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Forest rotation lengths under carbon sequestration payments

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Carbon dioxide emissions resulting from direct human activities, primarily fossil fuel use and land clearing, have altered the global carbon cycle. Carbon is absorbed (sequestered) by plant matter during photosynthesis, so that approximately 50% of the dry weight of a forest's biomass is carbon. This paper examines how payments to foresters for the carbon sequestered in their trees would affect harvesting decisions. It uses a theoretical multi-crop model adapted from the original Faustmann formula to consider different scenarios of the degree of carbon liability incurred at the time of harvest, and their impact on the length of the optimal crop rotation. These results are then contrasted with the equivalent output from a numerical model based on a simulated New South Wales *Pinus radiata* plantation. The finding of the paper provides an insight into which carbon sequestration payment policy would be the best at aligning public and private incentives.

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I am now working at the Productivity Commission.
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This paper examines how the harvesting decisions of forest owners would be altered by a system of carbon sequestration payments and whether this would lead to a more socially desirable outcome.

It would be expected that variables such as the length of a forest crop rotation might be changed by the introduction of a new income source from carbon sequestration payments, if forest owners act to maximise the profits derived from their trees. This type of analysis can be done by extending some generally used renewable resource models, as well as by the application of numerical examples. The motivation driving changes in optimal forest rotation lengths is the altered composition of the income stream which not only consists of selling timber, but also involves carbon sequestration returns and carbon dioxide emission liabilities. Rotation length is also influenced by the increased value that future crops may have, the sequestration income source, and the forester's rate of time preference. A further consideration is whether the expected changes in forest crop rotation length resulting from carbon sequestration payments are desirable from social or efficiency viewpoints.

1. Background

Carbon dioxide (CO_2) emissions resulting from human activities, primarily fossil fuel use and land clearing, have altered the global carbon cycle. It is estimated that the CO_2 concentration in the atmosphere is now about 30 per cent higher than 200 years ago (AGO 1999c). Carbon is absorbed by plant matter during photosynthesis from atmospheric carbon dioxide. Typically, approximately 50 per cent of the dry weight of a forest's biomass is carbon (AGO 1998). Considering the relative size of carbon atoms to carbon dioxide molecules, this means that the dry weight of one tonne of forest is involved in sequestering half a tonne of carbon, derived from more than 1.8 tonnes of carbon dioxide taken from the atmosphere. This makes forests a very effective means of locking away carbon derived from the atmospheric carbon dioxide source.

Rising greenhouse gas concentrations in the environment are predicted to lead to further enhancement of the greenhouse effect, and result in climate change around the world (IPCC 2001). To address this, contracting parties under the auspices of the United Nations put forward a framework called the Kyoto Protocol. Under the Protocol, developed countries, including the Eastern European economies in transition, would commit themselves to reducing their collective emissions of six greenhouse gases (AGO 2000a).

Article 3.3 of the Protocol provides scope for each country's emission reductions to take account of carbon sequestration in 'carbon sinks' such as forests (AGO 1999a). Negotiating the precise details of such an offsets arrangement has been a major barrier to implementing the Kyoto Protocol. Nevertheless, the importance of sinks to key parties such as the United States suggests that any initiative will be required to take carbon sequestration into account.

Emission reduction policies could be implemented with a system of tradeable emission permits. Tradeable permits are a market-based incentive mechanism gaining popularity over more traditional command and control measures such as emission taxes (Devlin and Grafton 1996). Permits are considered more cost effective in practice (Zhang and Folmer 1995) and more efficient in market structures which are not perfectly competitive in the output market as well as having heterogenous types of firms (different pollution technologies) (Norregaard and Reppelin-Hill 2000). An emission permit trading framework which acknowledges the role that plant matter plays in taking carbon dioxide out of the atmosphere could be designed so that carbon sequestration leads to the accrual of emission permits (to recognise the potential emissions offset generated).

The Faustmann model

Martin Faustmann provided one of the earliest known applications of the principle of discounted cash flow in his classic 1849 paper when he "reduce(s) to the present all the income and expenditures occurring until infinity..." (Faustmann 1849). The original Faustmann formula calculates the net present value of the income (*NPV*) derived from an infinite series of crops, with equal rotation lengths (u) and an equal cash value of the final yield (E), at a fixed interest rate (r) and in a discrete time setting, as the difference between the present value of income (K) and the present value (K') of establishment costs (C):

$$NPV = K - K' = \frac{E}{(1+r)^u - 1} - \frac{C.(1+r)^u}{(1+r)^u - 1} = \frac{E - C.(1+r)^u}{(1+r)^u - 1}$$

