THE COST-EFFECTIVENESS OF CARBON SEQUESTRATION IN HARVESTED AND UNHARVESTED EUCALYPT PLANTATIONS

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An earlier version of this paper was presented to the Greenhouse 2005 Conference, Melbourne, Australia, November 2005. The paper has subsequently been revised to take account of numerous suggestions made by various participants at that conference. The author is indebted to those conference participants for their suggestions, which have collectively strengthened the conclusions reached in this paper.

Considerable attention has been focussed in recent years in Australia and elsewhere on the sequestration of carbon in plantations, as one way of reducing the levels of carbon dioxide in the atmosphere. In anticipation of Australia one day ratifying the Kyoto Protocol, many organizations have structured their plantation management around the requirements of the Protocol.

One of the assumptions in the Kyoto Protocol about carbon sequestration in plantations is that if the plantation is harvested at some point in the future, then all the carbon that has been sequestered during the life of the plantation is immediately released back into the atmosphere. The credits that have been accrued during the life of the plantations must then be repaid. As a result of this assumption, plantations developed for carbon sequestration purposes have therefore generally been assumed to exist in perpetuity, with no plans for harvesting.

While the Kyoto Protocol regulations for carbon trading assume that all carbon is released back to the environment at the moment of harvesting (primarily because of the current difficulties with auditing the history of the timber once harvesting has taken place), it is clear that carbon will continue to be sequestered for as long as the timber product is in existence. For example, Jaakko Pöyry Consulting (1999) show that many timber products have extended service life spans from 3 years (for paper and paper products) up to 90 years (for timber used in house construction). Ximenes et al. (2005) have shown further that even after the end of a timber product's service life, carbon continues to be sequestered in the timber product for extended periods, depending on the eventual fate of the product.

There are three major advantages of harvesting a plantation primarily designed for carbon sequestration. Firstly, by harvesting trees which have reached maturity (and effectively stopped absorbing carbon dioxide) and replacing them with a new planting of rapidly growing new trees, the total sequestration can be increased over the long-term compared to leaving the original plantation in place. Secondly, as well as sequestering carbon in growing trees, harvesting allows carbon to be sequestered for long periods in a succession of timber products. Thirdly, the income obtained from harvesting cross-subsidises the costs involved in planting for sequestration, thereby improving the cost-effectiveness of the carbon sequestration.

This paper examines the relative cost-effectiveness of carbon sequestration (in present values of $/tonne sequestered) in harvested and unharvested eucalypt plantations. Using common tree growth models for a typical species (*E. globulus*), and by making reasonable assumptions about the fate of carbon in wood products, the revenue and costs associated with harvested and unharvested plantations and the discount rates to be applied to costs, revenues and carbon sequestered, the paper calculates and compares the cost-effectiveness of harvested and unharvested plantations in sequestering carbon in the long-term.

The paper concludes that harvested plantations, and their succession of timber products, sequester as much carbon as perpetual forests in the long-term (in present value terms) but at a far lower present value cost per tonne sequestered. The challenge now is to develop a certification process for the carbon sequestered in timber products after harvesting to make the harvested plantation scheme globally accepted.

Introduction

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Ximenes et al. (2005) have shown further that even after the end of a timber product's service life, carbon continues to be sequestered in the timber product for extended periods, depending on the eventual fate of the product. For example, timber products disposed of in anaerobic landfills stay intact for long periods of time with very little release of greenhouse gases to the atmosphere. Alternatively, timber products burnt for fuel enable the carbon in fossil fuels (which would otherwise have been burnt) to be sequestered in those fossil fuels for extended periods of time. Ximenes and Davies (2004) have developed a model (TimberCAM) which simulates the fate of timber products after harvesting, and tracks the continued sequestration of carbon in these post-harvest products.

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This paper examines the relative cost-effectiveness of carbon sequestration (in present values of $/tonne sequestered) in harvested and unharvested eucalypt plantations. Using common tree growth models for a typical species (E. globulus), and by making reasonable assumptions about the fate of carbon in wood products, the revenue and costs associated with harvested and unharvested plantations and the discount rates to be applied to costs, revenues and carbon sequestered, the paper calculates and compares the cost-effectiveness of harvested and unharvested plantations in sequestering carbon in the long-term.

Tree Growth Models

While many ways have been suggested for carbon sequestration (such as geo-sequestration and deep sea sequestration), one of the most popular methods proposed has been by the planting of trees which absorb CO_2 as they grow, and then by keeping the carbon in the trees sequestered for a long period of time. While such schemes have been mooted for some time (e.g. BTCE, 1996), they are only recently becoming a commercial reality. Because CO_2 (as a greenhouse gas) is a global problem, the sequestration can be done at a site which is distant from the source of the emissions and which is best suited for the growing of the trees. It doesn't matter where the CO_2 is emitted or where it is absorbed from a global warming perspective; all that matters is how much is left in the atmosphere and for how long it is left there.

As trees grow, they absorb carbon dioxide from the atmosphere and via a process of photosynthesis they use the energy from sunlight to convert the CO_2 into carbon that is stored in the wood of the tree (and as a by-product they release oxygen back to the atmosphere). The rate at which they absorb carbon dioxide will depend on the rate at which the trees grow.

The science of tree growth rates is a well-developed discipline, with many models of tree growth having been proposed in the literature. A comprehensive set of modelling options has recently been released by the Australian Greenhouse Office (AGO) as the National Carbon Accounting System (the FullCAM model based on the work of Richards and Evans, 2000). This modelling system contains various options for modelling tree growth. In essence, however, most of the models assume that tree growth over time can be described by a sigmoid curve, with low rates of growth in the early years of a tree's life (the juvenile phase), followed by a growth spurt in the middle years (the mature phase), and then a slowing down of growth in the later years (the senescent phase) until an equilibrium situation is reached whereby the tree effectively stops growing.

While there are many models of tree growth, the ones used in this paper are based on the models reported by Wong et al. (2000). In that report, they describe models of height, basal area, tree volume and mortality, and provide specific data for a range of eucalypt species. The results derived from these models are then modified by considerations of finite site carrying capacity and the concepts of competition embodied in a Stand Density Diagram by Reineke (1933) and others. The resultant model, while not necessarily precise in an absolute sense, gives an indication of tree growth over time that can be used in a comparative sense for unharvested and harvested forests.

Unharvested Forests

Height Modelling

The modelling of the height of trees is based on difference equations that predict a tree height in a given year based on the height in a different year. This year might be the previous year, one several years ago or even one in the future (if the height of the tree in the future can itself be predicted).

The height model is of the form:

$$H_{t_2} = H_{t_1}\left[\frac{1-e^{at_2}}{1-e^{at_1}}\right]^{b} \qquad (1)$$

where: H = height (m)

t_n = age (years) in n^{th} time period

a, b are parameters to be estimated

Wong et al. (2000) provide estimates of the parameters a and b for various species. For *E. globulus*, the species used in this paper, the values are a = -0.1114 and b = 1.033. Because height growth is largely independent of silvicultural management (pruning and thinning), the dominant height of a eucalypt plantation at age 10 years is commonly used as a measure of the quality of the site for tree growth, and is referred to as the Site Index (SI). For an assumed SI of 20 (i.e. the average tree height at age 10 is assumed to be 20 metres), the height growth curve is as shown in Figure 1.

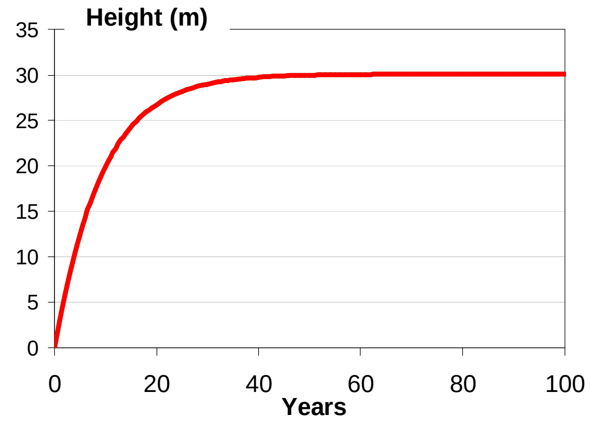

Fig 1 Height Growth Model

Basal Area Modelling

The modelling of the Basal Area (BA) of a stand of trees is also based on difference equations of the form:

$$BA_{t_2} = e^{\left[\left(\frac{t_1}{t_2}\right)\ln\left(BA_{t_1}\right)+\left(\frac{a}{c}+\frac{b}{c}SI\right)\left\{1-\left(\frac{t_1}{t_2}\right)^{c}\right\}\right]} \qquad (2)$$

where: BA = Basal Area (m^2/ha)

t_n = age (years) in n^{th} time period

SI = Site Index

a, b and c are parameters to be estimated

For *E. globulus*, the values given by Wong et al. (2000) are a=2.443, b=-0.00193 and c=0.4078. Equations 1 and 2 have the advantage of being path invariant, in that the same predicted values are obtained no matter what reference year is used, in either the past or the future. An estimate of the BA at age 10 can be obtained from the SI at age 10 by means of a BA initialisation equation (Candy, 1997) of the form:

$$\ln(BA_{10}) = a + b/SI \qquad (3)$$

where: a = 4.271 and b=-17.62

Using the above models and parameters, the BA growth curve is as shown in Figure 2.

