoming optimal at progressively younger stand ages. As the price of carbon rises, increased expected net returns can be obtained from delayed harvesting, but it also becomes profitable to spend more on reducing the probability of losing the delayed harvest to fire and incurring carbon-release charges.

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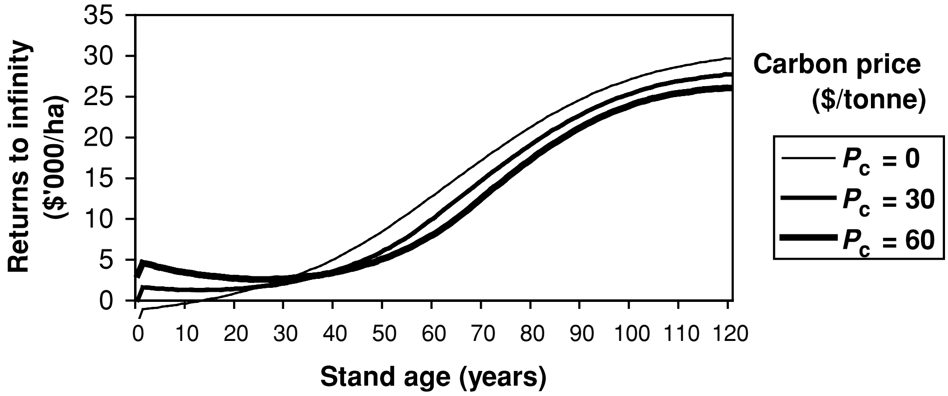

Figure 5 Expected present values of returns to infinity by age and carbon price.

An important result is that the carbon-offset scheme provides an incentive to produce sawlogs. In the absence of such a scheme, the optimal harvest age of 28 years is too low for sawlog production.

The DP solution based on Equation (9) gives the expected present value of returns across infinite years ($V\{x\}$), for all current and future tree ages from 0 to 120 years. The expected present values are obtained by implementing each year the optimal-policy decisions dependent on the current age of trees at the start of the year, which depends in turn on the decisions and any fire event in the previous year. Figure 5 shows $V\{x\}$ values at an annual discount rate of 4 per cent by current stand age for a range of carbon prices. Values are shown for all x from 0 to 120, which includes expected values for current ages, even though, in implementing the optimal policy across all future years, these ages will never be revisited.

In the absence of an offset scheme ($p_c = 0$), $V\{x\}$ is negative for stand ages less than 17 years. This means that the optimal policy for $p_c = 0$ is only optimal if replanting after felling or burning of the forest is forced. For prices of carbon of \$A30/tonne and \$A60/tonne, $V\{x\}$ is positive for all stand ages.

For tree age greater than 40 years, $V\{x\}$ is lower for higher carbon prices. This reflects the anticipated higher charges that must be paid out for release of carbon from pulpwood as trees reach cutting age or increased probability of loss through fire.

4.2 Cost of ignoring fire risk

How important is it to determine optimal cutting policies that allow for the probability of loss of the forest stand through fire? An answer is found for the current case study by using the facility in the GPDP package that gives the returns from state-dependent policies known to be suboptimal. In this case the suboptimal policy tested is the policy that is optimal when fire risk is ignored, with no fire protection program, referred to as π^*_{NF}.

For a price of carbon of \$A20/tonne, policy π^*_{NF} is to keep the trees at the start of any year if they are less than 56 years of age, and to fell otherwise. As shown in

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Figure 4, the corresponding optimal policy taking account of fire risk, referred to as π^*_F, is to implement fire protection program 2 and to keep the trees at the start of any year if they are less than 53 years of age.

Applying policy suboptimal policy π^*_{NF} instead of policy π^*_F, results in significantly reduced expected present values to infinity. For example, the reduction is \$A1582/ha (from −\$A853/ha) if the current age is 0. The maximum reduction is \$A2337/ha for a current age of 40 years. There are sizable returns from undertaking the optimal fire protection policy.

4.3 Sensitivity analysis

First, the effects of changing independently two policy assumptions made in the baseline model are examined: namely that carbon is permanently stored in harvested sawlogs, and that thinning is not conducted. Second, the sensitivity of results to changes in uncertain parameter values – the rate of discount, the costs of fire protection programs and salvage rates – is investigated.

Comparisons of optimal policies are displayed in Figures 6–9. In all cases the optimal policies include fire protection as a decision, but the optimal fire protection decisions by age are not shown in Figures 6–8 because the focus is on the effects on planned harvest age.