The analogous result, in a continuous time setting, that is to be used in this analysis is:

$$NPV = \frac{E - C.e^{ru}}{e^{ru} - 1}$$

Growth curves

Growth curves outline the growth in the aspects of the tree and forest. For simplicity, the value of sellable wood product in a forest can be considered as a per unit price times the volume of timber. The volume of timber is considered to take the functional form of V, with the volume of timber present at time t equal to $V(t)$. The cubic shape of this curve is generally used in theoretical modelling (Perman et al. 1996), and this is consistent with observed field data, such as that observed by Clawson (1977) in a stand of US northwest Pacific region Douglas firs. The amount of carbon sequestered in a standing forest comes directly from the forest's biomass and so at time t the amount of sequestered carbon is considered to be $S(t)$. This would clearly be closely related to the amount of timber present since woody parts generally make up around 80 per cent of a forest's total biomass (Satoo and

Madgwick 1982). Consequently, a cubic shaped function approximately describes biomass growth in many types of tree of major commercial importance in Australia, with examples being *Pinus radiata* (Grierson et al. 1992), as well as *Eucalyptus regnans* (Mountain Ash) and *Eucalyptus obliqua* (Messmate stringybark) (West and Mattay 1993). As the tree matures, the rate of growth of the timber content can be faster than the biomass growth rate.

The shapes of these curves and the correlation between volume of timber and amount of tree biomass (and hence the quantity of carbon sequestered) in a crop depends on the species of tree (Madgwick 1991). The varietal properties of a tree determine timber density (Wilkes 1989), degree of branching and leafyness (Cannell 1984) et cetera, and therefore determine the amount of carbon incorporated into non-saleable wood product. Even within a species, genetic variation between seed stocks can lead to more than a twofold difference in the foliage biomass (Satoo and Madgwick 1982).

2. Theoretical Model

The simplest model of a forest involves just a single stand of trees, when it is considered that it is growing on land that has no alternative value and hence no future resale value. There is no age distribution within the stand, and no opportunity cost for the land. The mathematics in this section considers the market price per unit volume of timber as p_v, the market interest rate is given by r. For a similar analysis that is complicated by the extra considerations of a cost of harvesting (which is proportional to the volume of timber harvested) and of an initial establishment cost (to prepare, plant and manage new crops) see Appels (2000).

If carbon credits are given for carbon sequestration activities over one unit of time, then the income generated by this sequestering earned at time t+1 (for sequestering between t and t+1) is the value of the extra amount of carbon sequestered in the recent period, or $p_s.\int_t^{t+1} S'(x).dx$ (the price of sequestering carbon, times the increase in the forest's carbon content in the preceding year). The present value of this at the time of planting the crop is equal to $\frac{p_s.\int_t^{t+1} S'(x).dx}{(1+r)^{t+1}}$. This means that, in a discrete time notation, the present value (at the time of planting) of all carbon sequestering over a crop is given by the summation of the present values of the sequestration income in each period:

$$\sum_{t=0}^{T-1} \frac{p_s.\int_t^{t+1} S'(x).dx}{(1+r)^{t+1}}$$

This is more readily considered in a continuous time context, with carbon credits being given instantaneously, which generates $p_s.S'(t)$ at any given moment t.

Consequently this would have a present value at the time of planting of $p_s.S'(t).e^{-rt}$. This approach results in the present value, at the time of planting, of all the carbon sequestration occurring in a crop being equal to the sum of present values of all the instantaneous revenues over the entire life of the crop:

$$\int_0^T p_s.S'(x).e^{-rx}.dx$$

The harvesting decision of the forest owner is concerned with the total present value of a stand which will consist of the value of sellable timber, emission liabilities (if all the carbon sequestered is deemed to be emitted at the time of harvest), and the income from carbon sequestration. In a continuous time context, this can be represented as the following:

$$p_v.V(T).e^{-rT} - p_s.S(T).e^{-rT} + \int_0^T p_s.S'(x).e^{-rx}.dx$$

Multiple crop models are similar to the single crop models except for the fact that plantation of a future rotation occurs when the stand in harvested.

In a traditional market

Intuitively, the optimal harvesting decision will wait while there is a net benefit to be obtained by delaying the harvest – until it ultimately equates the present value of the cutting this period and cutting next period, so that there is no marginal benefit gained by either waiting or harvesting earlier.

The financial return to cutting this period is the cash value of the crop. Waiting to cut next period brings with it the benefit of harvesting a more valuable crop (due to growth) but pushes the harvest of the current crop, as well as the plantings and subsequent harvesting of future crops, a period into the future.