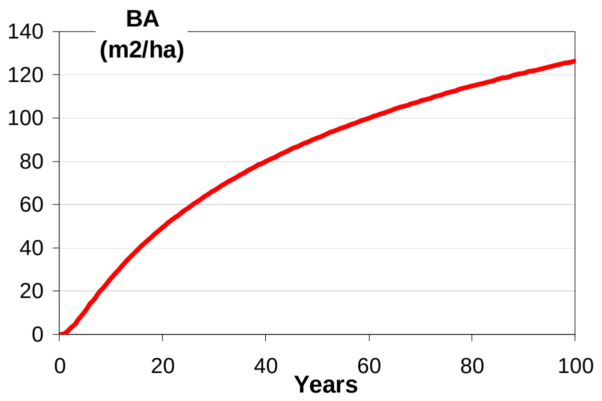

Fig 2 Basal Area Growth Model

The predicted growth in BA in later years in Figure 2 appears highly optimistic in that, unlike the growth in height, the growth in BA appears to not be slowed down by the carrying capacity of the site, with Basal Areas being predicted which are extremely high for *E. globulus*. A forest with this BA would be pushing well into the area of "imminent mortality" noted by Reineke (1933). However, as noted by Wong et al. in reference to their basic models, "extrapolations should only be considered as indicative of future growth". Therefore, the BA growth in later years will be modified by means of a logistic function that limits the maximum BA to an asymptotic value of 70 m^2/ha. Using this limitation to BA growth, the BA growth curve is now as shown in Figure 3.

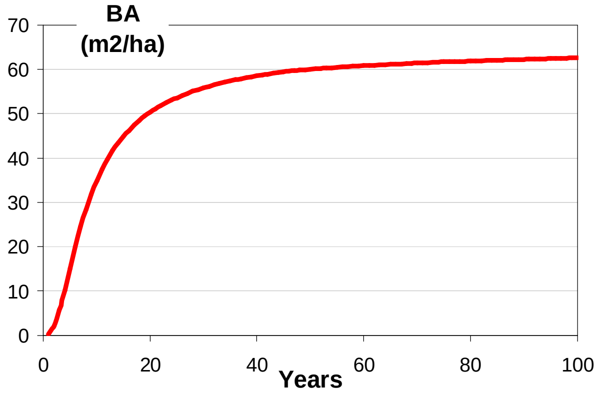

Fig 3 Limited Basal Area Growth Model

Restricting the Basal Area to a maximum of 70 m^2/ha is more in line with the concept of a finite Carrying Capacity of the site, which would be a function of soil type and depth, rainfall and climatic conditions at the site. It also ensures that the plantation does not enter into the region of "imminent mortality" noted by Reineke (1933), whereby an unsustainable combination of stocking density (stems per hectare) and tree diameter is assumed. Trees can only continue to increase in diameter if the stocking density is reduced, either by planned silviculture activities such as thinning or by a natural process of "self-thinning" whereby the weaker trees die in order that the stronger trees can continue to grow in diameter.

Figure 4 shows the Stand Density Diagrams for the unconstrained BA growth model (shown above in Figure 2) and the constrained BA growth model (shown above in Figure 3), as a function of the logarithms of the stocking rate (stems per hectare – sph) and the mean tree diameter (Quadratic Mean Diameter – QMD). While the unconstrained BA growth model shows the plantation entering the region of "imminent mortality" above the inclined line proposed by Reineke, the more conservative constrained BA growth model contains the growth within a fully stocked, but non-endangered, region. The constrained BA growth model is therefore used in this analysis.

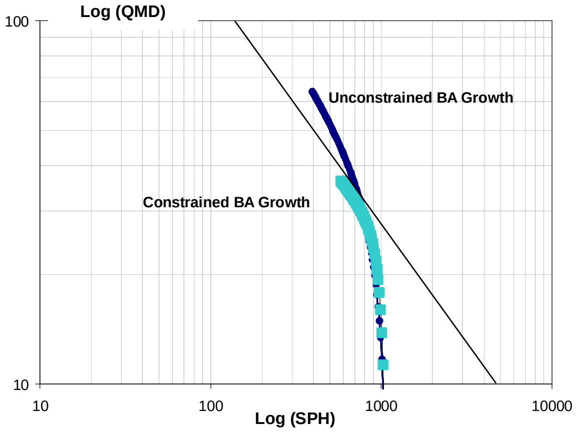

Fig 4 Stand Density Diagrams for Unconstrained and Constrained BA Growth

Tree Mortality Modelling

While the above model takes explicit account of the effect of "imminent mortality" (i.e. the limiting effect of stocking density on tree diameter growth), it does not take account of the ordinary "mortality" of trees, which is also a function of stocking density. Even when not approaching the regime of "imminent mortality" described by Reineke, plantations suffer from mortality of trees which die for various reasons including disease, and local soil and water conditions. These problems are exacerbated by the effects of competition between trees for the available nutrients, with the result that higher mortality levels are experienced in plantations with higher stocking densities.

Based on the model used in FARMTREE (as reported by Wong et al, 2000), a tree mortality model of the following form has been adopted to predict the Mortality Rate (MR) in terms of the percentage of trees that die each year as a function of stocking density (measured in stems per hectare - sph):

$$MR = 0.000016sph \qquad (4)$$

Tree Volume Growth Modelling

Combining the growth in tree height, the growth in BA and the effect of annual tree mortality, the growth in total tree volume can be estimated by assuming a specific trunk shape. Many simple models assume a conical trunk shape, where the total volume is one-third the height times the basal area. However, many other volume functions have been proposed (e.g. Inions, 1992). Wong et al. (2000) have tested many of these models for eucalypts and recommend the following function:

$$TV = 0.3983BA – 0.0661H + 0.35366BA.H \quad (5)$$

Applying this volume function to the height and BA growth models, one obtains a tree volume growth curve as shown in Figure 5.

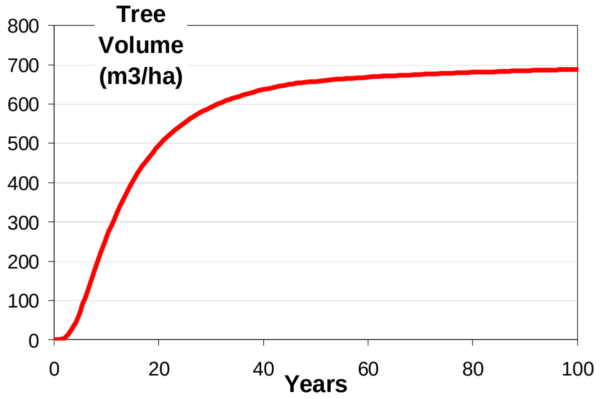

Fig 5 Growth in Plantation Tree Volume

This curve can be differentiated to obtain the Current Annual Increment (CAI) curve and the Mean Annual Increment (MAI) can be obtained by dividing the total tree volume at any age by the age of the plantation. These two well-known relationships are shown in Figure 6. Note that the highest annual growth occurs around year 8, while the highest average growth occurs around year 15.

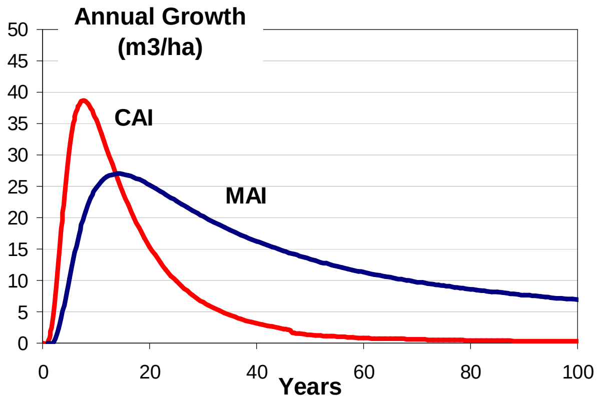

Fig 6 CAI and MAI as a function of Age

Harvested Plantations

The harvested plantation follows essentially the same growth processes as the unharvested plantation, except for the effects of silviculture on the growth rates and, of course, the effects of harvesting. In the early years, the height growth, BA growth and tree volume growth use exactly the same models as the unharvested plantation. The process changes when silviculture practices are introduced at about an age of three.