4.3.1 *Treating sawlogs as a permanent carbon sink*

Making carbon stored in sawlogs, a permanent sink after harvest means that harvesting does not result in a high carbon-release charge if a high proportion of the timber cut is of sawlog grade. As the price of carbon increases, there is the incentive to delay harvest and produce a larger volume of timber and thereby store more carbon, even if the carbon is not treated as trapped in cut sawlogs. However, if the carbon in cut sawlogs is trapped, there is a payoff from cutting timber earlier. This effect is confirmed in

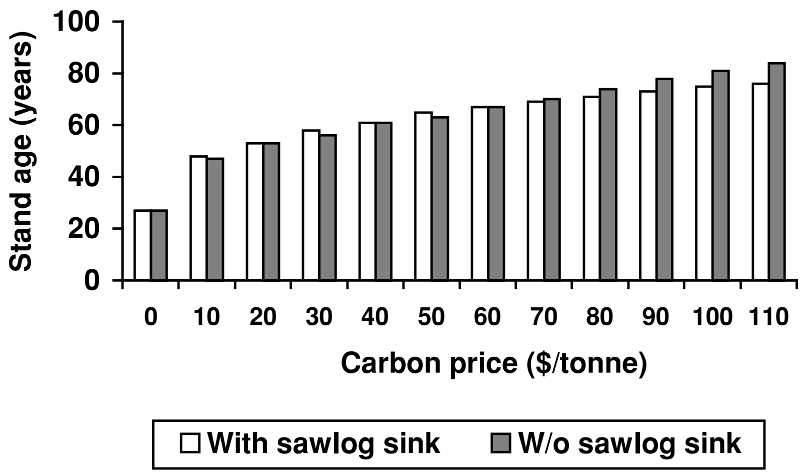

Figure 6 Optimal planned harvest age by carbon price with and without sawlogs, a permanent carbon sink.

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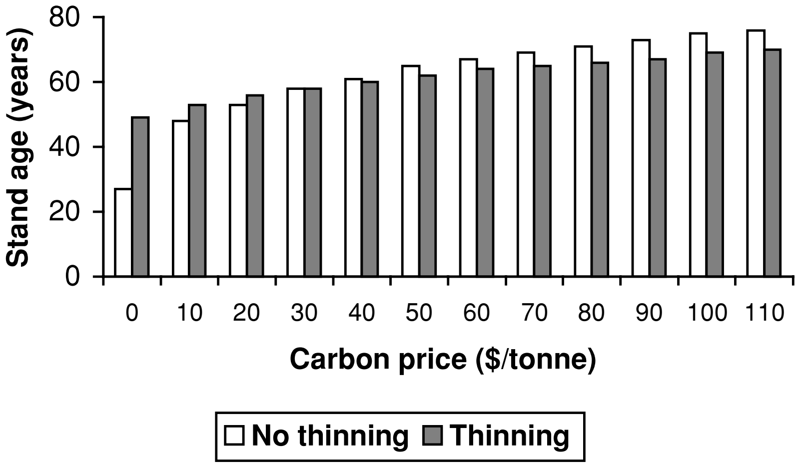

Figure 7 Optimal planned harvest age by carbon price with and without thinning.

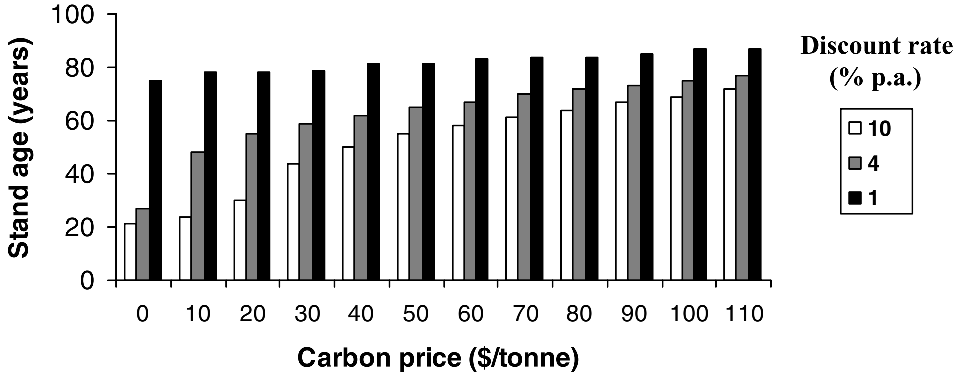

Figure 8 Optimal planned harvest age by carbon price and discount rate.