This is the same as acting to maximise the present value of the forest. This is given by adding up the present value of the cash values of the sequence of crops. For example the first crop in the series is planted in the present and harvested at time T, to give a cash value of $p_v.V(T)$ at time T, and hence has a present value of $p_v.V(T).e^{-rT}$. The next crop is planted at time T and grown until time $2T$, and so the cash value of $p_v.V(T)$ would have a present value of $p_v.V(T).e^{-r(2T)}$. In theory, this goes on for an infinite series of crops, with later crops having their incomes very heavily discounted when considered in present value terms and so do not impact on decision making significantly. Thus, the forester's problem is:

$$\text{choosing T to maximise } q(0) = \frac{p_v.V(T)}{e^{rT} - 1}$$

The first order condition of this maximisation implies:

$$p_v.V'(T) = r.\left[p_v.V(T) + q(0) \right]$$

The lefthand side of this equation represents the increase in crop value. The righthand side is the opportunity cost of (*r* times) delaying the harvest of the current crop ($p_v.V(T)$) as well as the subsequent series of crops ($q(0)$). This result can be seen intuitively since it implies that the harvester will maintain the trees while they are providing returns above the obtainable interest rate, and fell them before the yield of the forest investment falls below the market rate.

With carbon sequestering

In this case the returns to cutting in the current period is the market value of the timber harvest, while waiting not only yields biological growth, but also an additional income from extra carbon sequestering. The forest owner must now consider the present values of the carbon sequestering that occurs in each crop. The first crop would have a present value of timber value plus the total carbon credits accrued, which is equal to:

$$p_v.V(T).e^{-rT} + \int_{t=0}^{T} p_s.S'(x).e^{-rx}.dx = \left(p_v.V(T) + e^{rT}.\int_{t=0}^{T} p_s.S'(x).e^{-rx}.dx \right).e^{-rT}$$

Similarly, the second crop would have a present value of:

$$\left(p_v.V(T) + e^{rT}.\int_{t=0}^{T} p_s.S'(x).e^{-rx}.dx \right).e^{-r2T}$$

The forester would then act to maximise the present value of the forest, considering the entire series of future crops:

$$\text{choosing } T \text{ to maximise } q(0) = \frac{p_v.V(T) + e^{rT}.\int_{t=0}^{T} p_s.S'(x).e^{-rx}.dx}{e^{rT} - 1}$$

The first order condition of this maximisation implies:

$$p_v.V'(T) + p_s.S'(T) = r.\left[p_v.V(T) + q(0) \right]$$

This condition can be interpreted as equating the yield that the trees will return if left in the ground, derived from an increase in the timber quantity and the increased carbon content, to the yield that is foregone by holding on to the forest, the interest that could be earned on the funds obtained from selling both the trees and the forest site.

With sequestering and harvesting emissions

As mentioned, an emission permit trading framework could deem that the forester is liable for the emissions of all of the carbon sequestered in a forest, *S(T),* upon its felling.

When the carbon content of a forest is deemed to be emitted at the time of harvest, and hence offsetting carbon credits must be bought, the present value of the nth crop would consist of timber value minus emission liabilities plus the total carbon credits accrued components, to give:

$$\left(p_v.V(T) - p_s.S(T) + e^{rT}.\int_{t=0}^{T} p_s.S'(x).e^{-rx}.dx\right).e^{-rnT}$$

The forest owner acts to maximise the present value of the forest site (the sum of the series of crops):

$$\text{choosing } T \text{ to maximise } q(0) = \frac{p_v.V(T) - p_s.S(T) + e^{rT}.\int_{t=0}^{T} p_s.S'(x).e^{-rx}.dx}{e^{rT} - 1}$$

The first order condition of this maximisation implies:

$$p_v.V'(T) = r.\left[p_v.V(T) - p_s.S(T) + q(0)\right]$$

This condition can again be interpreted as equating the yield that the trees will return if left in the ground, to the yield that is foregone by holding on to the forest. In this case, the benefits arise purely from increased timber content since the further accrued carbon credits must be paid back immediately upon harvest due to the full harvest emission liability. The net opportunity cost of pushing back the felling of the stand of trees arises from not only the foregone interest on deferring the realisation of the value of the timber harvest ($p_v.V(T)$) and of future rotations (*q(0)*), but also from *deferring the emission liability* associated with the harvest ($-p_s.S(T)$).

Comparing rotation lengths

By considering the conditions for optimisation in the optimal crop rotation lengths it can be shown that $T_o < T_{cn} < T_{cf}$; for (o) no carbon crediting, (cn) carbon crediting with no harvest emission liability, (cf) carbon crediting with full emission liability. This comparison is done in box 1.