The Effect of Silviculture

The two major silviculture practices are thinning and pruning. Thinning is undertaken to deliberately reduce the stocking rate so as to stimulate the diameter growth of the remaining trees. This is in contrast to the “self-thinning” that occurs in unharvested forests, whereby high levels of competition force the death of some trees in order that the surviving trees may grow.

Pruning is undertaken to remove low-level branches to improve the quality of the sawlogs that might be obtained at harvest. The purpose of early pruning is to contain the stubs of the removed braches within a relatively small core, thus increasing the volume of clearwood that may be obtained from a log. In the context of the current study, pruning has two specific advantages. Firstly, maximising clearwood volume increases the proportion of the total tree volume that can be converted into long-lived structural and furniture timber, thus increasing the long-term levels of sequestration. Secondly, the economic value of the harvest is maximised by a program of audited early pruning, thus increasing the cost-effectiveness of the sequestration activities.

For this study, it is assumed that pruning is undertaken up to a height of about 6 metres, which is the desirable length of logs for sawmilling operations. It is also assumed that pruning takes place in three lifts (of 2 metres each) at years 3, 5 and 7. This timing is important to ensure that the size of the core (of low quality juvenile wood and branch stubs) is limited to 17cm DOS (diameter over stubs) or 20cm DOO (diameter over occlusions).

The effect of thinning on diameter growth is an inexact science, especially for Eucalyptus species, since such thinned plantations are relatively new in Australia and little long-term data has been accumulated from which silviculture models may be developed which show the precise effect of thinning on diameter growth.

For the purpose of this paper, it is assumed that the BA Growth Model shown in Figure 3 applies equally to unharvested and harvested plantations. As shown in Figure 3, beyond a threshold BA, BA growth declines with increasing BA. For an unharvested plantation, this means that BA growth tends to decline over time, since BA increases monotonically over time. However, for a harvested plantation that is deliberately thinned, BA growth does not decline monotonically over time because we have deliberately reduced total BA (thereby stimulating BA growth) by means of a designed thinning regime.

It is assumed that thinning is undertaken in years 3, 5 and 7 when BA has reached approximately 5, 10 and 15 m^3/ha, respectively. The effect of this thinning is to progressively reduce the stocking rate from an initial stocking rate (about 800 – 1100 sph) to a final stocking rate (about 100 – 250 sph). For a normal commercial eucalyptus plantation being harvested for sawlogs, a typical initial stocking rate might be 1100 sph and a final stocking rate might be 150 sph. The initial and final stocking rates are yet to be determined for a cost-effective carbon sequestration plantation.

At each thinning, it is assumed that the same proportion of stems are removed in order to achieve the desired stocking density at harvest (the model also allows for ordinary tree mortality during the life of the plantation, which will be lower in the harvested plantation because of the lower final stocking rates and the fact that weaker trees will usually have been specifically removed during thinning). While x% of stems will be removed at each thinning, the effect on BA will be less pronounced because smaller-than-average trees will have been removed at each thinning. In the absence of a complete statistical distribution of tree diameters, it is assumed that if stocking rate is reduced by x%, then BA will have been reduced by x/2%. Thus, if 30% of trees are removed at a thinning, then BA will have been reduced by 15%.

The effect of reducing BA through thinning is to stimulate diameter growth in two ways. Firstly, because the smaller diameter trees are removed at thinning, the average diameter of the trees in the plantation must increase simply because the smaller trees have been removed. For example, if 30% of the trees (and 15% of the BA) have been removed, then the remaining 85% of BA must now be spread across the remaining 70% of trees, resulting in a 21% increase in BA per tree (which is equivalent to a 10.2% increase in average diameter).

The second, more important, effect is for thinning to stimulate the growth in diameter of the remaining trees above what they would have experienced without the thinning. This accelerated diameter growth is modelled by assuming that, above a threshold BA, the BA growth is effectively an inverse function of BA, as shown in Figure 7 (which is based on a differentiation of the BA growth model shown in Figure 3).

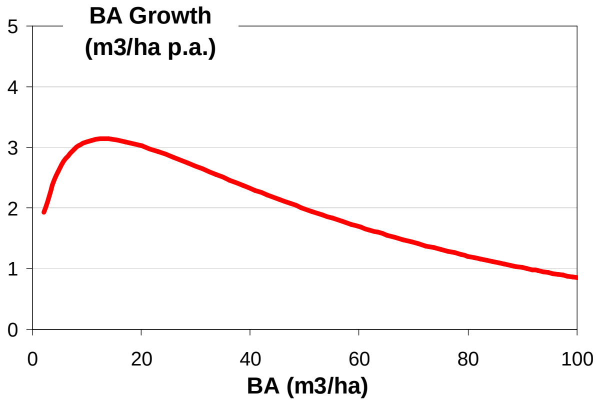

Fig 7 BA Growth as a function of BA

Thus, as noted earlier, BA growth declines with increasing BA. However, if total BA is reduced by thinning then the BA growth is increased, corresponding to the reduced total BA. Thus, thinning reduces BA but also increases the subsequent rate of growth of BA. Nonetheless, the overall BA is decreased by thinning until the plantation is mature, at which time the thinned plantation catches up to the unthinned plantation when the unthinned plantation reaches its maximum BA governed by the carrying capacity of the site, as shown in Figure 8.

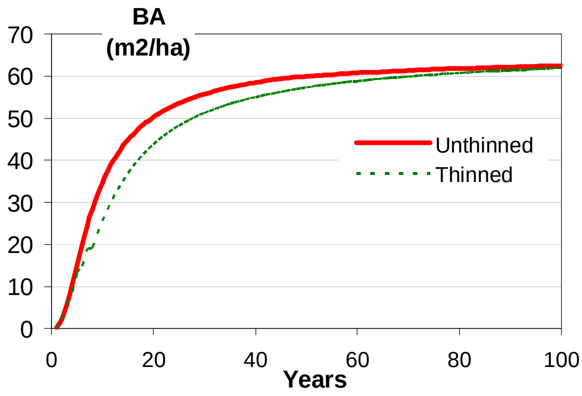

Fig 8 BA as a function of Thinning

Thinning also has a temporary effect on CAI, with the CAI decreasing in the thinning period (due to the removal of trees) and then increasing slightly due to the stimulating effects of the reduction in BA via thinning, as shown in Figure 9.

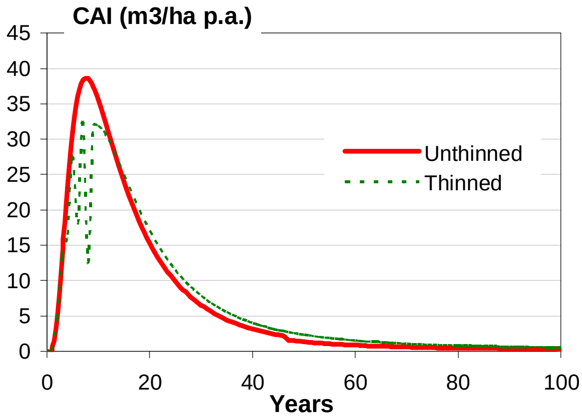

Fig 9 CAI as a function of Thinning

Thinning also has a temporary effect on MAI, with the MAI decreased in the thinning period and then gradually recovering until the same MAI is achieved at about 50 years, as shown in Figure 10.

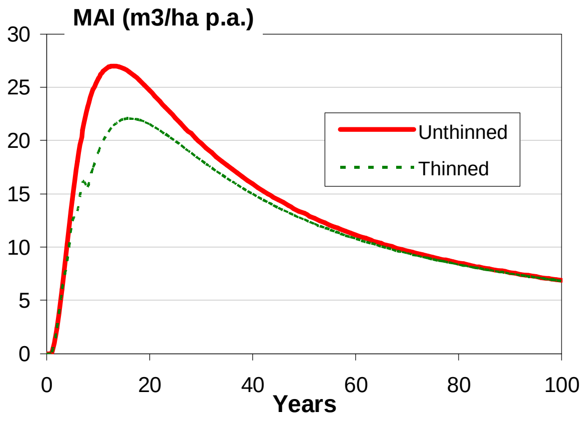

Fig 10 MAI as a function of Thinning

The major effect of thinning, however, and the real reason for thinning is the increase in tree diameter as shown in Figure 11. The removal of smaller diameter trees and the removal of competition, allowing the remaining trees to grow larger, is graphically illustrated in Figure 11. This increased diameter provides more clearwood for marketable timber and for long-lived timber products which will continue to sequester carbon well into the future.

