Trees and Greenhouse: Costs of Sequestering Australian Transport Emissions

Working Paper

The aim of this Working Paper is to estimate the cost of reducing greenhouse emissions by using a sink rather than by reducing the amount of travel or fuel usage. Because the sink can also be applied to other sectors of the economy, it provides a standard of comparison for most policy instruments.

Bureau of Transport and Communications Economics

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TREES AND GREENHOUSE: COSTS OF SEQUESTERING AUSTRALIAN TRANSPORT EMISSIONS

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FOREWORD

In his 21 December 1992 Statement on the Environment, the then Prime Minister announced that the Bureau of Transport and Communications Economics (BTCE) would provide a comprehensive analysis of the range of possible measures for reducing greenhouse gas emissions from the transport sector.

BTCE Report 88 Greenhouse Gas Emissions from Australian Transport: Long Term Projections, published in March 1995, provided the first detailed 'base case' or 'business as usual' projections by transport mode to the year 2015. Work since then has focussed on estimating the marginal costs of reducing emissions from base case levels. Initial results for a set of policy instruments were presented at a 'work in progress' seminar in Canberra on 7 December 1995. A final report is scheduled for completion in mid-1996.

The aim of this working paper is to estimate the cost of reducing greenhouse emissions by using a sink rather than by reducing the amount of travel or fuel usage. Because the sink can also be applied to other sectors of the economy, it provides a standard of comparison for most policy instruments.

Joe Motha (team leader), Catharina Williams, and Dr Leo Dobes carried out the analysis, with valuable input from Brett Evill. Anita Scott-Murphy carried out some initial research. The BTCE is grateful for the assistance of several individuals in the forest industry, including Bob Boardman (Primary Industries, South Australia, Forestry) and Marcia Lambert (Research Division, State Forests of NSW). Useful comments on a draft of the working paper were provided by Dr Ross McMurtrie (School of Biological Science, University of New South Wales) and Professor Christopher Adam (Department of Management Studies, Graduate School of Business, The University of Sydney). The manuscript was edited by Belinda Jackson.

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April 1996

ABSTRACT

Forestry is an alternative to policy instruments designed to reduce greenhouse emissions through reductions in the amount of transport fuel used. This study estimates the marginal costs of sequestering all or parts of the carbon emitted by the Australian transport sector for the years 2000, 2005, 2010 and 2015. Based on a 'steady state' equilibrium approach of perpetual generic tree plantations whose growth characteristics are similar to *Pinus radiata*, the analysis takes account of thinnings and carbon stored in tree roots, distinguishes decay rates of three broad categories of wood product, and uses previously unpublished data on land costs. The cost estimates may be used as a 'benchmark' opportunity cost in assessing the cost-effectiveness of abatement policies such as carbon taxes or mandated introduction of technology. The results indicate that the marginal cost of carbon dioxide absorbed in the year 2000 is $1.76 per tonne, rising to $5.18 per tonne in the year 2015.

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...AT A GLANCE

AIM

Permanent reclamation of carbon dioxide by wholesalers of fossil fuels used in the Australian transport sector.

KEY FEATURES OF THE ANALYSIS

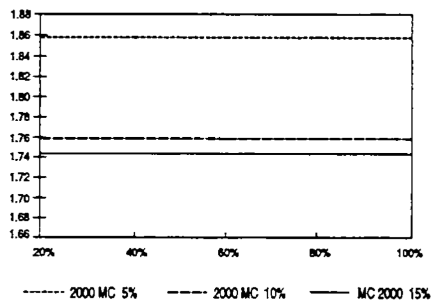
- Proposes new policy instrument—not proposed or analysed before from the perspective of the transport sector.
- Takes account of the varying productivity and cost of land for forestry in Australia.
- Takes account of carbon stored in thinnings, roots, soil and foliage in addition to merchantable wood.
- Separate decay rates used for three different classes of wood products.
- Takes into account potential revenue from the sale of timber.

RESULTS

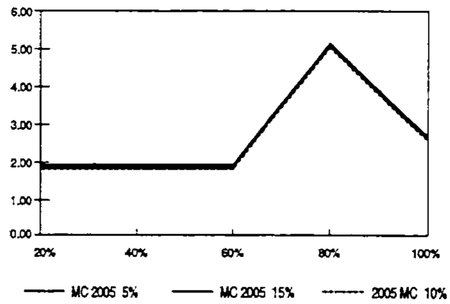
The following figures show marginal costs for the years 2000, 2005, 2010 and 2015 in 1996 dollars.

This instrument represents a relatively low cost means of sequestering carbon. The marginal cost (MC) of carbon dioxide absorbed in the year 2000 is $1.76 per tonne, rising to $5.18 per tonne in the year 2015. The graphs show marginal costs at discount rates of 5, 10 and 15 per cent.

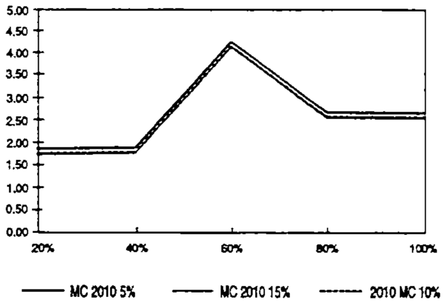
MARGINAL COSTS OF CARBON SEQUESTRATION—2000



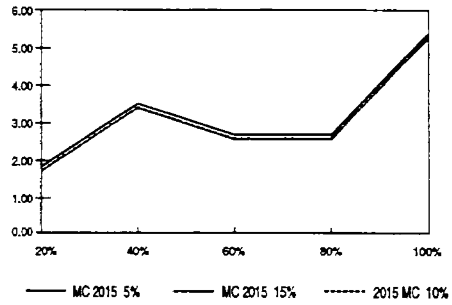
MARGINAL COSTS OF CARBON SEQUESTRATION—2005



MARGINAL COSTS OF CARBON SEQUESTRATION—2010



MARGINAL COSTS OF CARBON SEQUESTRATION—2015



BACKGROUND

An alternative to reducing emissions from fossil fuels used by vehicles is the use of a 'sink' to recover carbon dioxide (CO2) emissions after combustion is completed. Where the cost of reclaiming emissions is borne by the user of the fuel, this alternative effectively becomes a 'polluter pays' instrument of greenhouse gas abatement.

It is assumed that federal Government legislation requires wholesalers of all fossil fuels used domestically in vehicles to reclaim the CO2 emitted. Because the reclamation requirement is assumed to be permanent, the policy instrument is not merely one of 'buying time', like many other tree planting scenarios examined in contemporary greenhouse studies.

The concept is analogous to the German Duales System which requires supermarkets to accept for recycling the packaging in which their goods are sold. In the case of CO2 emissions, the carbon content can be considered as 'packaging'.

Wholesalers could reclaim CO2 emissions through a range of measures which include pumping CO2 under the ocean or into oil wells, planting trees, storing it in tanks, or freezing it. Ormerod et al (1993) indicate that planting trees is a relatively low cost option. While the many individual end users of the fuels could also be required to reclaim the carbon, it has been assumed that overall transactions costs are minimised by imposing the obligation on wholesalers.

Given the relatively large area of land available for planting trees in Australia, and because tree plantations yield revenues that can be set off against the cost of reclaiming carbon, it has been assumed in this study that wholesalers of fossil fuels would choose forestry as a least cost option to reclaim CO2 in fulfilment of Government requirements. An implicit assumption is that wholesalers will have a greater incentive to minimise net costs than a government run forestry program. Wholesalers are assumed to plant a relatively fast growing species, such as Pinus radiata (P. radiata), to sell the stem wood and to manage the plantations on a commercial basis.

A tree planting instrument is particularly attractive in Australia because it complements Government reforestation initiatives to reduce land degradation. Where plantation softwoods are a substitute for native hardwoods, the instrument could also complement Government policy to limit the logging of 'old growth' native forests.

It may be appropriate for the community (through the Government) to pay the fuel wholesalers for spin-off social benefits produced by their plantations. This aspect has not been considered in this study because such payments are currently not normal in other commercial operations. Benefits such as improved water quality, reduced soil erosion, species protection and enhanced biodiversity would also not be fully realised under conditions of periodic harvesting.

There are several options for the use of wood produced in plantations. Mature trees could be left standing in a forest, but the amount of carbon sequestered would be a one-off increase. The stored carbon would eventually be released into the atmosphere as the forest ages and decays. Hence, the sequestration of carbon could be increased only by planting more land.