Box 1 **Comparing rotation lengths under different policy types**

The first order conditions for profit maximisation can be rearranged to give:

(i) $p_v.V'(T_o) = r.p_v.V(T_o) + \frac{r.p_v.V(T_o)}{e^{rT_o}-1}$

(ii) $p_v.V'(T_{cn}) = r.p_v.V(T_{cn}) + \frac{r.p_v.V(T_{cn})}{e^{rT_{cn}}-1} + \frac{r.p_s.\int_0^{T_{cn}} S'(x).e^{-rx}.dx}{1-e^{-rT_{cn}}} - p_s.S'(T_{cn})$

(iii) $p_v.V'(T_{cf}) = r.p_v.V(T_{cf}) + \frac{r.p_v.V(T_{cf})}{e^{rT_{cf}}-1} + \frac{r.p_s.\int_0^{T_{cf}} S'(x).e^{-rx}.dx}{1-e^{-rT_{cf}}} - \frac{r.p_s.e^{rT_{cf}}.S(T_{cf})}{e^{rT_{cf}}-1}$

- Consider[a] if $T_{cn} \leq T_o$:
  Since $\frac{V'(T_o)}{V(T_o)} = \frac{r}{1-e^{-rT_o}}$, then $\frac{V'(T_{cn})}{V(T_{cn})} \geq \frac{r}{1-e^{-rT_{cn}}}$ from the properties of the growth curves.
  Since optimally, $r.V(T_{cn}) - (1-e^{-rT_{cn}}).V'(T_{cn}) = \left[(1-e^{-rT_{cn}}).V'(T_{cn}) - r.\int_0^{T_{cn}} V'(x).e^{-rx}.dx\right].\frac{p_s}{p_v}$
  then p_s, p_v >0 implies $(1-e^{-rT_{cn}}).V'(T_{cn}) \leq r.\int_0^{T_{cn}} V'(x).e^{-rx}.dx$.
  But $V(x) > \int_0^x V'(t).e^{-rt}.dt$ when $r > 0$, therefore the above condition is false. This means that $T_{cn} > T_o$ by contradiction.
- The different terms between equations (ii) and (iii) are:
  $\frac{r.p_s.e^{rT_{cf}}.S(T_{cf})}{e^{rT_{cf}}-1} - p_s.S'(T_{cn}) = \frac{p_s}{e^{rT_{cf}}-1}.\left[r.S(T_{cf}).e^{rT_{cf}} - S'(T_{cn}).(e^{rT_{cf}}-1)\right]$
  which will be strictly positive if $r.S(T_{cf}) \geq S'(T_{cn})$. This holds since it is known that $T_{cn} > T_o$, and $r.S(T_o) \geq S'(T_o)$. Therefore $p_v.V'(T_{cn}) > p_v.V'(T_{cf})$ and $T_{cn} < T_{cf}$.
- This gives the overall ranking of: $T_o < T_{cn} < T_{cf}$.

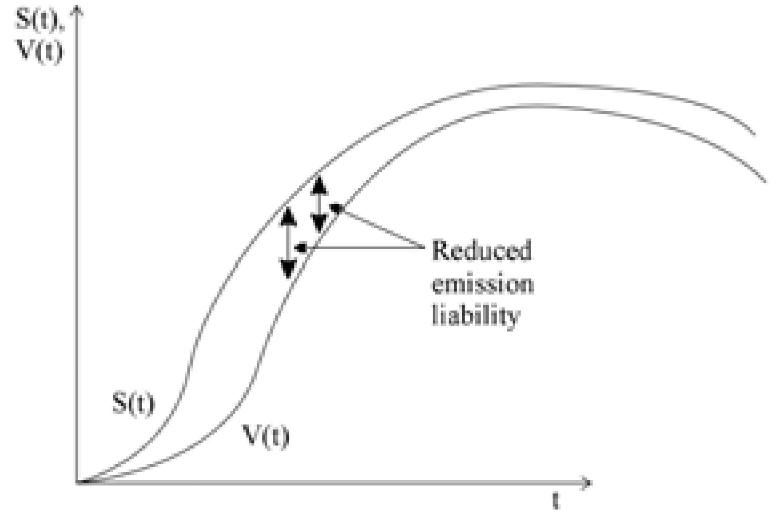
[a] For the example of the biomass curve overlaying the timber curve; S(t)=V(t).

It is also important to note that although prices here do not seem to determine the time lengths of T_o ,T_{cn} and T_{cf}, they do impact when setup and harvesting costs are taken into account (see Appels 2000) but the same relative ordering as above still applies. Prices are also clearly important in whether or not a forest investment is undertaken, since they do influence the profitability of the venture.

An intermediate fourth case

A result that is intermediate to full liability for the emission of sequestered carbon at the time of harvest and having no emission liability, is if the emission liability more accurately reflects carbon released after harvesting. For example, some trees are generally destined for use in construction, such as *Pinus radiata* (radiata pine). This is one example of a use which will lock-up the carbon in timber form for a long time. In such cases, a more appropriate measure of the amount of carbon emitted upon harvest may be *S(T)-V(T)* (as opposed to all of *S(T)*).