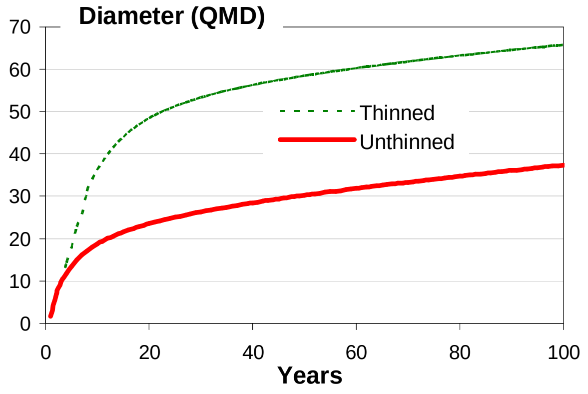

Fig 11 Diameter as a function of Thinning

Initial and Final Stocking Densities

The decision on initial and final stocking density in harvested plantations being used for sequestration is a matter of trade-offs. High initial stocking densities (about 1100 sph) are often used in commercial plantations to allow for considerable thinning by removal of trees with poor form which would not have high marketable values. Low final densities (100-150 sph) are often used to maximise sawlog diameter and hence market value.

However, from the viewpoint of carbon sequestration, very high initial stocking densities may merely mean higher establishment and silviculture costs with no significant increase in sequestration. Similarly, very low final densities may increase the diameter of individual trees but may do so at the expense of total carbon sequestered in the long-term.

While more research is required to determine the optimum initial and final stocking densities for maximising the cost-effectiveness of carbon sequestration, it would appear that a lower initial density and a higher final density (compared to those used for commercial plantations designed for sawlog production) would be warranted. For the analysis reported in this paper, an initial density of 800sph and a final density of 250sph is assumed.

As a result of the various assumptions about initial and final stocking density and silviculture regime, the Stand Density Diagram for a thinned plantation is shown in Figure 12. It can be seen that the plantation is kept in the non-competitive area well under the zone of “imminent mortality” during its early years, and only starts to approach this zone during its later years. However, because of the reduced stocking density, the trees are able to reach larger diameters than they would have in an unthinned plantation.

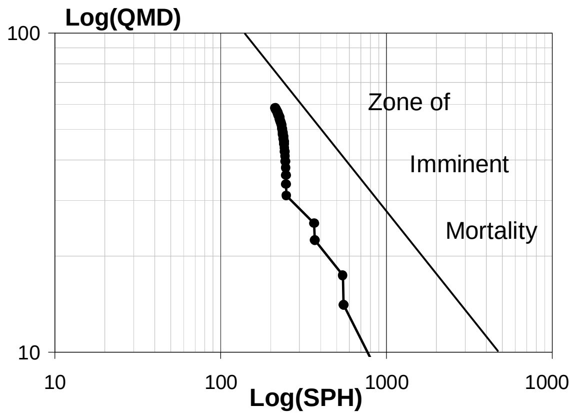

Fig 12 Stand Density Diagram for a Thinned Plantation

Carbon Sequestration

Carbon may be sequestered in forests in four major “carbon pools”, namely:

- In the above-ground sections of the trees themselves (i.e. the trunk, branches and leaves);
- In the below-ground sections of the trees (i.e. large and small roots);
- In the debris on the forest floor; and
- In the soil of the forest.

Yanai et al. (2003) note that the soil contains more carbon than any other terrestrial carbon pool (about three times as much as vegetation), while the forest floor carbon pool is the most dynamic part of soil organic matter. Snowden et al. (2000) note that the root:shoot ratio of eucalypts is about 25% for a mature plantation, with slightly higher values for younger plantations. However, from the perspective of the current study, what matters is not the total size of the different carbon pools, but how they change in response to the growing and harvesting of trees.

It has often been thought (e.g. Covington, 1981) that harvesting can dramatically change the carbon content in the soil and forest floor. However, Yanai et al. (2003) have shown that such conclusions are based on faulty methodologies and selective interpretations of the data. Others (e.g. Johnson and Curtis, 2001) have used more rigorous methodologies and have concluded that forest harvesting has little or no effect on soil carbon or nitrogen, but that the results depended on the harvesting method employed. While whole-tree harvesting could reduce soil carbon, they found that sawlog harvesting could increase soil carbon. Overall, however, there was little effect of harvesting on soil carbon.

Because harvesting appears to have little effect on soil carbon, and roots are a small proportion of above-ground carbon, the analysis in this paper concentrates on the differences in carbon sequestered in the above-ground section of the trees.

The previous sections have described the growth of unharvested and harvested plantations, with the final output being the volume of wood in the final plantation. For the purposes of this paper, this volume of wood needs to be converted into the quantity of CO_2 absorbed over the life of the trees in order to produce that wood.

Conversion of the volume of the tree into the amount of CO_2 absorbed over the life of the tree requires a number of conversion parameters, such as:

- Convert tree volume to tree weight (assume basic density of 0.60 tonne/m3)
- Convert tree weight to weight of carbon sequestered (assume 50% carbon by weight)
- Convert carbon sequestered to CO_2 absorbed (assume 44 tonnes CO_2 absorbed for every 12 tonnes carbon sequestered, based on molecular weights)

Using the above conversion factors, every cubic metre of wood produced in trees will have absorbed 1.1 tonnes of CO_2 over its lifetime. The total sequestration may be spread over the life of the tree according to the rate of growth of the tree each year, as represented by the CAI shown in Figures 6 and 9. The cumulative absorption of CO_2 in trees in a perpetual unharvested forest is shown in Figure 13.

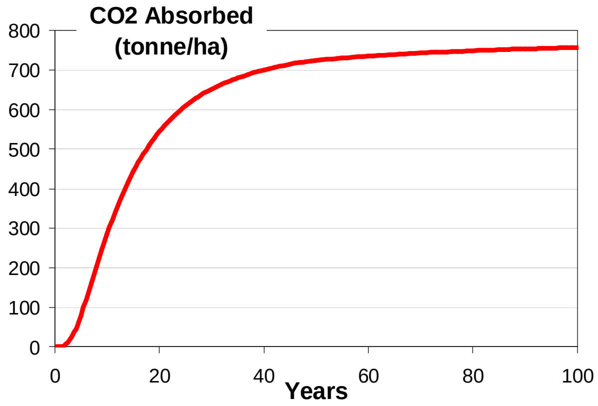

Fig 13 CO_2 Absorbed by Trees in a Perpetual Unharvested Plantation

Timber Products Sequestration

The previous section has shown how the carbon sequestered in living trees may be estimated. For the perpetual forest plantation, the amount of carbon sequestered each year gradually declines until an equilibrium situation is achieved where the rate of CO_2 absorption is balanced by the rate of CO_2 release from the forest, via tree mortality and the decay of material on the forest floor.

The Kyoto Protocol acknowledges that carbon is stored in trees as they grow as illustrated in Figure 13. However, the Kyoto Protocol regulations for carbon trading also assume that all carbon is released back to the atmosphere at the moment of harvesting. For example, if the plantation depicted in Figure 13 was harvested after 20 years, the cumulative sequestration assumed by the Kyoto Protocol would be as shown in Figure 14.

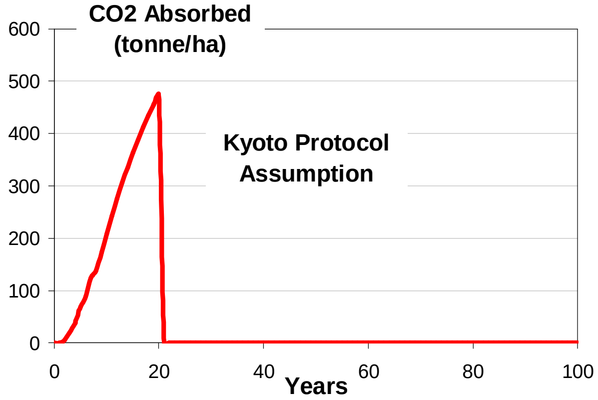

Fig 14 Kyoto Protocol Assumptions of CO_2 Absorbed by Trees in a Harvested Plantation

While the Kyoto Protocol regulations for carbon trading assumed that all carbon is released back to the atmosphere at the moment of harvesting (primarily because of the current difficulties with auditing the history of the timber once harvesting has taken place), it is clear from recent research that carbon will continue to be sequestered for as long as the timber products derived from the trees after harvesting are in existence. For example, Jaakko Pöyry Consulting (1999, 2000) show that many timber products have extended life spans from 3 years (for paper and paper products) up to 90 years (for timber used in house construction). Not all products in each category last for the maximum life span, however, and so the concept of a half-life has often been adopted, with 50% of the carbon being assumed to be released back to the atmosphere in a given time span (either through degradation of the product or through accidental or planned destruction of the product). Assuming that these timber products continue to sequester carbon for some time after harvest, the true profile of cumulative sequestration would look more like Figure 15.