Many studies that examine forestry as an option for creating a carbon 'sink' analyse wood only in terms of its decay rate (and hence storage time for carbon). However, the use of wood as a renewable source of energy would permit substitution for fossil fuels. To the extent that less fossil fuel is used, firewood represents an 'opportunity benefit' in terms of greenhouse mitigation. The fossil fuel saved is the true measure of the contribution of forestry. There has recently been a renewed interest in coppicing as a means of increasing the rate at which biomass can be generated for use as fuel (Read 1994). Coppicing is the felling of mature trees to leave short stumps from which new shoots, nourished by a mature root system, are rapidly produced.

An increased availability in Australia of softwood such as P. radiata is likely to be reflected in increased opportunities for substitution of wood for concrete and steel, particularly in flooring and frames of residential buildings. Concrete and steel production require fossil fuel inputs, and production of concrete itself produces CO2. Substitution of wood for concrete and steel would therefore indirectly sequester carbon to the extent of any fossil fuel not used. For example, Maclaren (1994, p. 14) cites estimates by Honey and Buchanan (1992) indicating that 59 GJ of energy is required to manufacture one tonne of structural steel compared with only 2.4 GJ per tonne of treated timber.

Potential substitution of wood for fossil-intensive fuels or other products was not analysed in this study. To do so satisfactorily would require a detailed carbon budgeting approach taking into account, among other things, the precise extent of substitutability and related energy usage, including fossil fuel used to transport raw material inputs and final products. A 'program' analysis of this sort was beyond the scope and intent of the current study.

METHODOLOGY

The amount of carbon that will be emitted from fuel used in transport in any year up to 2015 is known from base case projections of CO2 emissions reported in BTCE (1995).

In practice, fuel is not completely oxidised into CO2, but methane (CH4) and carbon monoxide (CO) break down on average within 11 years and 3 months respectively into CO2. For example, in 1996, 68.5 million tonnes of CO2 are expected to be emitted from domestic transport on a fully oxidised basis (BTCE 1995, appendixes VIII to XI), so that the amount of carbon emitted will be 18.7 million tonnes [{12/(12+16+16)}*68.5 where 12 and 16 are the atomic weights of carbon (C) and oxygen (O) respectively].

Knowledge of the amount of carbon that can on average be sequestered per ha by a pine plantation that is continually harvested and replanted in perpetuity permits estimation of the land area required to be planted to offset all or part of the CO2 emitted in a given year. Estimation of the costs associated with establishing and maintaining successive plantings provides sufficient information to calculate the marginal cost of sequestering carbon.

The sense in which the term 'marginal cost' is used in this study is somewhat different from its traditional meaning in economics. In this study, marginal costs refer to the costs of sequestering increments of 20 per cent of CO2 emissions in a given year divided by the corresponding quantities of CO2 sequestered. Specifically, the marginal costs estimated in this study are the additional costs of sequestering zero to 20 per cent, 20 per cent to 40 per cent, 40 per cent to 60 per cent, 60 per cent to 80 per cent and 80 per cent to 100 per cent of emissions in each of the years 2000, 2005, 2010 and 2015. The specification of marginal costs in this manner makes it possible to compare the costs of the policy at levels of intensity varying from 20 per cent to 100 per cent of emissions in 20 per cent increments in any of the selected years. To permit comparisons of marginal costs over time, and against other abatement instruments, all costs have been discounted at 10 per cent to provide present values in 1996 dollars.

Over a long period, a natural, unharvested (old growth) forest may be assumed to reach a state of equilibrium where the total amount of wood or carbon per unit area is, on average, constant. In this 'steady state' equilibrium, the rate of growth (addition to the stock of wood) and the rate of decay (depletion of wood) would be equal.

A natural forest comprises trees of different ages. In the case of plantations, individual annual plantings involve trees of identical ages, but the total plantation estate can be considered a forest of trees of mixed ages. Whereas trees in a natural forest will die at a biological limit, it has been assumed that the trees in a plantation estate will be harvested at 35 years of age, with immediate replanting of the land. The concept is most easily explained in figure 1 which shows plantation strips of one ha, with each strip containing trees of uniform age. Taking all the strips together, even in a different sequence to that shown in figure 1, results in a 'natural' mix of tree ages.

The fact that timber is harvested, and that it decays in locations away from the forest (for example, as paper), does not preclude envisaging the estate as a mixed-age natural forest. The difference between a natural mixed age forest and a forest in a 'steady state' is that the steady state amount of carbon sequestered at any point in time over a plantation estate may be higher than in a natural forest. In particular, the rate of decay of timber derived from a plantation is slower because timber stored as frames of houses, for example, decays more slowly than a log exposed to the elements in the forest. Further, commercially grown plantation timber is often cut roughly at the time of greatest average growth rate rather than being permitted to grow more slowly to maturity. A greater amount of carbon is thus 'harvested' over time in plantations.

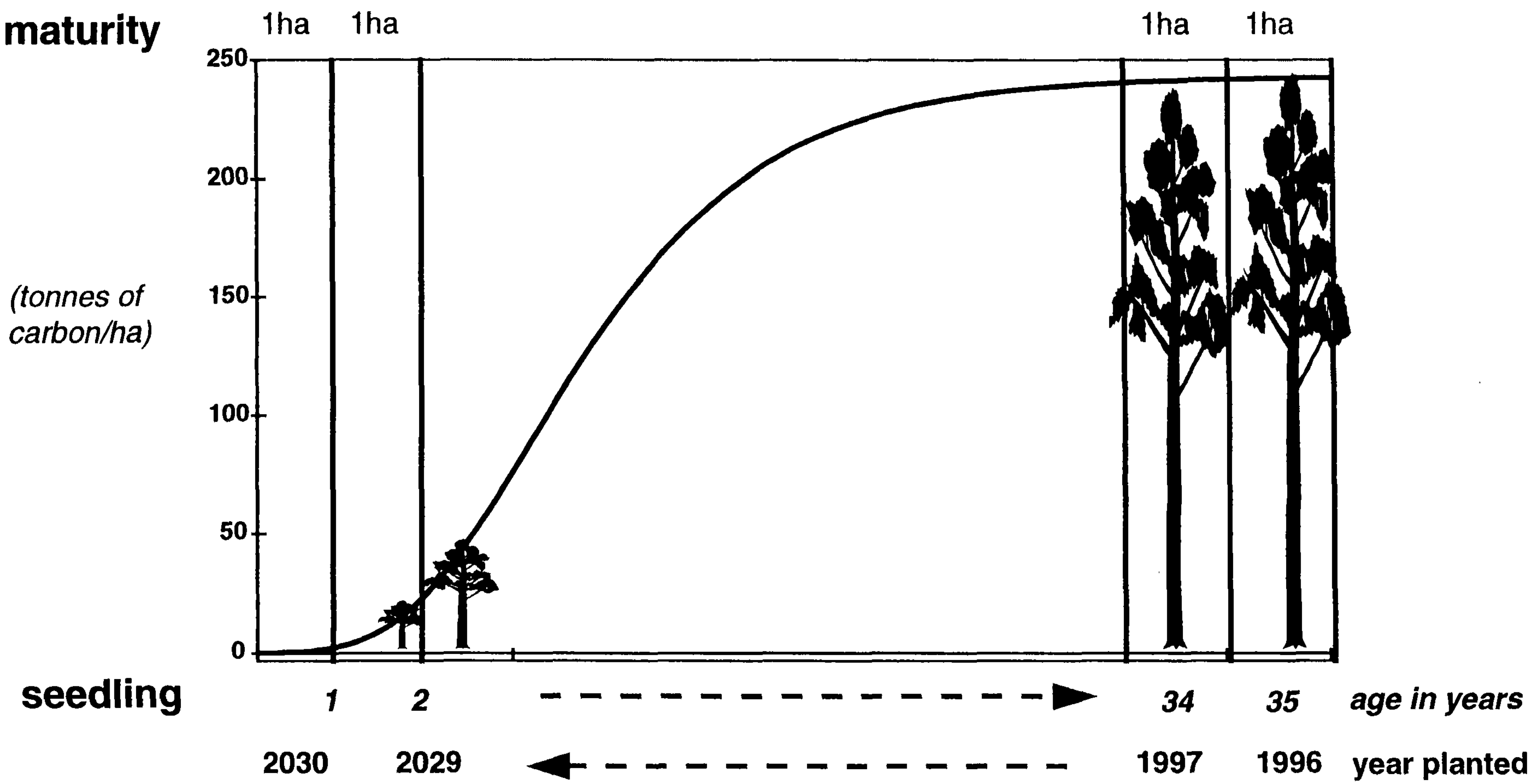
Carbon sequestration in standing timber

Figure 1 illustrates the sequestration of carbon in standing timber. The estate shown is assumed to be a species with growth characteristics similar to *P. radiata* harvested when 35 years old. At the end of the year 2030, the largest trees (planted in 1996) are harvested. The '1996' area is replanted during 2031. A new area is also planted in that year to soak up emissions from fuel used in 2031. At the end of 2031, the '1997' plantation is harvested; it is replanted in 2032 and a new plantation for year 2032 emissions is planted at the same time.
Therefore, in practice, the total area of the plantation estate will need to expand each year (to the extent of land availability) because of the assumption that fuel wholesalers are required by the Government to permanently reclaim some or all of the CO_2 emitted each year.
Several authors observe a lack of consensus among foresters about the best form of a mathematical function to describe tree growth, possibly because of the lack of data and limited understanding of the growth process (Zeide 1993, Clutter et al 1983, Leech & Ferguson 1981). Appendix I describes and discusses various mathematical functions that have been used, or considered for use, in modelling tree growth. However, Zeide (1993, p. 604) shows that all but the Weibull equation can be reduced to one of two basic growth functions, differing essentially in only the decline component. Because of its mathematical tractability, and the fact that it is used by a number of researchers, the Gompertz function was adopted in this study to describe the yield of a plantation estate over time. Its form may be expressed as

$$V = V_m e^{-be^{-kt}} \qquad (1)$$

where V is the volume or weight of wood or carbon, V_m is the maximum or saturation level of V, t is time and b and k are constants.