Figure 1 **Timber (V) and Biomass (S) growth curves**



This difference between the total biomass and the volume of saleable timber is the volume of biomass which is not going to be locked up in timber form, and comes from waste in the harvesting and processing stages. Under this different emission criteria, the foresters' maximisation problem now becomes:

$$\text{choosing } T \text{ to maximise } q(0) = \frac{(p_v + p_s).V(T) - p_s.S(T) + e^{rT}.\int_{t=0}^{T} p_s.S'(x).e^{-rx}.dx}{e^{rT} - 1}$$

The first order condition for this maximisation gives:

$$(p_v + p_s).V'(T) = r.\left[(p_v + p_s).V(T) - p_s.S(T) + q(0)\right]$$

This is identical to the fully liable emission case but with the timber price now being inflated by the carbon credit awarded for the carbon stored through incorporation within the timber's structural matrix, to give a higher effective price for timber. The partial emission liability leads to a optimum rotation length, T_{cp}, that is between the zero (T_{cn})and full (T_{cf}) liability cases, therefore:

$$T_o < T_{cn} < T_{cp} < T_{cf}$$

There is incentive to extend the rotation length beyond T_{cn} because leaving the stand for a period will bring the added benefit of reducing and deferring the emission liability. This can be seen from figure 1.

This deferral benefits the forester by delaying the emission liability. Since the emission liability has not grown by the entire biomass growth, because timber growth has occurred, there are also the benefits of generating carbon credits that do not have to be paid back upon harvest.

3. Quantitative analysis

A numerical model of forest value was used to compare the results obtained through theoretical modelling. The advantages of using numerical data of forest yield and value is that a more realistic view of forest management can be utilised, without overly complicating calculations and results.

The use of numerical data also makes it possible to incorporate the process of commercial thinning as well as recognising the quality increase in more mature timber. Thinning in forest management operations is performed to relieve overcrowding within the stand, and open up the canopy to permit increased future growth. The thinned timber can be sold in commercial markets. This technique encourages higher quality final product in the remaining trees since it results in more valuable, large diameter, trunks. The costs of forest land preparation, plantation, and ongoing management such as pruning can also be incorporated.

The data used is based on a typical *Pinus radiata* plantation in New South Wales and is generated by the 'Showtime' simulator in the modelling system STANDPAK (see box 2 for a full description). This provides yield volume and the subsequent value of clearfelling stands of various ages. It is estimated for rotation lengths of 25 to 40 years. Although prices remain constant over time in this numerical model (as was assumed in the theoretical model), there are separate prices for veneer logs, sawlogs of various sizes, and timber for pulping. As a tree grows over time the proportion of timber volume in each category changes, with increases in the larger diameter and more valuable log classes. This means that the average price per unit volume of timber rises with maturity. The only change which has been made in this numerical exercise is to alter the rotation length. As a result, management practices such as incurred costs and thinning times remain unchanged.

Optimisation by the forest owner will act to maximise the present value of the possible series of crop rotations. The present value of a single crop, when the interest rate is r and the rotation length is T years, is derived from the difference between income generated and costs incurred (see table 1).

For example, the present value of a series of 34 year rotations, involves planting a future crop at the time of harvest, and therefore would consist of the present value of the crop planted initially, plus that of the crop planted in 34 years, plus the present value of the crop planted in 68 years, et cetera.

Box 2 **Description of "Showtime"; a simulation of growth and yield for a plantation of Radiata Pine**

The simulator used is called STANDPAK. It is designed to simulate the growth, yield and financial results of stand level (as opposed to estate level) silviculture of radiata pine plantations. Results are therefore all expressed as ''per hectare''. The program is built upon results from many research papers (Horne and Robinson 1988; Whiteside 1990; Whiteside et al. 1989).

The growth model used is that developed by Horne and Robinson (1988) for use by State Forests NSW. Site index is assumed to be 28.1 (top height at age 20).

The timing of the management regime[a] is determined by the STANDPAK system once parameters which determine the quality of the pruning are set. The year in which the pruning/thinning is calculated is the year that the respective costs[b] are incurred.

The simulation period is 0 to 40 years. At age 40 the stand is calculated to have an average height of 35.9 m, a basal area of 54.39 m^2/ha. and a mean DBH of 58.8 cm. Volume tables are those developed for the Tumut region. Breakage tables are also as developed for Tumut by State Forests NSW.

Logs are assumed to be harvested; first as pruned logs in lengths of 5.4 m, second as unpruned logs in lengths of 5.4 m are thirdly as short lengths from 3.6 to 5.4 m.

These logs were graded into: Pruned veneer logs (>45 cm small end diameter), Pruned sawlogs (>30 cm s.e.d), Unpruned veneer logs (>45 cm s.e.d., small branches), Sawlog 1 Unpruned (> 45 cm s.e.d.), Sawlog 2 (unpruned 35–45 cm s.e.d.), Sawlog 3 (25–35 cm s.e.d.), Sawlog 4 (18–25 cm s.e.d) and Pulplogs.