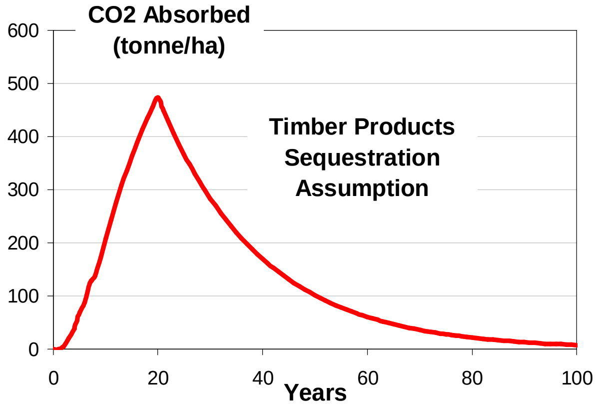

Fig 15 CO_2 Absorbed by Trees in a Harvested Plantation assuming Continued Sequestration in Timber Products after Harvesting

More recent research, however, has shown that the fate of sequestered carbon in timber products is not only more complex, but also more promising from a harvested plantation perspective. Ximenes et al. (2005) have shown that even after the end of a timber product’s service life, carbon continues to be sequestered in the timber product for extended periods, depending on the eventual fate of the product. For example, timber products disposed of in anaerobic landfills stay intact for long periods of time with very little release of greenhouse gases to the atmosphere. Ximenes et al. (2005) show that less than 4% of carbon in forest products (including paper and cardboard products) was lost to the atmosphere after up to 50 years of burial in a landfill.

Ximenes and Davies (2004) have also noted that timber products (e.g. offcuts, waste and materials that have reached the end of their service life) that are burnt for fuel enable the carbon in fossil fuels (which would otherwise have been burnt) to be sequestered in those fossil fuels for extended periods of time. Ximenes and Davies (2004) provide a table of fuel displacement factors (based on the Australian Greenhouse Office Factors and Methods Workbook (2003)) that shows the amount of carbon saved (displaced) when one tonne of wood carbon is used in lieu of the specified fuel source. These displacement factors range from 0.642 for natural gas up to 3.68 for electricity generated from brown coal. Thus in addition to wood burned for fuel being “carbon neutral” in itself (i.e. the carbon released to the atmosphere when the wood is burnt has only relatively recently been absorbed from the atmosphere via photosynthesis), the generation of power (heat) by burning the wood allows carbon to be retained in an alternative fossil fuel that would have be burned instead. The recognition of this “opportunity benefit” is important in gaining a full appreciation of the carbon sequestration potential of harvested plantations.

Ximenes and Davies (2004) have developed a model (TimberCAM) which simulates the fate of timber products after harvesting, and tracks the continued sequestration of carbon in these post-harvest products. Many of the concepts employed in TimberCAM have been incorporated into the modelling developed within this paper. For example, consider the fate of trees which have been harvested for sawlogs, with the intention of producing frames for timber structures, as shown in Figure 16.

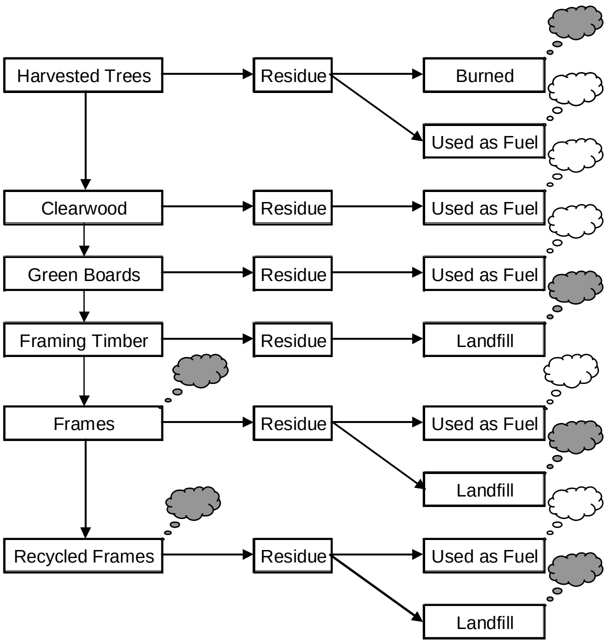

Fig 16 The Fate of Trees Harvested for Sawlogs for Conversion into Timber Frames

The total volume of wood in the trees at harvest time can be split into two major categories. The clearwood in the pruned section of the trunk will eventually be milled; the rest of the tree can be classed as residue. The smaller branches and leaves may well be burned on-site as part of the cleaning up after harvest. The carbon in this wood is immediately released back into the atmosphere, as denoted by the small black cloud. The larger branches and the upper part of the trunk may be gathered as firewood fuel, and sold for use in generating energy as an alternative to use electricity for heat production in households.. The small white cloud indicates that the carbon in this firewood is released back to the atmosphere when it is burnt as fuel, but this is partly or completely balanced by the carbon that remains sequestered in alternative sources of fossil fuel that would otherwise have been burnt to produce the equivalent energy.

At each stage of the subsequent production process (converting the clearwood to green boards, then framing timber, then frames and finally recycled frames), some of the wood ends up as residue, which may either be used as fuel or disposed of in landfill. If the residue goes to landfill, then the carbon is gradually released back to the atmosphere, but at the very slow rates identified by Ximenes et al. (2005).

Of the timber than is used for the production of frames, some of the carbon in this timber also returns to the atmosphere, via bacterial breakdown and via occasional catastrophic event (e.g. a house burning down). However, as noted by Ximenes and Davies (2004), the rate at which this occurs is also very small.

The proportion of wood in a harvested tree that goes into different types of timber products (clearwood or residue) will depend on the height of the tree (H), the pruned height (PH), the diameter at breast height (measured by the Quadratic Mean Diameter, QMD, which is the diameter at breast height on a tree with mean basal area), the diameter over occlusions (DOO) and the shape of the trunk. Assuming a conical trunk, the diameter at pruned height would be QMD(PH/H). Assuming a cylindrical core of juvenile wood and branch stubs, the volume lost from sawlogs in the central pipe would be $3.142*DOO^2/4$. The total volume of sawlog clearwood (CWV) that could theoretically be converted into long-lived timber products is therefore:

$$CWV = 3.142(PH(QMD(1+PH/H))^2 - DOO^2)/4 \qquad (6)$$

However, not all of this clearwood will be converted into long-lived timber products. During harvesting and milling there will be a certain amount of wastage in the remaining stump, offcuts, trimmings and sawdust. Given that all this residue is produced within the controlled environment of a mill, it is assumed that all this residue can be collected and burnt as a fuel to help power the operations of the mill.

The green boards that are produced in the initial milling operation are then left to dry. At a later time, after drying, they are then trimmed to final size as framing timber, with the residue in the dry mill again being used as fuel. It is assumed that the framing timber is then used in the manufacture of frames, with manufacturing residue being used as fuel, while residue from the final on-site assembly of the frames going to landfill. The material going to landfill will slowly release carbon back to the atmosphere, often in the form of methane (which has a high CO_2 equivalency as a greenhouse gas).

During the service life of the frames, they will release some carbon back to the atmosphere due to decay and the effects of occasional fires. At the end of the service life of the frames, it is assumed that some of the framing timber will be recycled as framing in another building, some will be burnt as fuel (firewood) while most will go to landfill. At the end of life of the recycled framing timber, all the material goes to landfill or is used as firewood.

All the residue proportions used in the current model are based on the default values used in the TimberCAM model (Ximenes and Davies, 2004). The fuel displacement factors are based on a combination of alternative fuels. Where wood is used as a direct substitute for another fuel (such as in an on-site furnace used to generate power in a mill), the fuel replacement factor is typically less than unity, because of the higher fuel efficiencies of other fuels compared to wood. However, where wood is used as a substitute for electricity generated at a remote site and distributed by a network, the fuel displacement factors are typically much greater than unity. As a compromise between these two options, and taking into account the efficiency of wood burning, the current modelling uses a fuel displacement factor of unity, i.e. every tonne of carbon in the burnt wood saves a tonne of carbon in the alternative fuel.

Having taken the specific fates of the carbon in the harvested timber into account, the CO_2 sequestration profile earlier depicted as shown in Figure 15 now looks more like that shown in Figure 17.