FIGURE 1 SEQUESTRATION OF CARBON IN PLANTATIONS



Source BTCE estimates

At any point in time the average stock of carbon sequestered per ha in a plantation estate that accords with this yield function is given by

$$V_m \frac{\int_{t=0}^{t_n} e^{-be^{-kt}} dt}{t_n} \qquad (2)$$

where t_n is the rotation period or time between successive harvests.

The rotation period was taken as 35 years and the carbon sequestered (V) in a 35 year old *P. radiata* plantation was conservatively taken as 243 tonnes per hectare (ha) (R. Boardman, pers. comm. 9 October 1995). The possible growth enhancing effect on trees of increased concentrations over time of atmospheric CO_2 has not been taken into account in this study. This CO_2 'fertilisation' effect is not presently well understood (appendix V).

Summation of carbon mass per ha for each year from planting to harvesting, divided by 35, produced an average amount sequestered at any point in time of 176 tonnes of carbon per ha for the plantation estate as a whole. Unfortunately, data were not available to permit full, independent estimation of the parameters of the Gompertz function. It was necessary to assume that the 35-year value of 243 tonnes per ha (assuming that the point of inflection of the Gompertz yield curve occurs when the forest is eight years old) was equivalent to the saturation level V_m, giving values of b=8.49 and k=0.27.

P. radiata will not grow well on all the land considered in this study (appendix IV). In some areas, planting of other types of pine would be necessary and there may also be areas that would have to be planted with species other than pine. This study therefore effectively assumes the planting of generic trees whose productivity approximates that of *P. radiata*.

The productivity of land for generic tree plantations with similar growth characteristics to *P. radiata* varies widely across Australia. The analysis took account of this to a limited extent by classifying land into four groups and applying two different yield values to them (appendix IV). The productivity of 243 tonnes per ha was assigned to land with medium plantation capability and low or medium agricultural intensity because it was based on yield class 3 in South Australia (R. Boardman pers. comm. 9 October 1995). Based on data in yield tables (Lewis, Keeves & Leech 1976), a 14 per cent premium was added to land with high plantation capability and low or medium agricultural intensity resulting in a productivity of 277 tonnes per ha. These two levels of land productivity were matched with a range of land costs to generate a planting order of different areas of land in each state and territory (see appendix IV for details).

Decay of wood products

Decay occurs according to the standard formula

$$V_t = V_f\, e^{-\gamma t} \qquad (3)$$

giving

$$\frac{dV_t}{dt} = -\gamma V_f e^{-\gamma t} \qquad (4)$$

where V_f is the stock of wood or carbon at the time the forest is felled, and V_t is the stock at any time t

so that

$$\frac{1}{V_t} \cdot \frac{dV_t}{dt} = -\gamma \qquad (5)$$

Therefore, the proportionate rate of decay at any time is given by the constant γ and indicates the proportion of a product that decays per year.

Decay is normally expressed in terms of half lives, so that $V_t/V_f = 1/2$ and substituting this in equation (3) yields

$$e^{-\gamma t} = 1/2 \qquad (6)$$

from which

$$\gamma = 0.693/t \qquad (7)$$

where t is in half-life values.

If t=1 (assumed below in the case of short-lived products such as paper), then γ=0.69. Therefore, almost 70 per cent of paper will decay during the course of the first year after harvesting; and a further 70 per cent of the remaining 30 per cent will decay during the second year, and so on.

The 'steady state' equilibrium approach

The concept of a 'steady state' involves the assumption that the forest is replenished at the same rate as it decays. This assumption means that the annual addition to the wood stock (average rate of growth of the forest) equals the annual rate of decay.

It has also been assumed in this study that the wood stock can be classified into three products which decay at different rates after harvesting, so that

$$\gamma_i . S_i = p_i . A \qquad (8)$$

where p_i is the fraction of wood product i (i = 1,2,3), S_i is the stock of product i per ha at any time, γ_i is the decay constant for p_i at any time and A is the average annual growth rate per ha of the forest at any time ($A = V_m/t_n$).

The total carbon sequestered in harvested, but non-decayed wood products is given by

$$\sum_{i=1}^{3} S_i = \sum_{i=1}^{3} \frac{p_i . A}{\gamma_i} \qquad (9)$$

Following the general approach of Maclaren and Wakelin (1991), it has been assumed that the generic trees grown form three product fractions: short life (for example, paper products), medium life (for example, particle board) and long life (for example, timber used in building construction). Having examined available data on the uses of softwood (appendix II), these fractions were assumed to form 47, 29 and 24 per cent of the total biomass (p_1=0.47, p_2=0.29, p_3=0.24) with half lives of 1, 5, and 10 years respectively. Their respective decay constants (γ) are therefore 0.69 (0.69/1); 0.14 (0.69/5); and 0.07 (0.69/10).

Thus the average per ha stock of undecayed biomass is

$S_1 + S_2 + S_3 = 4.7 + 14.5 + 24.0 \approx 43$ tonnes per ha

The total amount of carbon sequestered at any time in a steady state plantation estate is the sum of the carbon contained in (live) standing trees, as well as the undecayed stock of biomass and wood products derived from harvested timber, (equation (2) plus equation (9)). This sum was taken as 176 tonnes per ha in standing timber and 43 tonnes per ha in undecayed wood product, totaling 219 tonnes per ha.

A steady state equilibrium situation will only be attained after many years. However, the steady state carbon content of 219 tonnes per ha has been applied in this analysis to carbon sequestered in the period 1996 to 2015. Therefore, the approach assumes that the steady state quantity of C is attained much sooner than would actually occur. The implications of this assumption are the overestimation of the amount of carbon sequestered over the period 1996–2015 and the underestimation of the total and marginal costs per tonne of carbon sequestered. However, over the longer term, this limitation would be less relevant because plantations are assumed to be kept under forest in perpetuity.

This study does not consider possible changes in soil carbon storage associated with forest clearing, reforestation and fire practices. It was considered that the uncertainties involved in terms of current knowledge were too great to generate reliable figures. However, it is likely that a commercial wholesaler of fuel forced by the Government to maximise sequestration of carbon would implement plantation methods that minimised soil disturbance in order to be able to claim a greater amount of carbon sequestration.

Costs and revenues of plantations

Foresters recognise at least four different types of rotation (Kula 1988):

- technical rotation refers to the point in time when the plantation meets the specification of a given market (for example veneer logs, saw logs, pulp wood);
- rotation for maximum volume production occurs when the mean annual increment is at its maximum;
- rotation for natural regeneration is determined by the age at which maximum viable seed is produced;
- financial rotation is the period which produces the maximum discounted net revenue.

Growth and yield cycles for plantations are often illustrated in the literature (for example, Clutter 1983) in terms similar to figure 2. Maximum harvestable volume occurs at point *C*, just before senescence. Maximum annual growth rate occurs at point *A*, after which the annual rate of growth slows. At point *B*, where a ray drawn from the origin would be tangential to the yield curve, the average rate of growth is at a maximum. None of these points is necessarily economically optimal for harvesting.

The economically optimum range for harvesting usually lies between points *A* and *C*. The economic objective is to maximise the net present value of revenue per ha per year. This objective is achieved when the rate of change in the value of the forest just equals the opportunity cost (rate of return) of capital invested. If a zero discount rate is applied, the optimum rotation would generally correspond to the point where maximum biomass is obtained (point *C*). Maintaining the plantation involves a cost in the form of the forgone interest on the revenue that could be earned by selling the timber. Therefore, if a positive discount rate is applied, harvesting should occur before maximum biomass is attained.