The sales are assumed to be stumpage or Royalty sales where the contractor performs the harvesting and the price is therefore net. The only harvesting costs allowed are those of supervision (e.g. preparation of harvesting plans and inspection to see that contractors comply with conditions; and scaling of produce).

Clearfelling is simulated from age 25 years to forty years. This last age is about the physical limit of the trees and past the point of best financial results.

a Initial stocking 1000 per hectare. Prune 350 stem per hectare to 2.2 metres and thin to waste (remove 500 stem per hectare). Prune 275 per hectare to 4.0 metres. Prune 200 to 5.8 metres and thin to waste (remove 150 per hectare). Thin to yield (commercial thinning) to 200 stems per hectare. **b** Total land preparation costs were $1000 per hectare and included: Roller chopping, Ripping and mounding, Herbicide application, Herbicide, Fertiliser, Fertiliser application and seedlings. Planting costs $150 per hectare. Assumed silvicultural costs were; Prune 1: $210/ha, Prune 2: $330/ha, Prune 3: $400/ha, Thin to waste 1: $170/ha, Thin to waste 2: $75/ha, Commercial thinning (supervision): $95/ha, Annual costs $65/ha/ann.

Source: James, R.D., Australian National University Department of Forestry, pers. comm., 4 October 2000

Table 1 **Income sources and costs in the forestry model**

Financial	*Value*
Income	
Present value of timber at the time of clearfelling	$\frac{\text{market value of clearfelled timber}}{(1+r)^T}$
Present value of the timber derived from thinning (after 20 years in 'Showtime')	$\frac{\text{market value of commercial thinning}}{(1+r)^{20}}$
Present value of carbon sequestration credits accrued during the rotation	$\sum_{t=1}^{T} \frac{\text{market value of carbon sequestered in the } t^{th} \text{ year}}{(1+r)^t}$
Costs	
Initial forest management costs	cost of land preparation and planting
Cost of pruning (after 8 years)	pruning cost/$(1+r)^8$
Present value of carbon emission liability incurred at the time of clearfelling	$\frac{\text{market value of } CO_2 \text{ emitted in clearfelling}}{(1+r)^T}$
Present value of carbon emission liability incurred by thinning	$\frac{\text{market value of } CO_2 \text{ in commercial thinning}}{(1+r)^{20}}$

This numerical manipulation was undertaken for each of the possible rotation lengths from the data (25-40 years), as well as for each of the four policy scenarios; no carbon crediting, carbon credits but zero harvest emission liability, carbon credits with partial harvest emission liability. Partial harvest emission liability refers to a policy which requires; (i) no payment for the harvest of timber that is destined to lock up carbon for a long period of time, as in saw logs and veneer logs, but (ii) requires the payment of full carbon emission liability on waste and pulp timber, and for carbon credits with full harvest emission liability (as discussed above). The rotation length that maximises the present value of the forest to the forester can then be identified by inspection.

An increase in the value of forestry is consistent with the results of the theoretical modelling. The value of the forest rises from $5473 to $5940 per hectare for a carbon dioxide permit price of $10 per tonne under the implementation of a full emission liability policy. This significant rise in the value of forestry will lead to entry into forestry markets, or to expansion by existing firms.

Table 2 **Optimal harvest rotation lengths (in years)**[a]

Carbon Policy Type Carbon Price (per tonne)	$10	$30	$50
No carbon crediting	31	31	31
Carbon crediting with no harvest emission liability	32	33	34
Carbon crediting with partial emission liability[b]	32	34	38
Carbon crediting with 100 per cent harvest emission liability	34	>40	>40

[a] At an interest rate of 5 per cent. [b] Liability for the amount of harvest that does not end up as log products.

Source: Estimates from numerical modelling using STANDPAK.

The degree of separation between the T's depends on the carbon credit/emission permit price. The carbon dioxide permit price that could be faced under the Kyoto Protocol cannot be determined with certainty. It is considered feasible to assume that permits could be valued at between $10 and $50 per tonne of carbon dioxide (AGO 1999).

The above results confirm that the optimal rotation varies in response to different types of carbon credit/emission liability policies. The results also confirm the prediction of the theoretical model that optimal rotation length increases in the following order:

$$T_o < T_{cn} < T_{cp} < T_{cf}$$

(o) no carbon crediting, (cn) carbon crediting with no harvest emission liability, (cp) carbon crediting with partial emission liability (liability for the amount of harvest that does not end up as log products), and (cf) carbon crediting with full (100 per cent) harvest emission liability.