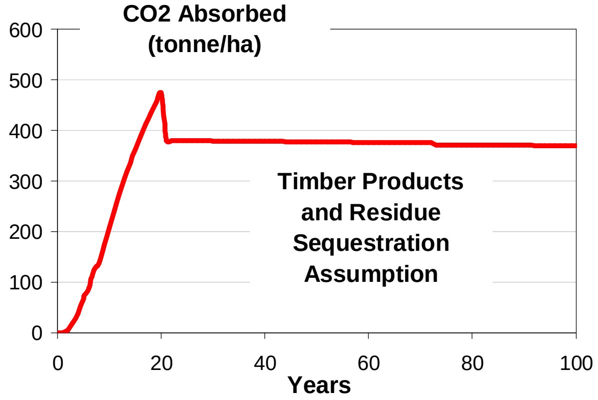

Fig 17 Actual CO_2 Absorption Profile in Trees in a Harvested Plantation and in Timber Products and Residues after Harvesting

By comparison with the theoretical half-life assumption shown in Figure 15, the more realistic assumptions shown in Figure 17 indicate a sudden drop in sequestration following harvest as some residues are burnt as waste, without any energy recovery or fuel displacement. However, from there on the fall in sequestration is very small as the timber products release very little CO_2, the landfill breaks down very slowly and most burning of residues is done to produce energy, with consequent fuel displacement. The profile shown in Figure 17 is very consistent with the finding reported by Ximenes et al. (2005) that “approximately 70% of the carbon from harvested logs in Australia is in equivalent long-term storage in forest products”.

Cycles of Growth, Harvest, Decay and Regrowth

For a harvested plantation, therefore, the dynamics of carbon sequestration are quite different to that of an unharvested plantation. The amount of CO_2 that can be absorbed under a continual regime of plant-and-harvest can be estimated by means of a simulation of the planting-growing-harvesting-replanting cycle using a variety of rotation lengths. Fundamental to a plant-and-harvest regime is that the timber harvested at the end of the life cycle must be converted into one of three forms:

- timber products that continue to sequester the carbon for an extended period of time, such as furniture or building timber;
- timber products that are burned for energy production, thereby leading to fossil fuel displacement; or
- timber products that are consigned to anaerobic landfills, where decomposition rates are very slow.

The full picture of sequestration in a harvested plantation can only be obtained by considering repeated cycles of growth, harvest, decay and regrowth. Assume that the plantation depicted in Figure 12 is harvested at year 20 and replaced with new seedlings. Further assume that the carbon remaining sequestered by timber products after harvest is as shown in Figure 17. The amount of carbon sequestered in each successive plantation of trees (and hence the amount of CO_2 removed from the atmosphere) will be as shown in Figure 18. For each planting, there is a juvenile phase, followed by a mature phase, but just as the senescent phase is approached at year 20, the plantation is harvested and re-planted. The timber products from the initial plantation then have an immediate drop in sequestration followed by a long slow decline in sequestration according to the fates chosen for the timber products. As this is happening, however, the next plantation is growing and absorbing CO_2. This process repeats ad infinitum (or at least as long as the re-plantings are continued).

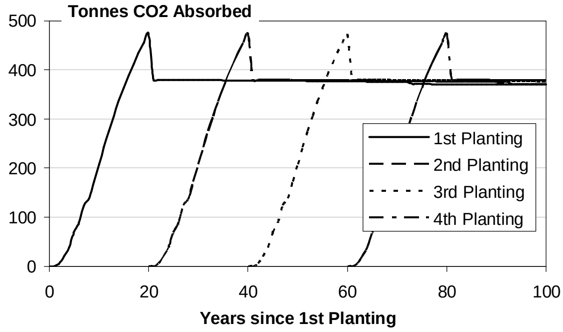

Fig 18 Cycles of Growth, Harvest, Decay and Regrowth

The total amount of CO_2 removed from the atmosphere during the overall sequence of planting-and-harvesting on a 20 year rotation can be obtained by adding the amount sequestered in each planting (or subsequent conversion into timber products) at any given year. This total sequestration will fluctuate over time as shown in Figure 19, in which the unharvested perpetual forest sequestration is also shown. It can be seen that for the first two rotations, the harvested plantation has less total sequestration than the unharvested plantation. However, after two rotations, the harvested plantation has consistently more cumulative sequestration.

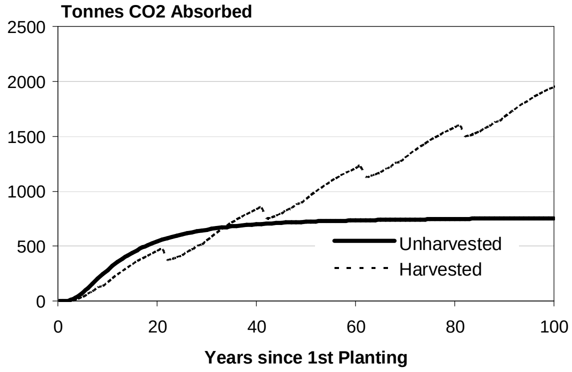

Fig 19 Comparison of Unharvested and Harvested Plantation Sequestration

A consideration of Figures 18 and 19 also reveals another advantage of the harvested plantations. At any point in time, the unharvested plantation has all its sequestered carbon tied up in one asset – the living trees. On the other hand, after the first rotation, the harvested plantation has its sequestered carbon embodied in two or more assets – one crop of living trees and a multitude of timber products that are probably geographically dispersed. Therefore, from a risk management perspective, the harvested plantation sequestration is a much safer option. One major fire through the plantation will wipe out all the sequestered carbon in the unharvested plantation, but only remove the sequestered carbon from one crop of living trees in the harvested plantation, leaving the carbon sequestered in the timber products untouched. One thing that is known about Australian forests is that fires occur on a semi-regular basis – therefore a risk-minimised strategy is a decided advantage.

Figure 19 has been based on an assumed rotation length of 20 years. Simulations have been run with rotations of various length, and the results are shown in Figure 20 in terms of cumulative CO_2 absorption since the start of planting.

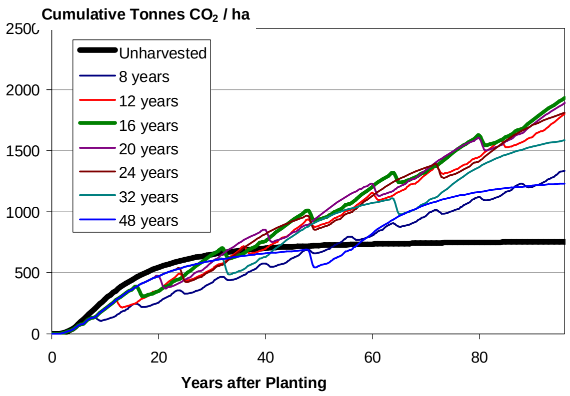

Fig 20 Comparison of Unharvested and Harvested Plantations with various Rotations

It can be seen that all the harvested plantations eventually sequester more CO_2 than the unharvested plantation. Because the fluctuations in Figure 20 make it difficult to read, Figure 21 has been prepared based on a project lifetime which is an integer number of rotations for each rotation interval (96 years for all except the 20 year rotation which has a lifetime of 100 years). The perpetual unharvested plantation is represented by a plantation with an assumed rotation of 100 years at the far right of the diagram. It can be seen that a rotation of 16-20 years has the highest cumulative CO_2 absorption.

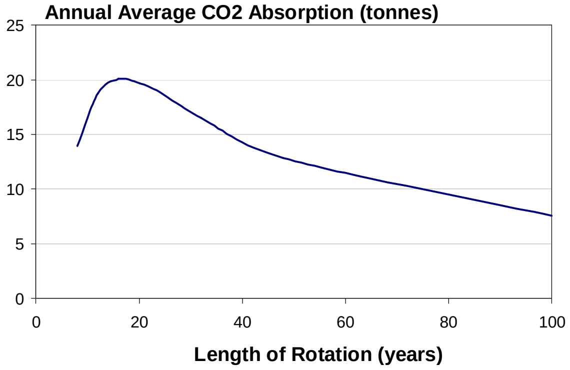

Fig 21 Comparison of Total Sequestration from Unharvested and Harvested Plantations with various Rotations

Since the sequestration depicted in Figure 20 extends over many years, the annual sequestrations must be discounted to allow for the Social Time Preference rate for CO_2 reductions. Most carbon accounting models (e.g. Boscolo et al., 1998; Hean et al., 2003) now agree that CO_2 reductions in the future must be discounted in the same way that monetary costs and benefits in the future must be discounted. A discount rate of 6% p.a. (as a compromise between public and private sector evaluations) has been assumed for both monetary amounts and CO_2 reductions in this evaluation.

The cumulative CO_2 absorptions shown in Figure 21 are undiscounted, and are merely the total tonnes of CO_2 absorbed over the project lifetimes. However, it is clear from Figure 20 that the harvested plantations have a time lag in sequestration, and only exceed the sequestration from the unharvested plantation after 40-60 years. Because of the time lags, it is appropriate that the CO_2 sequestrations be discounted over time. Applying a discount rate of 6% p.a., the discounted results are shown in Figure 22.