However, when further rotations are to be implemented, there is an additional opportunity cost involved in postponing the harvesting of the current stock, because of the potential returns from future harvests (RAC 1992, p. Q4). Consequently, in the case of continual rotations, it is necessary to take account of the relatively faster growth that occurs during the early part of each rotation. The maximum yield per ha per year occurs when the average rate of growth is at a maximum (point *B*). Hence, when a positive discount rate is applied, the optimal economic rotation would be reduced, and would correspond to a point to the left of *B* such as *D*.

The use of a single cycle is not the correct approach for calculating the net present value (NPV) for a project of long duration that can be replicated in perpetuity. In a review of the issue, Samuelson (1976) points out that even eminent economists such as Hotelling, Fisher and Boulding have erroneously used the single-cycle approach instead of a steady state equilibrium of indefinite replantings.

The formula used to calculate the present value of an infinite cycle of planting and harvesting over a 35 year rotation is

$$PVS = (PVC + V_l) + \frac{PVC}{(1+r)^{35} - 1} \tag{10}$$

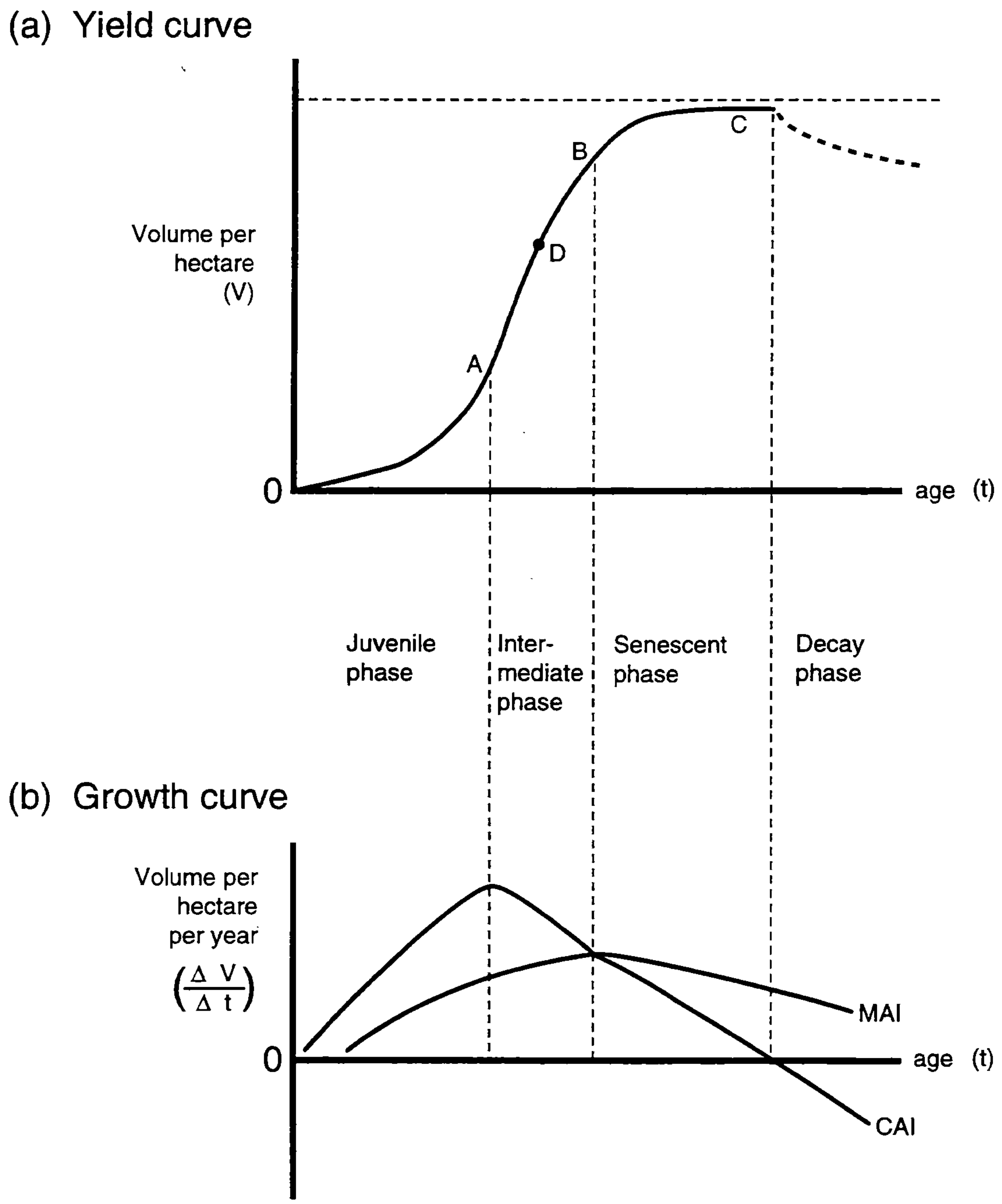
where *PVS* is the net present value of the infinite cycle of planting, *PVC* is the net present cost of a single cycle (establishment and annual recurring costs minus revenue from stumpage), V_l is the value of land (purchase price per ha) and *r* is the rate of interest (see appendix VI for details of the derivation of equation 10).

Because the policy instrument is cast in terms of fuel sellers effectively claiming credit for carbon sequestered in terms of both standing timber and in terms of undecayed product, it is arguable that revenues and costs should take into account the process of turning trees into timber products. If this view is accepted, then a full carbon budgeting analysis should be conducted, including costs and emissions involved in delivery of wood products to final consumers.

However, it is equally arguable that inclusion of downstream effects such as transport of wood products would risk double counting and circularity in analysis. The partial equilibrium analysis adopted in this study was chosen to permit comparisons of a carbon 'sink' with other policy instruments. Afforestation is intended as a sink for all transport emissions, including those arising from transport of wood products, and their effects would be reflected in a marginally greater number of trees planted.

Establishment and recurring costs of planting were derived from RAC (1992) and are set out in appendix III. To compensate for the expected decline in land productivity over many planting cycles, it was assumed that land preparation and fertilising costs of $465 (N. Byatt, ACT Forests, pers. comm. 21 November 1995) were incurred at the beginning of each 35 year cycle after the first cycle (that is, excluding the first cycle).

FIGURE 2 YIELD AND GROWTH CURVES



A = INFLECTION POINT $\left(\frac{d^2V}{dt^2} = 0\right)$

B = OPTIMAL HARVESTING AGE IN TERMS OF PHYSICAL PRODUCT (YIELD)

C = MAXIMUM BIOLOGICAL YIELD $\left(\frac{dV}{dt} = 0\right)$

MAI = MEAN ANNUAL INCREMENT

CAI = CURRENT ANNUAL INCREMENT

Source BTCE.

Land costs are normally excluded from greenhouse studies involving forestry instruments, mainly because of the lack of suitable data. However, unpublished data on land suitable and available in each state and territory purchased from Commonwealth Scientific and Industrial Research Organisation (CSIRO) were used in this study. Values of land suitable for softwood plantations in Australia were estimated from information provided by the Valuer General's offices in each state and territory, forestry authorities and other sources. Data on land values are presented in appendix IV.

The stumpage (trees sold as standing crop) value used in this study was $32 600 per ha. This value was derived by adjusting the stumpage value in RAC (1992) to 1996 dollars using timber price indexes (ABARE 1994).

Arguments are sometimes advanced in the literature for low discount rates of around 3-5 per cent to be applied to forestry on the basis that it is a long term investment. For example the Forestry Commission in Britain was required to apply a discount rate of 3 per cent in real terms in evaluating forestry projects (HMSO 1972). Nevertheless, normal investment analysis should apply to forestry because it is no different to any other investment that uses scarce resources. This view is supported by authors like Samuelson (1976) and Price (1976). Price (1976) observes that economists might argue that the long growing period increases uncertainty, thus requiring a more stringent test of viability. As the instrument analysed in this study relates to forestry investment by petroleum wholesalers on a commercial basis, a rate of discount of 10 per cent has been applied. The results were also tested for sensitivity to discount rates of 5 and 15 per cent.

Planting order

A planting order for land available for *P. radiata* plantations in Australia was derived using both yield data and a range of land values for each state and territory. Appendix IV describes the procedure adopted to derive the planting order.

Table IV.6 (appendix IV) sets out the planting order used. The land in the table is arranged in ascending order of cost per tonne of carbon sequestered, from the lowest to the highest.

RESULTS

Land required to absorb transport emissions

Table 1 sets out the areas of land required to be planted in perpetuity to absorb various proportions (in 20 per cent increments) of transport emissions in each year from 1996 to 2015. The base case transport emissions in the table are derived from BTCE (1995) and represent emissions from transport in a 'business as usual' scenario (that is, without the implementation of any policies intended to affect the use of transport). The last row of the table represents the estimated total area of land (in '000 ha) required to absorb varying proportions of transport emissions between 1996 and 2015.