Thia conclusion wuld hold for larger forests with more complex rotation strategies involving plots of different ages, since the optimum rotation decision can be considered at the single stand level.

Another unambiguous result of introducing a policy which recognises carbon sequestration activities is that the profitability of forestry developments increases. This is clearly the case under a policy such as (cn) since the present value of the forest is boosted by the new income source of carbon sequestration. The observation of increased profits will also hold under the full harvest emission policy since the present value of the carbon sequestration during a rotation is always greater than that of the subsequent required repayment, in the form of the emission liability, when the interest rate is positive:

$$\int_{x=0}^{T} p_s S'(x).e^{-rx}.dx > p_s.S(T).e^{-rT} \qquad \text{for all } T, \text{ when } r > 0.$$

This increased profitability of forestry will provide incentives to increase the amount of forestry undertaken in Australia. This could result in forestry on more marginal land and have productivity implications. There is also a possible impact on timber prices that could result from the increased supply of timber products.

The effect of changing the interest rate is to change one of the parameters in the forester's maximisation, and therefore the optimal rotation lengths for the different policies will be altered. Increasing the interest rate will shorten the optimal rotation length for a given policy while maintaining the relative order already discussed. A rise in the interest rate also acts to reduce the present value of the forest because the income stream is being more heavily discounted. This impact can act to reduce the relative value of forestry compared to other potential uses due to the periodic nature of the forest income stream, in comparison to the relatively smooth income stream derived from farming or other, shorter rotation, crops. This may act to reduce forestry activity if the present value of using an area of land for forestry purposes falls below the potential value of alternate land uses such as agriculture. Sensitivity of profitability to the interest rate is reduced if carbon sequestration is considered, due to the smoother income stream it provides through yearly carbon credit accrual.

4. Comparison of private and social optima

An accurate reflection of the fate for the carbon that is incorporated into a tree during its growth does not neatly fit into either of the 'no harvest emission liability' or 'full harvest emission liability' policy reasoning. This is due to the wide variety of end uses that the harvested tree has. For example, wood that is waste in the harvest process or timber sold as pulp wood is likely to readily re-emit the sequestered carbon through degradation or short term end product usage. At the other end of this spectrum is timber sold as saw logs or veneer logs, that ends up in long-term uses such as construction or furniture and therefore effectively keeps the carbon content locked up.

Generating a 'social preference' criterion to judge the impacts of an emission permit trading framework on forestry is always going to be rather subjective in nature. With the above argument in mind, a formulation that resembles the foresters' optimisation process could be considered. This would parallel the societal value of timber to the market price. Similarly, the market price of a carbon credit/emission permit is paralleled to the social value of carbon sequestration. The 'harvest emission liability' would then depend on the end use of the forest product, which is in line with the proposed 'partial emission liability' whereby timber log products are free of emission liability, but waste and pulp require payment. By this measure, the socially optimal outcome would maximise the present value to society of forestry:

$$Social\ PV = \frac{p_v.V'(T) - p_s.[S(T) - V(T)] + e^{\rho t}.\int_{t=0}^{T} p_s.S'(x).e^{-\rho x}.dx}{e^{\rho t} - 1}$$

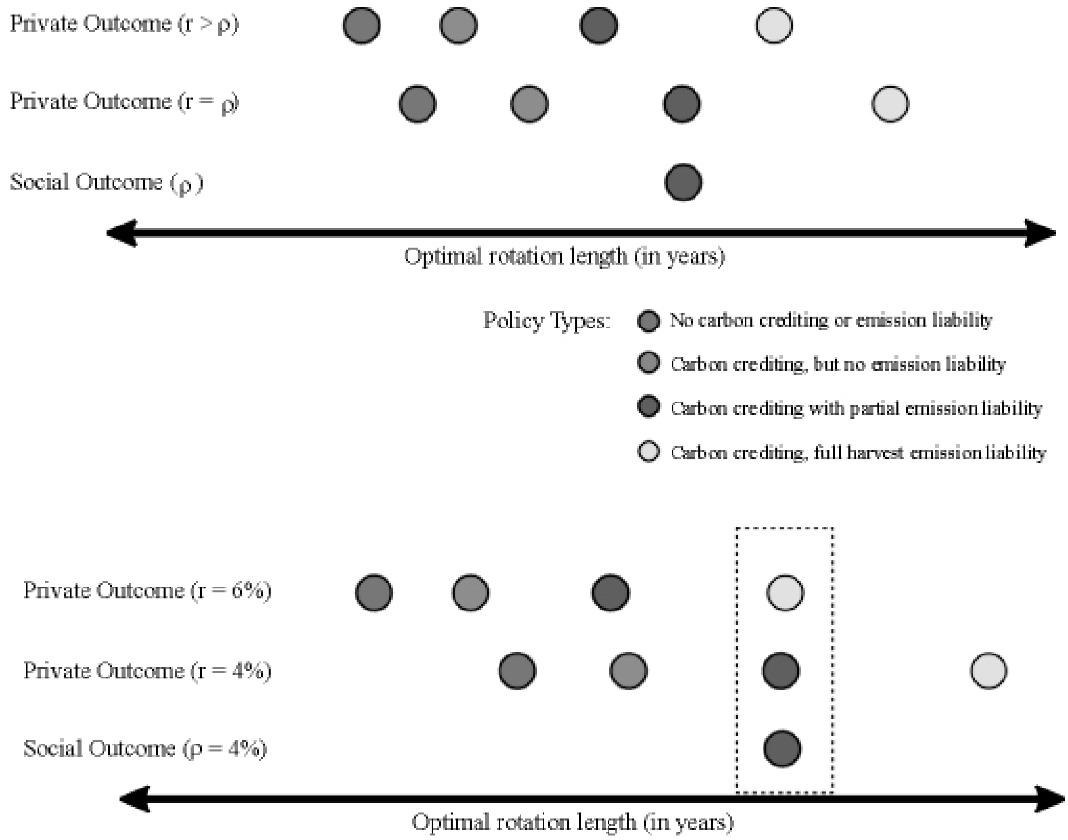
where ρ is the social rate of time preference (as opposed to the private rate of time preference which was the interest rate).