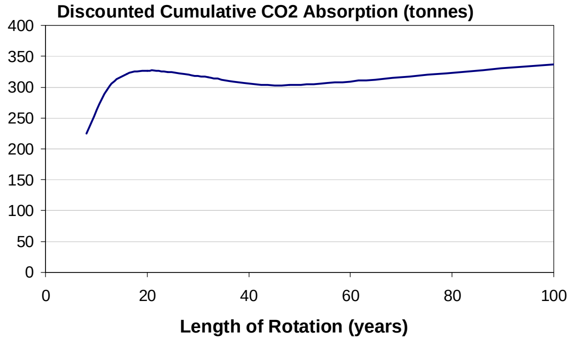

Fig 22 Comparison of Total Discounted (6% p.a.) Sequestration from Unharvested and Harvested Plantations with various Rotations

Once discounting has been applied, it is clear that the total discounted sequestration is slightly higher for the perpetual unharvested forest (the 100 year rotation), because of the earlier sequestration as shown in Figure 20. Thus while harvested plantations have higher total undiscounted sequestration, the unharvested perpetual plantation has a higher discounted sequestration (when discounted at 6% p.a.). For the harvested plantations, a local optimum appears for a rotation length of about 20 years.

Costs

Given the possible similarities in sequestration ability of harvested and unharvested plantations over an extended period, the decision about relative cost-effectiveness of the two options will depend heavily on the net costs involved in the establishment and ongoing management of the two options.

For both unharvested and harvested plantations, there are some common costs that must be incurred, including:

- Land costs
- Setup costs
- Preparation and planting
- Ongoing management costs
- Finance costs

In addition, the harvested plantations will incur extra costs for silviculture (pruning and thinning), and some extra management costs for monitoring and taking extra care of the growing trees.

On the other hand, the harvested plantations will also generate revenue from harvest which can offset some of the extra costs incurred in establishment and management.

Land Costs

Land cost can be a significant component of the total plantation cost, depending on how it is handled. There are at least five major options for obtaining land for the establishment of plantations:

Plantations on own property

A plantation can be established on property already owned by the forester. In such a case, a decision must be made as to whether the land cost is assumed to be zero (if the land was lying vacant and unused) or whether an opportunity cost must be attributed to the land (if the plantation is displacing or preventing an otherwise profitable use of the land, e.g. farming or grazing)

Plantations of donated property

A plantation could be established on land donated by a third party at no cost to the forester. An example of such a situation is where a landowner donates their land for the planting of a perpetual forest.

Plantations on bought property

If land is currently not available, it could be purchased under a variety of financial arrangements. In buying such land, a clear trade-off exists between buying less expensive land that might not support the growing of quality plantations, and more expensive land with good soil and rainfall which will support the development of a higher yield plantation.

Plantations on leased property

Rather than buying land, plantations could be established on land that is leased from the current landowner. This avoids a high up-front cost and instead requires an ongoing annual lease payment. Many farmers are happy to retain ownership of their land while at the same time obtaining a guaranteed annual income stream to supplement their other farming activities, especially if the tree planting complements their other activities by, for example, providing shade and shelter for grazing livestock.

Joint Venture Plantations

An alternative to buying or leasing land is to enter into a Joint Venture agreement with the landowner, whereby the landowner provides the land and the forester pays for the establishment and management of the plantation. In return, the landowner receives a share of the proceeds from the harvest. This avoids both the up-front costs of land purchase and the ongoing costs of land leasing, in return for surrendering some of the value of the harvest.

While all of the above methods have advantages and disadvantages, it is important for the current evaluation that the same method of obtaining land be used for both the unharvested and the harvested options, to ensure that the method of obtaining the land does not unduly influence the comparison between the two options. For the purpose of this evaluation, a leasing option (based on an annual percentage of the land value) will be used.

Setup costs

The major set-up costs in the establishment of a plantation are plantation planning costs and legal costs. While not strictly a variable cost, it is assumed that both these costs are a function of the size of the plantation.

Preparation and planting

One of the major up-front costs is the cost of establishment of the plantation. This includes the costs of weed control, vermin control, ripping and mounding (if required), supply of seedlings, and planting of the seedlings. While essentially the same processes are involved in both unharvested and harvested plantations, the cost per stem planted is typically higher for the harvested plantation, because better quality seedlings are generally used, more site preparation is required, and greater care is required in the planting (given that these plants will grow into trees which must later be removed at harvest time).

Ongoing management costs

Both unharvested and harvested plantations will have ongoing management costs, although the ongoing costs for harvested plantations will generally be higher because of the greater need for monitoring of the growth and health of the plantation. However, the unharvested plantation will also need some management to ensure a basic level of health is maintained, and to monitor and audit growth to verify the quantity of carbon that is being sequestered.

Finance costs

Both unharvested and harvested plantations will have ongoing costs to finance each venture. It is assumed that each type of venture starts with a zero financial balance, and that costs incurred must be financed by debt. That is, a loan must be taken out to finance the upfront costs and this loan will exist until income is received to pay off the loan. It is assumed that the interest rate on the loan is 5% above Consumer Price Index (CPI). If the venture uses existing funds of the organisation, then an opportunity cost will exist which is equal to the interest that could otherwise be earned on those funds (again assumed to be 5% p.a. above CPI).

Silviculture costs

Unharvested plantations will require very little in the way of silviculture, since the plantations are essentially “plant and forget”. Harvested plantations on the other hand require extensive silviculture in the form of pruning and thinning. Pruning is required to minimise the diameter of the core of juvenile wood and branch stubs, over which the clearwood will grow. Thinning is required to enable the surviving trees to grow to maximum diameter, thereby maximising the volume of clearwood. Typically thinning and pruning are conducted in three waves in the early life of the plantation, around the years 3, 5 and 7 (depending on the rate of growth of the trees). The up-front costs involved in silviculture must be more than repaid by the increase in the discounted value of the sawlogs at harvest time.

Harvest revenue

Unlike the unharvested plantation that only has costs associated with it, the harvested plantation eventually generates a revenue at harvest time (there may also be intermediate revenues from the sale of thinnings, but these have been ignored in this evaluation). The magnitude of the net revenue generated at harvest will depend on the volume and quality of the sawlogs produced, the revenue generated from other parts of the tree, the costs of harvesting, and the costs of transport to the sawmill (which will depend on access to the plantation site and distance to the sawmill on various types of road). Revenues are often quoted in net stumpage rates, which is the price paid at the sawmill door per cubic metre of wood of various types. In this study, two types of wood are considered; sawlogs which are the high quality wood in the pruned length of the tree, and residue log which is all other components of the tree apart from the sawlog. The stumpage rates quoted below are assumed to be current prices, which will continue into the future with no relative increase or decrease relative to CPI.

Costing simulation

To compare the costs of the various options, a costing simulation model has been developed (in Excel) using the following input parameters.

Table 1 Costing Model Parameters

Parameter	Unharvested	Harvested
Initial Stocking Rate	1100 sph	800 sph
Final Stocking Rate	---	250 sph
Harvest Rotation	---	20 years
Land Value	$4000/ha	$4000/ha
Annual Land Lease	$80/ha	$80/ha
Legal Fees	$10/ha	$10/ha
Planning and Setup	$20/ha	$20/ha
Annual Management	$20/ha	$70/ha
Preparation & Planting	$1.00/stem	$2.00/stem
1st Silviculture	---	$0.80/tree
2nd Silviculture	---	$1.20/tree
3rd Silviculture	---	$1.50/tree
Net Sawlog Stumpage	---	$80/m3
Net Pulplog Stumpage	---	$15/m3

Using the above parameters, a project lifetime of 100 years, a Consumer Price Index of 0% (i.e. assuming real prices, independent of inflation), a financial interest rate for repayment of loans of 5% p.a. (i.e. 5% above CPI) and a discount rate of 6% p.a., the Present Value (PV) of the costs of the unharvested plantation is $6,526/ha, while the PV of the net costs of the harvested plantation (after allowing for revenue generated by the harvest) is $1,723/ha. The PV of the harvested plantation costs is actually $9,540/ha, but this is largely offset by the PV of the harvested plantation revenue of $7,817/ha. Thus despite the higher initial costs of the harvested plantation, the revenue at harvest means that the discounted net cost of the harvested plantation is much lower than that of the unharvested plantation (using a discount rate of 6% p.a.). The discount rate would have to rise to 10% p.a. before the PV of the net costs of the two options became equal.