TABLE 1 LAND AREA REQUIRED TO ABSORB 20 PER CENT INCREMENTS OF BASE CASE TRANSPORT EMISSIONS

Year	Proportion of base case emissions	Land required ('000 hectares) 20%	40%	60%	80%	100%	Base case transport emissions (million tonnes of C)
1996		17.58	35.15	52.73	70.31	87.89	19.27
1997		17.91	35.82	53.74	71.65	89.56	19.63
1998		18.26	36.51	54.77	73.03	91.28	20.01
1999		18.60	37.20	55.80	74.40	93.01	20.39
2000		18.95	37.90	56.85	75.80	94.75	20.77
2001		19.32	38.64	57.96	77.28	96.60	21.18
2002		19.70	39.39	59.09	78.79	98.48	21.59
2003		20.07	40.14	60.21	80.29	100.36	22.00
2004		20.43	40.86	61.29	81.72	102.15	22.39
2005		20.83	41.65	62.48	83.30	104.13	22.83
2006		21.23	42.47	63.70	84.94	106.17	23.28
2007		21.65	43.30	64.95	86.60	108.25	23.73
2008		22.07	44.14	66.22	88.29	110.36	24.19
2009		22.48	44.96	67.44	89.93	112.41	24.64
2010		22.92	45.84	68.76	91.67	114.59	25.12
2011		23.39	46.79	70.18	93.58	116.97	25.64
2012		23.86	47.73	71.59	95.46	119.32	26.16
2013		24.35	48.69	73.04	97.39	121.73	26.69
2014		24.84	49.69	74.53	99.38	124.22	27.23
2015		25.40	50.80	76.20	101.60	127.00	27.84
Total 1996–2015		423.85	847.70	1271.54	1695.39	2119.24	464.59

Source BTCE estimates.

Total and marginal costs of carbon sequestration

Costs were calculated on the basis of land and trees required to absorb varying proportions of total base case transport emissions in each year, beginning with 20 per cent and proceeding in increments of 20 per cent (that is, 20, 40, 60, 80 and 100 per cent of base case emissions). This approach permits calculation of marginal costs at varying levels of application (intensity) of the instrument. Marginal costs per tonne of carbon absorbed have been calculated for each of four years (2000, 2005, 2010, 2015). Tables 2 to 5 show marginal costs for each year.

TABLE 2 COSTS[a] AND EMISSION REDUCTIONS FOR THE YEAR 2000

Per cent of base case emissions	*Land required ('000 hectares)*	*Emission reduction (million tonnes carbon)*	*Total cost ($ million)*	*Marginal cost ($ per tonne of CO_2 absorbed)*
20	18.95	4.15	26.8	1.76
40	37.90	8.31	53.6	1.76
60	56.85	12.46	80.4	1.76
80	75.80	16.62	107.3	1.76
100	94.75	20.77	134.0	1.76

a. Costs are in 1996 dollars discounted at 10 per cent.

Source BTCE estimates.

TABLE 3 COSTS[a] AND EMISSION REDUCTIONS FOR THE YEAR 2005

Per cent of base case emissions	*Land required ('000 hectares)*	*Emission reduction (million tonnes carbon)*	*Total cost ($ million)*	*Marginal cost ($ per tonne of CO_2 absorbed)*
20	20.83	4.57	29.4	1.76
40	41.65	9.13	58.8	1.76
60	62.48	13.70	88.2	1.76
80	83.30	18.26	171.7	4.99
100	104.13	22.83	214.5	2.56

a. Costs are in 1996 dollars discounted at 10 per cent.

Source BTCE estimates.

TABLE 4 COSTS[a] AND EMISSION REDUCTIONS FOR THE YEAR 2010

Per cent of base case emissions	*Land required ('000 hectares)*	*Emission reduction (million tonnes carbon)*	*Total cost ($ million)*	*Marginal cost ($ per tonne of CO_2 absorbed)*
20	22.92	5.02	32.4	1.76
40	45.84	10.05	65.5	1.79
60	68.76	15.07	141.8	4.14
80	91.67	20.10	189.2	2.57
100	114.59	25.12	236.3	2.56

a. Costs are in 1996 dollars discounted at 10 per cent.

Source BTCE estimates.

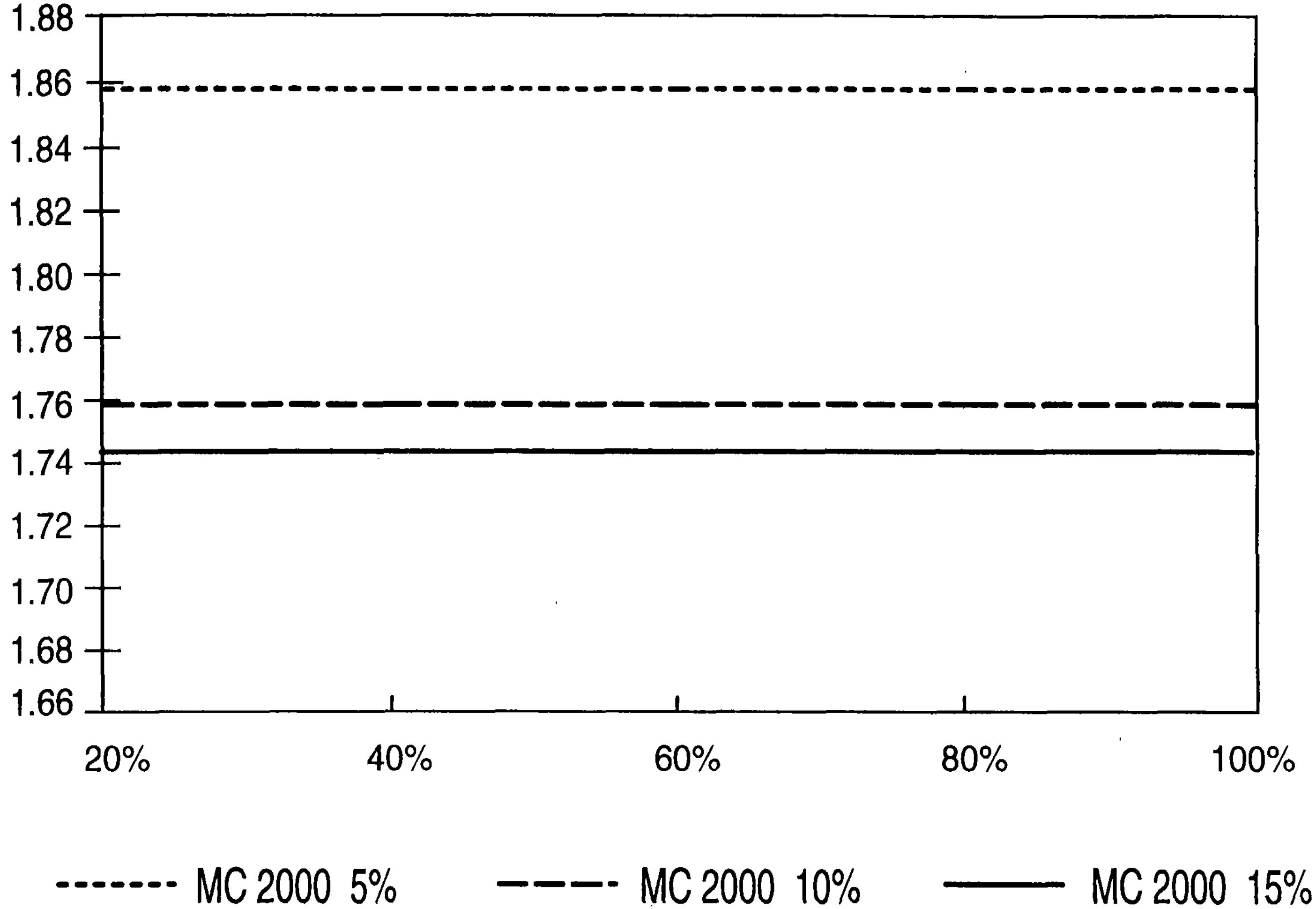
TABLE 5 COSTS[a] AND EMISSION REDUCTIONS FOR THE YEAR 2015

Per cent of base case emissions	*Land required ('000 hectares)*	*Emission reduction (million tonnes carbon)*	*Total cost ($ million)*	*Marginal cost ($ per tonne of CO_2 absorbed)*
20	25.40	5.57	35.9	1.76
40	50.80	11.14	104.8	3.37
60	76.20	16.71	157.1	2.57
80	101.60	22.27	209.6	2.57
100	127.0	27.84	315.3	5.18

a. Costs are in 1996 dollars discounted at 10 per cent.