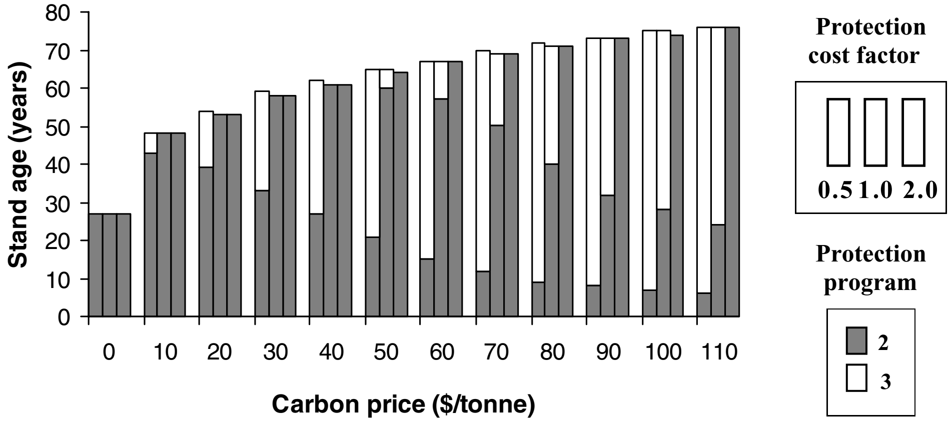

Figure 9 Optimal planned harvest ages and fire protection programs by protection cost factor.

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Figure 6, where a pronounced trend to earlier cutting appears as the price of carbon is increased above $A60/tonne.

4.3.2 *Comparing results with and without thinning*

Thinning can be used to increase the overall rate of carbon sequestration. Those trees remaining after thinning have been selected for their growth potential. The economic gains from thinning are greater, the greater the proportion of increased growth that is in sawlogs, if sawlogs store carbon over the long run after felling or salvaging. Offsetting these gains are the charges for earlier release of carbon from thinnings.

As discussed, for example, by Kennedy (1986), the inclusion of thinning as a decision option considerably increases the size of the problem because of the additional state variables required, such as tree volume and number of trees. To roughly gauge the extent of gains from thinning when the stand is subject to fire risk, SDP results were obtained for one thinning regime thought likely to be beneficial.

The thinning regime selected consists of a pre-commercial thinning (PCT) at age 5, which yields no merchantable timber, followed by a commercial thinning (CT) at age 30, which yields pulplog revenues but not sawlog revenues. Rawlins (1991) found it to give the highest net present value out of a number of regimes tested, although in the absence of fire risk and without accounting for carbon sequestration benefits.

In the case study, thinning operations were simulated with STANDSIM using the method developed by West (1991). Both thinning operations were assumed to remove 50 per cent of the basal area (as in West 1991; LaSala 2000). The PCT brings forward the first carbon-release charge and increases the rates of carbon uptake and sawlog growth thereafter, bringing increased annual carbon uptake revenues. The pulpwood cut in the CT incurs a carbon emission charge and provides timber revenue net of the cost of thinning.

Data for estimating the net timber revenue from thinning of *Eucalyptus regnans* stands are limited. Net revenues reported in previous studies range from a small loss to a small profit (LaSala 2000). To highlight the effect of changed carbon net emissions associated with thinning, it is assumed that thinning revenues and costs (excluding carbon payments) offset each other exactly. Thus, in this analysis, the main financial impacts of thinning are the carbon charge made at the commercial thinning (the PCT releases very little carbon) and the revenue from higher sawlog yields.

The main impacts of thinning are as follows: the first thinning (at age 5) emits a negligible amount of stored carbon; the second thinning (at age 30) removes approximately 50 per cent of the pulpwood and non-merchantable wood, amounting to approximately 50 per cent of the stored carbon. It takes approximately 60 years for the stored carbon to return to the level it would have reached without thinning, after which it increases to 5 per cent above the no-thinning level by the time the stand reaches 120 years. Thinning also affects merchantable timber yields. The volume of pulpwood, immediately after the second thinning, falls to approximately 50 per cent of its unthinned volume; thereafter it takes approximately 50 years for pulpwood to return to its no-thinning level. Thinning brings forward sawlog yields, with yields between the ages of 47 and 54 years being approximately 40 per cent higher than in the absence of thinning.