The key difference between the social maximisation problem, and the maximisation faced by the forester under a partial emission liability policy, is the potential disparity between the social (ρ) and private (r) rates of time preference. Simply put, "the interest rates that emerge from capital markets reflect society's underlying rate of discount, the riskiness of a particular asset or portfolio, and the prospect of general inflation" (Conrad 1999). These factors tend to raise the market rates of interest, and hence private rates of time preference, above the social rate of time preference. Arguments have been given to take the social rate of time preference as far below the market interest rate as to approach zero (Solow 1986). The important observation to make from this is that with a social rate of time preference being below the private rate, the optimum rotation length that is socially desirable is extended beyond the private forester's 'partial emission liability' optimum rotation length ($T^{Socially\ Optimal} > T_{cp}$, when $\rho < r$).

A time line is a convenient way of comparing the various optimal rotation lengths. The comparison depends on the relative size of the rates of time preference (determines the position of the series), and the price of carbon emission permits (determines the separation within the series). In Figure 2 it can be seen that the social optimum lines up with the same optimal rotation length as private outcome (cp) when the private and social rates of time preference are the same. This is the result of the same maximisation occurring in both the private and social settings, since the partial emission liability facing the forester is the analog of the conjectured social emission liability. The social outcome's analogues to the other three private outcomes ((o), (cn) and (cf)) are not considered to be appropriate since they do not realistically represent the societal impact of carbon sequestration or the subsequent carbon emission at the time of harvest.

As an example, if the difference between the time preference rates is sufficient, then the private outcome under the full harvest emission liability (cf) can occur at the socially optimal outcome. At the mid-range estimate of $30 for a one tonne carbon dioxide permit, an interest rate of 6 per cent and a social rate of time preference of 4 per cent, the full liability outcome and the social optimum are aligned. Both lead to an optimum rotation length of 39 years in the numerical model.

Figure 2 **Private and social optimal rotation lengths**



Data source: Modelling calculations

Conclusions

It has been found, through theoretical and numerical modelling techniques, that the mechanisms such as crediting carbon sequestration activity and the requirements of permits for the emission of carbon dioxide will impact on the harvesting decision made by foresters. It seems likely that the introduction of an emission permit trading framework provide incentives to lengthen the rotation period, as the forest owner acts to maximises a forest's present value. Increases to the profitability of forest ventures will also result.

Another likely result is that the change in rotation length will move towards a 'socially optimal' length that considers timber log products to keep carbon locked up. This relies on the social rate of time preference being less than the private forester's rate of time preference, the interest rate. Under some circumstance, for given pairs of the interest rate and social rate of time preference, the private outcome under full harvest emission liability can result in exactly the appropriate socially optimal rotation length. Therefore, this outcome could act to align private incentives to move towards the social optimum.

It is probable that a global initiative to deal with climate change will utilise some kind of a tradeable carbon permit and an associated recognition for carbon sequestration activities. This means that valuable directions for further study include extending the models presented here to incorporate uncertainty in the market prices of timber and carbon sequestration credits in the future, as well as considering uncertainty in the interest rate which acts as the private rate of time preference. Considering the movements from current carbon policy to the new steady state would also provide useful insights, since there is a disequilibrium in the optimum rotation length over this time and over the an emission permit trading transition period. In doing this it would be important to consider the impact on timber markets of the increased profitability of forestry, and the resultant entry and likely increases in future timber supply, that this encourages.

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