Source BTCE estimates.

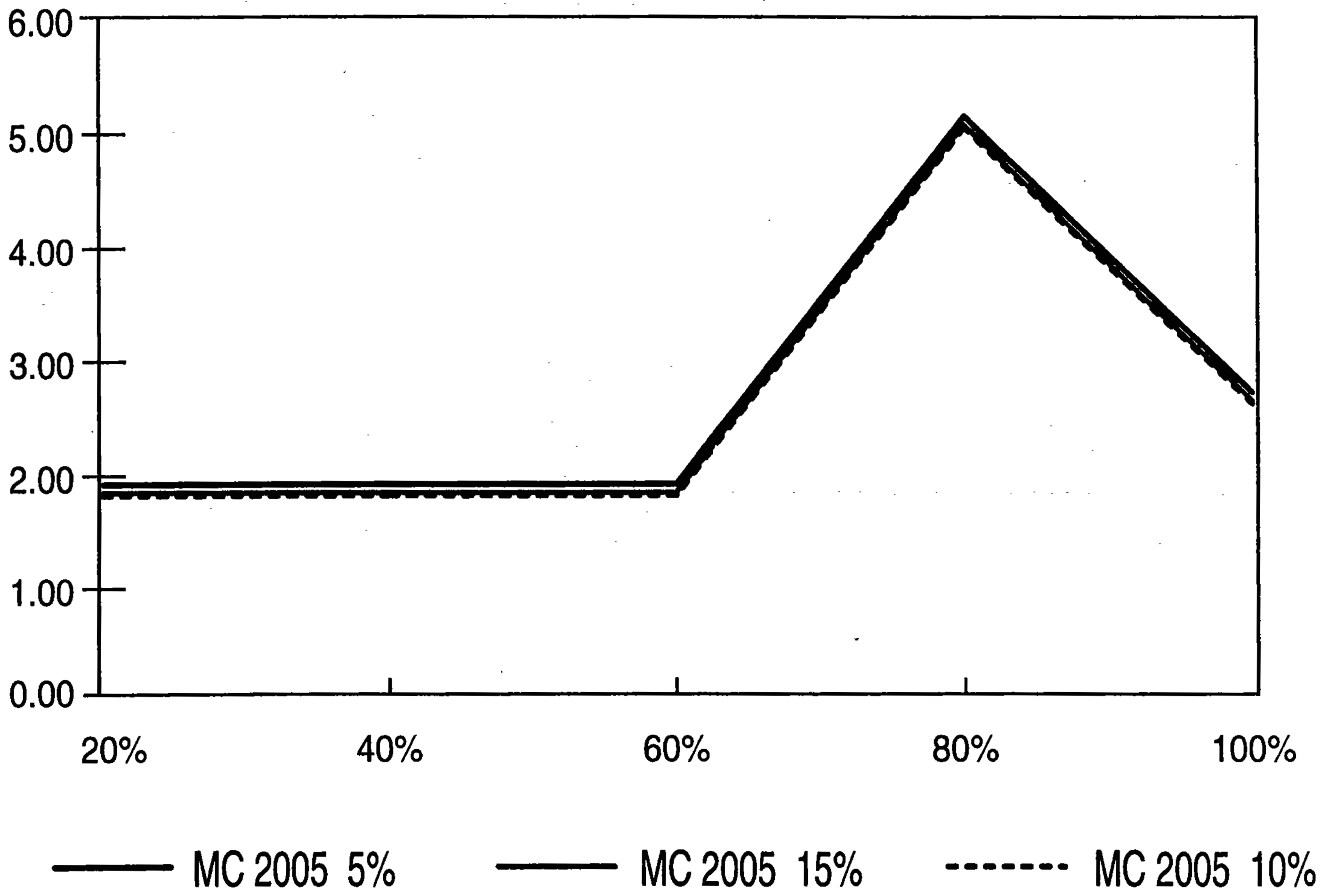
FIGURE 3 MARGINAL COSTS OF CARBON SEQUESTRATION IN THE YEAR 2000



Note Each line represents marginal costs in $1996 at a different discount rate.

Source BTCE estimates based on data from various sources.

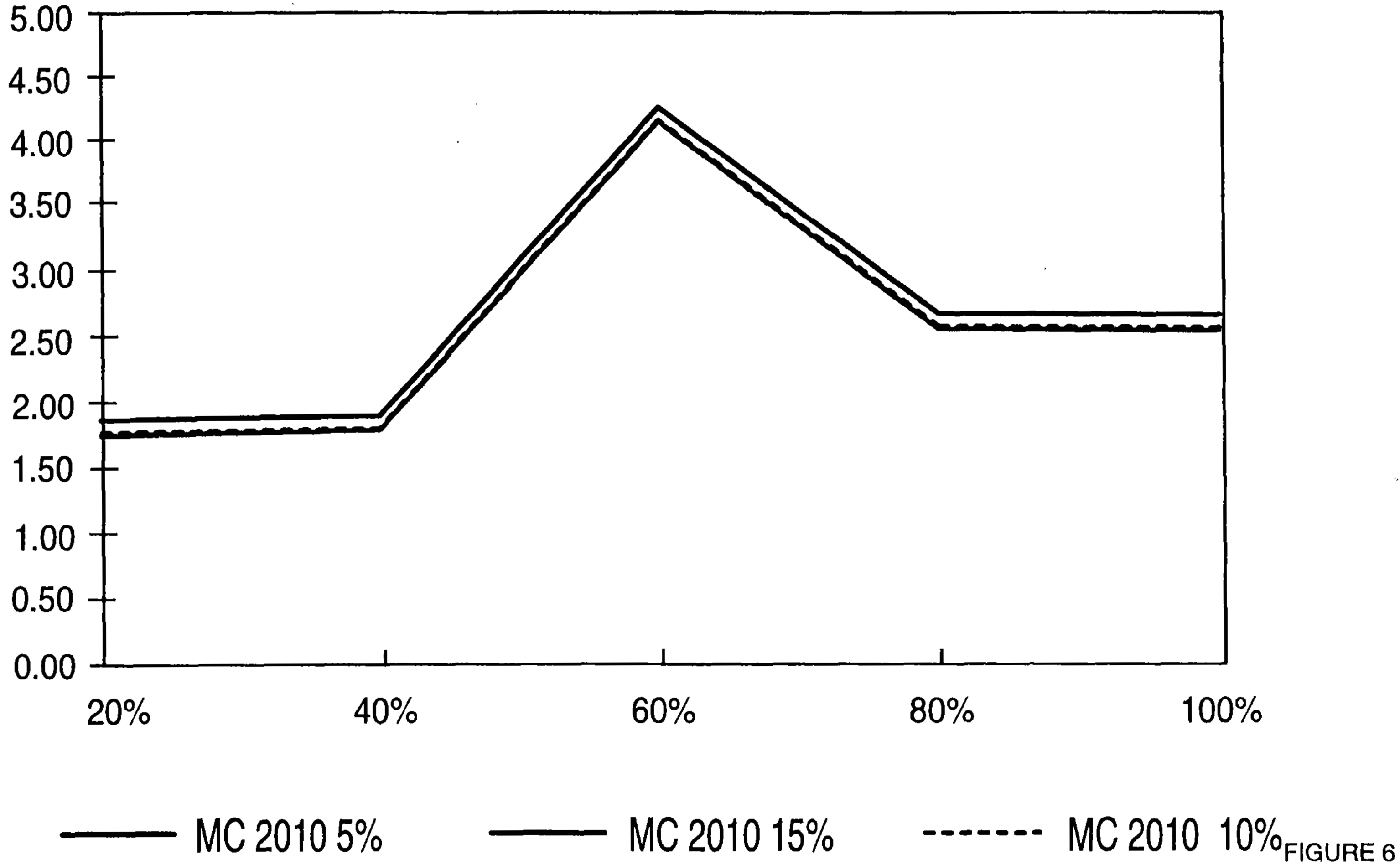
FIGURE 4 MARGINAL COSTS OF CARBON SEQUESTRATION IN THE YEAR 2005



Note Each line represents marginal costs in $1996 at a different discount rate.

Source BTCE estimates based on data from various sources.