Cost-effectiveness

Combining the results of the previous sections on carbon sequestration and plantation costs, one can calculate the cost-effectiveness of carbon sequestration via harvested and unharvested eucalypt plantations, as shown in Table 2, assuming a discount rate of 6% p.a.

Table 2 Cost-Effectiveness of Carbon Sequestration

	Unharvested	Harvested
Tonnes CO_2/ha	337	324
Net Cost/ha	$6,526	$1,723
Net Cost/Tonne CO_2	$19.34	$5.32

While the unharvested plantation absorbs slightly more CO_2 (in discounted terms) than the harvested plantation, the much lower net cost of the harvested plantation means that the harvested plantation is much more cost-effective, with a net cost/tonne CO_2 only about 28% of that for the unharvested plantation. This higher cost-effectiveness would therefore allow about three to four times as many tonnes of CO_2 to be absorbed per dollar of investment in harvested plantations compared to unharvested perpetual plantations.

The above analysis has assumed that harvested and unharvested plantations face the same basic cost structures, with the only differences arising because of the fact that the perpetual plantations are not harvested, thus giving cheaper planting costs, lower annual management costs and no silviculture costs. Proponents of perpetual forest sequestration may rightly point out that such forests are usually established on donated land, with volunteer labour and very little maintenance and monitoring after establishment, thus leading to much lower costs. Bearing this in mind, the costing has been re-run with a zero land cost, and an annual management cost of only $5/ha (the original costing already assumes lower planting costs and zero silvicultural costs). Under the new assumptions for perpetual forests, the net cost/tonne CO_2 is reduced to $6.92, which is much more comparable with the harvested plantation cost of $5.32/tonne CO_2. However, it should also be noted that if the harvested plantation was established on zero-cost land, the net cost/tonne CO_2 would be reduced to -$2.55, (i.e. a profit of $2.55/tonne CO_2 sequestered).

Sensitivity Testing

Like many economic evaluations that rely on the discounting of costs and benefits, the results should be tested for their sensitivity to the choice of discount rate. In the results reported above, a discount rate of 6% has been used. This section will test the sensitivity of those results to the chosen discount rate.

In the current study, changes in the discount rate will affect the balance between three quantities; the present value of the carbon sequestration, the present value of the net costs, and the present value of the cost-effectiveness. In the following analyses, the CPI is maintained at 0%, while the finance rate is kept at 5% above CPI. The change in relative present values of carbon sequestration is shown in Figure 23. Below a discount rate of about 5%, the harvested plantation has a higher total carbon sequestration than the unharvested plantation. Above a discount rate of 5%, the unharvested plantation sequestration is marginally higher than the harvested plantation.

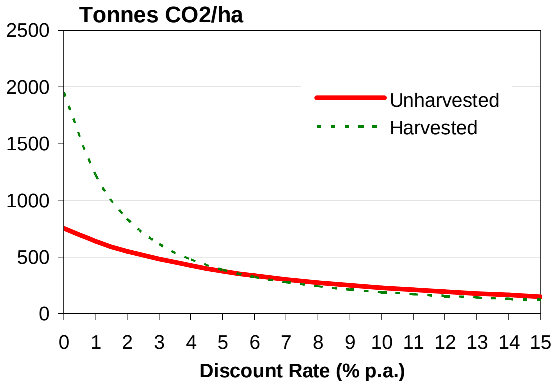

Fig 23 Sensitivity of Present Value of Carbon Sequestration to Discount Rate

The discount rate has a much greater effect on the net cost, as shown in Figure 24. Because the unharvested plantation has only costs associated with it, the net cost is always positive irrespective of the discount rate, but increasing with decreasing discount rate because the future costs of the perpetual forest (especially the financing costs) become less and less discounted. On the other hand, the harvested plantation actually has a negative net cost (i.e. a profit) below a discount rate of about 5%. This means that the Internal Rate of Return of the harvested plantation is about 5% p.a. under the assumptions tested in this evaluation. Between 5% and 10%, the present value of the net cost is positive, but lower than the unharvested plantation. At higher discount rates (above 10% p.a.) the present value of the net cost of the harvested plantation is marginally higher than that of the unharvested plantation, because the high discount rate effectively negates the revenue obtained at the end of each 20-year harvest cycle.

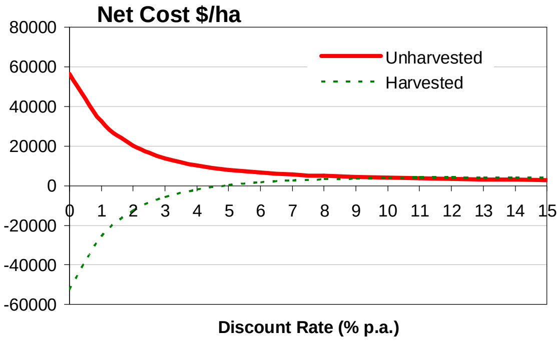

Fig 24 Sensitivity of Present Value of Net Cost of Plantation to Discount Rate

Combining these two effects, Figure 25 shows the effect of discount rate on the cost-effectiveness of harvested and unharvested plantations. Below a discount rate of 5% p.a., the perpetual forest has a very high net cost per tonne CO_2, because of the high net costs of perpetual forests when the future costs are not heavily discounted. On the other hand, below a 5% discount rate, the harvested forests make a profit while sequestering each tonne of CO_2. Above 5% discount rate, the unharvested perpetual plantation shows a relatively stable cost-effectiveness of about $20/tonne CO_2, irrespective of the discount rate. On the other hand, between 5% and 9%, the harvested plantations have a net cost per tonne of CO_2 sequestered, but the cost-effectiveness of the harvested plantations is still better than that of the unharvested plantations. Above 9%, the unharvested plantations are more cost effective. Since carbon sequestration would largely be regarded as a public sector environmental benefit, a moderate discount rate of 3-6% would probably be the most likely range for such an evaluation. In this range, the harvested plantation is relatively cost-neutral, and much more cost-effective than the unharvested plantations.

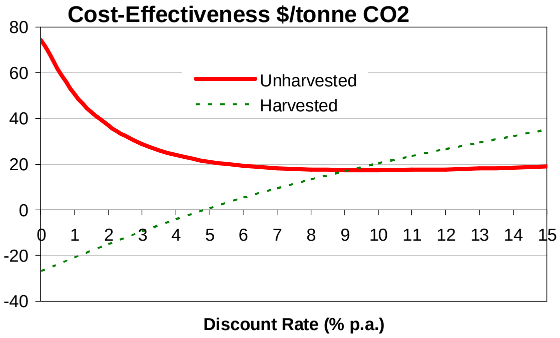

Fig 25 Sensitivity of Present Value of Cost-Effectiveness of Sequestration to Discount Rate

Conclusions

This paper has challenged the conventional assumption of plantation sequestration embodied in the Kyoto Protocol that assumes that carbon sequestered in trees is released back to the atmosphere when the trees are harvested. Drawing upon research on the retention of sequestered carbon in long-lived timber products for many years after harvesting, the paper has analysed the total carbon sequestered in unharvested perpetual forests, and in harvested plantations with varying rotation lengths. It has found that a 20-year rotation with an initial stocking rate of 800 stems per hectare and a final stocking of 250 sph produces a near optimum carbon sequestration for a harvested plantation. The total undiscounted sequestration is higher than for an unharvested plantation, but when discounted at 6% p.a., the unharvested plantation yields marginally higher rates of sequestration.

The net costs of harvested and unharvested plantations are then examined, including any revenue obtained from harvesting, and it is shown that harvested plantations are much lower net cost than unharvested plantations. Indeed, below a discount rate of 5% p.a., the harvested plantation actually makes a small profit, while the unharvested plantation always has a positive net cost.

Finally, the cost-effectiveness of harvested and unharvested plantations are compared in terms of the net cost per tonne of CO_2 absorbed from the atmosphere. At a discount rate of 6%, the harvested plantations are about three to four times more cost-effective than the unharvested plantation. At public sector discount rates of 3-6%, the harvested plantation is close to cost-neutral as a means of removing CO_2 from the atmosphere.

The results obtained from this study have demonstrated that harvested plantations can be equally effective in sequestering carbon in the long-term, and much more cost-effective in doing so. They also have the added benefit of being a lower risk option, since the sequestered carbon is stored in many forms (living trees and geographically dispersed timber products) which are not all at risk in the event of a major disaster striking the plantation.

The challenge ahead is to develop an auditing process that can monitor the carbon sequestered in timber products in a similar manner to the way in which carbon sequestered in living forests is currently measured and audited. Once such an internationally recognised method is developed, the artificial rule about harvesting that is currently embodied in the Kyoto Protocol can be removed, opening the way for more cost-effective carbon sequestration in plantations of the future.

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