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Figure 7 shows that at a low carbon price of \$A10/tonne, the optimal planned harvest age increases by 5 years, whereas at carbon prices greater than \$A60/tonne, the planned harvest age falls by 4–6 years. With sawlog yields brought forward under thinning, and the associated bringing forward of carbon storage in sawlogs, the risk that fire will destroy a proportion of this timber makes it optimal to reduce the planned felling age. As the consequences of fire risk are more significant, the higher is the price of carbon, the planned felling age is brought forward more at the higher carbon prices.

Though it is not illustrated in Figure 7, the expected present value of net returns to infinity, starting with a bare stand, $V\{1\}$, is higher without thinning for all carbon prices.

4.3.3 *Rate of discount*

A rate of discount of 4 per cent per annum is typical of rates used in appraising forestry projects. For sensitivity analysis, the planned harvest rates for rates of 10 and 1 per cent are compared in Figure 8. Because fire protection costs include an annualised component, the fire protection costs change with the rate of discount as shown in Table 1. Without returns from carbon sequestration ($p_c = 0$), the planned harvest age is 75 years for $i = 1$ compared with 25 years for $i = 4$. The difference in planned harvest age is much reduced as the price of carbon increases. As the price of carbon increases and planned harvest age increases to take advantage of higher returns from sawlogs, net returns from carbon storage and release eventually dominate net returns from timber. Carbon revenues and charges are spread more evenly over the production cycle, so that optimal planned harvest age is much less sensitive to the rate of discount.

4.3.4 *Fire protection costs*

Because the subjective elements in estimating the probabilities of fire destroying the stand under alternative fire protection programs, sensitivity analysis was conducted using protection expenditures double and half those shown in Table 1 for the three programs. Results are illustrated in Figure 9.

The middle bar for each carbon price (representing the baseline protection cost factor (PCF) = 1.0) has already been presented in Figure 4. Results show that halving and doubling the PCF has virtually no effect on the optimal planned harvest age for all carbon prices. Without a carbon-offset scheme ($p_c = 0$), protection program 2 is implemented at all tree ages for all three PCF. For all carbon prices of \$A10/tonne and higher, protection program 3 is optimal for PCF = 0.5, starting at lower ages as the price of carbon increases. However, increasing PCF to 2.0 results in program 2 being optimal for all ages for all carbon prices. As anticipated, higher protection is optimal starting at lower ages to planned harvesting age as the carbon price increases and the expected value of loss through fire increases. This is provided the cost of higher protection is not too high.

The value of the bare stand ($V\{1\}$) is relatively insensitive to halving and doubling fire protection cost. For a zero carbon price, halving fire protection costs increases ($V\{1\}$) by \$A147, whereas doubling it reduces ($V\{1\}$) by \$A293. The same applies for all tree ages. As the price of carbon increases, the differences in stand value increase

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and become age-dependent. The differences tend to be greatest for tree ages between 20 and 40 years.

4.3.5 *Salvage rates*

Given that there is significant natural variation in fire intensities and associated variation in salvage rates, we conducted sensitivity analysis on the salvage proportion, θ. It is difficult to predict the effect of a lower θ on protection expenditure. The incentive to reduce protection expenditure due to the reduced expected value of the stand is countered by the expected benefits to be gained from reducing the risk of greater loss. When θ is lowered, planned harvest age is expected to fall, because timber returns are lower and carbon emission charges are higher, as detailed in section 3.2.

Reducing θ below the baseline value of 0.5 has a marked effect on the level of fire protection, though only a small reduction in the planned harvest age. For example, at a carbon price of $A30/tonne, reducing θ from 0.5 to 0.25 leads to increased protection (from program 2 to program 3) over the 8 years before the planned harvest age, with only a 1 year reduction in the planned harvest age (from 58 to 57 years). Increasing θ from 0.5 to 0.75 has no effect on protection but leads to a 1 year increase in the planned harvest age. The effect of varying θ on the level of protection is considerably larger at higher carbon prices.

5. Conclusions

Carbon sequestration and the risk of stand-replacing fire add further dynamic considerations to the optimal forest replacement problem. The growth of non-merchantable timber needs to be included, and the change in the mix of pulpwood and sawlogs produced as trees age assumes greater importance, given the different rates of carbon release from each timber class after planned harvest or fire. Few studies have explored the effect of treating sawlogs as a permanent carbon sink after harvesting. We find the effect is a reduction in the optimal planned harvest age as the price of carbon is increased more than $A60/tonne. We also found that the sensitivity of optimal planned harvest age to the rate of discount decreases with the increasing price of carbon.