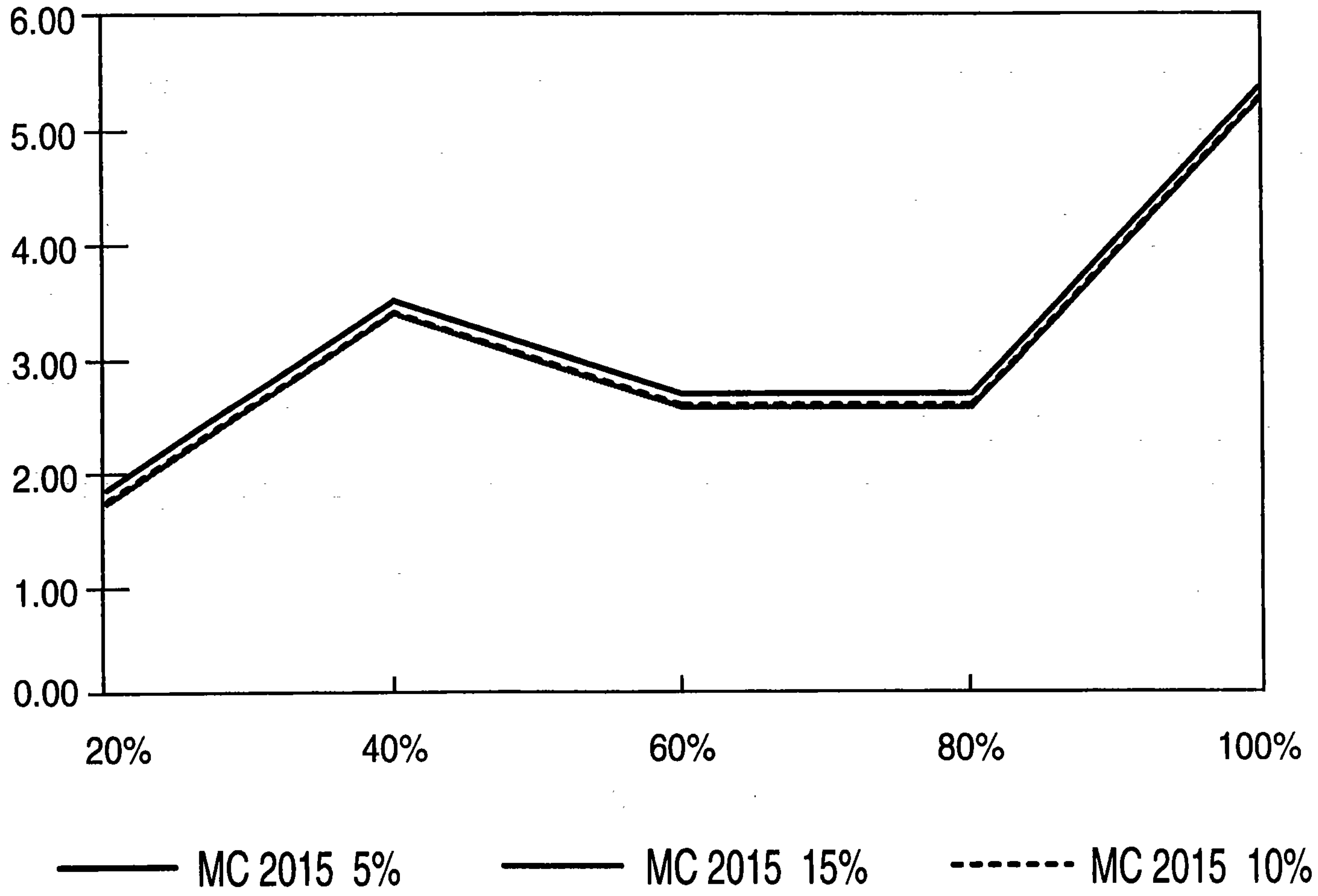
FIGURE 5 MARGINAL COSTS OF CARBON SEQUESTRATION IN THE YEAR 2010



Note Each line represents marginal costs in $1996 at a different discount rate.

Source BTCE estimates based on data from various sources.

FIGURE 6 MARGINAL COSTS OF CARBON SEQUESTRATION IN THE YEAR 2015



Note Each line represents marginal costs in $1996 at a different discount rate.

Source BTCE estimates based on data from various sources.

Figures 3 to 6 show the marginal costs of carbon sequestration for the years 2000, 2005, 2010 and 2015 in 1996 dollars at a benchmark discount rate of 10 per cent and alternative rates of 5 and 15 per cent. The figures show that the results do not vary markedly at discount rates of 5 and 15 per cent.

Total costs of afforestation in any year include land costs because new land needs to be planted each year (and kept under forest thereafter in perpetuity) to absorb that year's transport emissions. Annual planting and maintenance costs are included, but the dominant component of total costs is land. Land is acquired each year according to a 'planting order' (appendix IV) that is determined by choosing the lowest-cost land remaining, combined with its expected productivity.

To enable a proper comparison of costs between different levels of intensity of the instrument (a level of intensity corresponds to each 20 per cent increment in emission reduction) each level of intensity has been costed independently with its own planting order. This means that each level of intensity represents an independent policy option with its associated cost. For instance, in 2015 (see table 6), the total costs for each level of intensity have been calculated by commencing the planting order from the first year (1996) and starting with the cheapest land. Table 6 shows that the 20 per cent level of intensity costs $35.9 million, whereas for 100 per cent level of intensity the cost rises markedly to $315.3 million. This is because at a 100 per cent level of intensity, a much greater proportion of available land is drawn upon, involving incursions into relatively high cost land.

Total costs increase continuously as more trees are planted. However, because of the varying amount and cost of land required to absorb each 20 per cent increment in emissions, there are correspondingly disproportionate increments in total cost as is evident from table 6 (column 5). This is the reason for the peaks and troughs in the marginal cost graphs (figures 3 to 6 derived from tables 2 to 5). As the increments in total cost (column 5) are divided by a constant number representing a 20 per cent reduction in CO_2 emissions (20 417 242 tonnes) to generate marginal costs, the varying pattern of change in total costs is reflected in the pattern of marginal costs. The same explanation applies to the patterns of the marginal cost curves for the other years.

Overall, the marginal cost of absorbing CO_2 is relatively low. Even if all of the CO_2 emitted by the transport sector in 2015 were to be absorbed through tree planting, the marginal cost would be of the order of $5 per tonne (1996 dollars).

Because the costs of the greenhouse effect are not known, it is not possible to estimate the benefits of reducing emissions. However, the 100 per cent sequestration scenario provides an estimate of the 'control cost' of total avoidance of any damage. That is, if eliminating greenhouse gas emissions from the Australian transport sector were to be worthwhile, the benefits of doing so would need to be worth at least $5 per tonne of CO_2. Since trees can equally absorb CO_2 emitted from other sectors of the economy, the same is also true for those sectors.

TABLE 6 TOTAL AND MARGINAL COSTS FOR THE YEAR 2015

(1) Proportion of CO_2 sequestered (Per cent)	(2) Emission reduction (tonnes of CO_2)	(3) Increment in emission reduction (tonnes of CO_2)	(4) Total cost (1996 dollars)	(5) Increment in total cost	(6) Marginal cost ($/tonne of CO_2)
20	20 417 242	20 417 242	35 916 002	35 916 002	1.76
40	40 834 484	20 417 242	104 768 339	68 852 337	3.37
60	61 251 726	20 417 242	157 152 509	52 384 170	2.57
80	81 668 968	20 417 242	209 639 893	52 487 384	2.57
100	102 086 210	20 417 242	315 301 362	105 661 469	5.18

Note The marginal costs (column 6) are derived by dividing the increment in total cost (column 5) by the increment in emission reduction (column 3). For example, 3.37= 68 852 337/ 20 417 242.

EQUITY ISSUES

One means of correcting a negative externality is to impose a tax. The concept of a pollution tax was first proposed by the British economist Pigou in 1920. The purpose of a Pigovian tax is to increase the private marginal cost of production faced by the polluter to a level that reflects the full social cost of the activity. However, establishing an optimal level for a Pigovian tax on greenhouse gas emissions is difficult because there is no reliable estimate of the damage caused by the greenhouse effect.

Taxing fossil fuels in proportion to their carbon content is a commonly suggested greenhouse mitigation policy option. But such 'carbon taxes' differ fundamentally from a Pigovian tax in that they are set to achieve quantitative targets rather than an optimal level of externality. Their main purpose is to penalise usage of fossil fuels and reduce usage to levels determined without reference to the social costs of the emissions.

Because afforestation involves some (net) cost, fuel wholesalers will pass on a proportion of the residual fuel cost to consumers. The magnitude of this cost will depend on costs and revenues of forestry, and taxation arrangements relating to forest industries. Consequently, consumers would effectively face a 'forestry tax' akin to a monetary tax on fuel. As a result, fuel usage is likely to fall.

Both a monetary carbon tax and a forestry carbon tax would discourage consumers from using fossil fuels and encourage producers to find substitutes. But the mandated growing of trees which generates the forestry tax would also result in the absorption of emissions. A forestry tax would therefore be lower than a carbon tax in achieving any target reduction in CO_2 emissions.