Relaxing the assumption that prices, costs, growth functions and fire probability distributions do not change over infinite time may be worthwhile. Timber and carbon prices are likely to increase over time, and the probability of intense fires may increase with global warming. In such cases it is likely that greater investment in fire protection would be optimal.

Major sources of uncertainty in this work are the probabilities of fire and the cost of reducing fire probability. More research is required on how the probability of fire destroying a stand depends on fire protection programs and the area of the stand. Another factor is the relationship between the probability of fire and tree age, which was not considered in this study. However, it was found that halving and doubling the costs of programs with different probabilities of fire had very little effect on the planned harvest age. It was also found that as the price of carbon increased, the optimal age span for undertaking a high protection program became much more sensitive to program costs.

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Because the future price of carbon is highly uncertain, sensitivity analysis was conducted for prices ranging from \$A0/tonne to \$A110/tonne. Optimal decisions are certainly sensitive to carbon prices in this range. Almost certainly, once a market for carbon storage is established so will a market for futures in carbon storage be established. A current major uncertainty is the adoption of an international scheme facilitating these markets and whether Australia will be part of such a scheme.

References

Australian Bureau of Statistics (2002). *Time Series Spreadsheets*, Canberra. Available from URL: http://www.abs.gov.au/Ausstats/ [accessed May 2003].

Bauhus, J., Khanna, P.K., Hopmans, P., Ludwig, B. and Weston, C. (2003). Evaluation of soil organic matter as a meaningful indicator of important soil properties and processes in native forest ecosystems. Project PN99.803, Forest and Wood Products Research and Development Corporation, Melbourne.

Brigham, D. (1997). Optimal strategies for reducing the risk of forest fires, B.Ec (Hons) thesis, School of Business, La Trobe University, Melbourne.

Cacho, O.J., Hean, R.L. and Wise, R.M. (2003). Carbon-accounting methods and reforestation incentives. *Australian Journal of Agricultural and Resource Economics* 47, 153–180.

Clark, N.B. (1991). Pulpwood quality and value, in Kerruish, C.M. and Rawlins, W.H.M. (eds), *The Young Eucalypt Report – Some Management Options for Australia's Regrowth Forests*. CSIRO, Melbourne, pp. 210–244.

Coleman, J. (1989). *STANDSIM User Manual*. CSIRO Division of Forestry and Forest Products, Canberra.

Creedy, J. and Wurzbacher, A.D. (2001). The economic value of a forested catchment with timber, water and carbon sequestration benefits, *Ecological Economics* 38, 71–83.

Gill, A.M. (1981). Post-settlement fire history in Victorian landscapes, in Gill, A.M., Groves, R.H. and Noble, I.R. (eds), *Fire and the Australian Biota*. Australian Academy of Science, Canberra, pp. 77–98.

Gong, P. and Kristrom, B. (2003). *Regulating Forest Rotation to Increase CO_2 Sequestration*. Unpublished manuscript. Available from URL: http://www.sekon.slu.se/~bkr/carbon1.pdf [accessed June 2003].

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.

Hoehn, H.F. and Solberg, B. (1994). Potential and economic efficiency of carbon sequestration in forest biomass through silvicultural management, *Forest Science* 40, 429–451.

Jacobs, O.L.R. (1967). *An Introduction to Dynamic Programming*. Chapman and Hall, London.

Kennedy, J.O.S. (1986). *Dynamic Programming: Applications to Agriculture and Natural Resources*. Elsevier Applied Science, London.

LaSala, A.V. (2000). Predicted growth response to pre-commercial thinning of Eucalyptus obliqua in southern Tasmania, *Tasforests* 12, 1–9.

Loane, I.T. and Gould, J.S. (1986). *Aerial Suppression of Bushfires. Cost–Benefit Study for Victoria*. National Bush Fire Research Unit, CSIRO, Canberra.

Lutze, M.T., Campbell, R.G. and Fagg, P.C. (1999). Development of silviculture in the native state forests of Victoria. *Australian Forestry* 62, 236–244.

Rawlins, W.H.M. (1991). Economics of alternative management regimes, in Kerruish, C.M. and Rawlins, W.H.M. (eds), *The Young Eucalypt Report*. CSIRO, Melbourne, pp. 246–268.

Victorian Government (1986). *Timber Industry Strategy*. Government Printer, Melbourne.

West, P.W. (1991). Thinning response and growth modelling, in Kerruish, C.M. and Rawlins, W.H.M. (eds), *The Young Eucalypt Report*. CSIRO, Melbourne, pp. 28–49.

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