Both a carbon tax and a forestry tax would result in a deadweight loss in consumer welfare. Because its absolute level would be lower, however, the forestry tax would entail a lower deadweight loss. Forestry plantations may also decrease soil erosion, add to recreational facilities, and increase biodiversity and water quality, although regular harvesting and replanting of non-native species will limit such benefits. Consequently, in theory the afforestation policy analysed in this study is preferred to a carbon tax.

The incidence of a fuel tax will be determined by the slopes of the supply and demand curves. In the case of petrol for which demand is relatively inelastic (Luk and Hepburn (1993) estimate the short run own-price elasticity at -0.10 and the long run elasticity at -0.26), consumers would be likely to pay a greater proportion of the tax than fuel sellers. The financial penalty increases with the amount of fuel used under either a carbon tax or forestry tax regime, and users of both private and public transport will be affected. Also, both taxes are likely to be considered inequitable because lower income earners would pay a higher proportion of their total income as pollution tax than those on higher incomes.

As the purpose of most energy taxes is to encourage shifts to less polluting forms of energy rather than to affect overall output, it is sometimes proposed that energy tax revenues be returned to society by reductions in other taxes or the provision of subsidies. However, the majority of the Australian population uses transport powered by fossil fuels. Any form of compensating adjustment to other taxes or subsidies could result in restoring incomes to pre-tax levels. Such compensating increases in income could lower consumer incentives to reduce their fossil fuel use.

APPENDIX I FOREST GROWTH AND DECAY MODELS

Sigmoidal functions are used increasingly in a wide range of socio-economic analyses, even where the underlying growth and retardation processes cannot always be fully or explicitly identified.

Wood yield of a tree or identical aged stand is usually portrayed as sigmoidal functions as shown in figure 2a where initial exponential growth slows after reaching a maximum rate at the point of inflection (A). The saturation level (C), which is reached asymptotically, represents the maximum biomass of the stand, after which growth continues but is matched by decomposition.

Figure 2a is a yield curve which shows the total number of what is being measured, or some attribute such as tree diameter or mass at different points in time. Yield curves for forests normally include any removals such as thinnings that occur during the growth process (Vanclay 1994, p. 106).

Yield curves for plantation forests are normally defined in terms of volume of wood (for example, cubic metres of merchantable stemwood) per unit area (for example, ha). The corresponding growth function (figure 2b) is usually referred to as the Current Annual Increment (CAI) and is expressed as volume per ha per year. Because the CAI curve shows the growth in a specific year, it is analogous to the marginal product curve used in economic analysis. The Mean Annual Increment (MAI) curve shows the total yield per year for a given age of tree and is analogous to an average product curve.

The maximum annual growth rate (maximum CAI) occurs at the inflection point ($d^2V/dt^2 = 0$) on a yield curve. If more than one crop is planted, the rotation period (time from planting to harvesting) for a plantation is determined as the point where average product (MAI) is at a maximum (the intersection with the CAI curve). The maximum rate of average productivity can also be found as point B in figure 2a where a ray from the origin is tangential to the yield curve. A rotation period determined in this way will maximise the volume of wood harvested over successive plantings and thus represents a physical product optimum. Determination of a commercial optimum would require information on costs and revenues and a discount rate.

CHOICE OF YIELD OR GROWTH FUNCTION

For more than a century, forest biometricians have sought a generalised function capable of describing the biological growth process of individual trees and forest stands. According to Yang, Kozak and Smith (1978, p. 424), substantial effort has been expended unsuccessfully to find a function that is flexible enough in form to accommodate all biological growth behaviour, and logical enough in theory to justify its application in practice.

For example, using data on spruce height increase and fir volume growth, Yang et al (1978, p. 427) favoured a modified Weibull function, but claim that their tests show that 'the best models are the Gompertz, the generalised von Bertalanffy, and the modified Weibull functions'. Applying it to three mature softwood species, Nokoe (1978 p. 41) considers the Gompertz function (modified by the addition of a parameter representing site quality) to be sufficiently flexible to warrant its use as a composite yield model. Fabens (1965) was attracted to von Bertalanffy's curve, but does not appear to have compared it empirically to other options. Richards (1969) preferred a generalised version of the Bertalanffy function, subsequently referred to in the literature as the Chapman-Richards equation, although Zeide (1993, p. 599) claims that it was reported by the German agronomist Mitscherlich in 1919. Barson and Gifford (1989) used the Gompertz function in a study of the potential role of tree plantations as CO_2 sinks in Australia.

The Gompertz function has a point of inflection whose value is $1/e$ times the asymptotic yield. Leech and Ferguson (1981 p. 233) point to the difficulty of rationalising why the point of inflection of forest growth should conform to this relationship. In their study, which compared different yield models for unthinned stands of *P. radiata*, Leech and Ferguson (1981, p. 242) found that the maximum current annual increment of 19.5 years predicted by the Gompertz function was about double the age indicated by actual data.

Zeide (1993) examines a wide range of functions; some of them previously unknown in the West as the relevant literature was available only in a number of Slavonic languages. The range of functions identified by Zeide is set out in table I.1. Drawing on the work of others as well as his own tests, Zeide casts doubt on the relative accuracy of the logistic, Weibull, Gompertz and Chapman-Richards functions when compared to the Korf or Levakovic equations. He dismisses the monomolecular function as an unrealistic portrayal of growth because it lacks an inflection point.

Zeide's (1993) major objective is to compare the set of growth functions shown in table I.1 from the point of view of their two components: growth expansion (anabolism) and decline or retardation (catabolism). He finds that all but the Weibull are particular cases of the following two forms:

$$ln(V') = z + pln(V) - q\ln(t) \quad (1)$$

$$ln(V') = z + pln(V) - qt \quad (2)$$

where V' is growth (first differential) of V, z is an intercept constant, and p and q respectively are constants associated with size (V) and age (t).

In both forms the expansion component is proportional to $ln(V)$ or, in the antilog form, it is a power function of size. The two forms differ only in the last term, the decline component.

Zeide (1993, pp. 611-612) explores the possibility of combining the two basic forms into one equation, but, like other authors he cites, finds that reduction to a single form would require the introduction of additional parameters. He notes that 'although a single general solution is attractive, it is not clear whether it is worth the cost of additional variables'.

Testing the two basic equation forms against a data set of Norway spruce, Zeide (1993, p. 613) offers no firm conclusion about which form is to be preferred, stating only that:

> Unlike the expansion component, growth decline in individual trees can be rendered with equal accuracy by a variety of expressions. This result may be explained by the great number of factors that hinder growth: scarcity of resources, competition, reproduction, aging, diseases, herbivory, disturbances, etc. This makes the growth path inherently imprecise. It should be regarded as a broad valley rather than a single line.

This lack of a firm conclusion by Zeide (1993) is paralleled in the literature by an apparently high degree of disagreement over an ideal functional form. For example, Richards (1969, p. 15) reveals that he is well aware that

> ...the greater the number of constants that are fitted to experimental data the more flexible is the resulting curve, and the more closely can it reproduce the data...yet the addition of further constants...cannot lead to better representation of the unknown ideal growth curve, but only to inclusion of the very errors it is desired to exclude.

However, Zeide (1993, p. 600) quotes, seemingly approvingly, another author (Leary) to the effect that the Chapman-Richards function is 'a giant leap backwards from explanation to description' because of its generalisation of the parameter values in the Bertalanffy equation. Fabens (1965, pp. 270-271) claims that Bertalanffy made an error (easily corrected) in his equation with respect to units of weight. Vanclay (1994, p. 111) claims that Zeide (1993) concluded that the Bertalanffy equation 'and two variants [but here Vanclay reproduces Zeide's two basic equation forms rather than variants of Bertalanffy growth or yield functions] were the best descriptors of height, diameter and volume growth'. A close reading of both Zeide (1989) and Zeide (1993) reveals no support for this contention regarding Zeide's views on the Bertalanffy equation, and one can only conclude that Vanclay (1994) has misread the source.

TABLE I.1 EXPANSION AND DECLINE COMPONENTS OF GROWTH EQUATIONS

		Subtraction components		*Division components*	
Equation name and its integral form	*Differential form*	*Expansion*	*Decline*	*Expansion*	*Decline*
Hossfeld IV $V = t^k / \left(b + t^k / V_m\right)$	$V' = bkt^{k-1} / \left(b + t^k / V_m\right)^2$	kV / t	$kV^2 / V_m t$	bkV^2	t^{k+1}
Gompertz $V = V_m e^{-be^{-kt}}$	$V' = V_m bke^{-kt} e^{-be^{-kt}}$	$k \ln(V_m)V$	$kV \ln(V)$	$(bk)V$	e^{kt}
Logistic $V = V_m / \left(1 + ke^{-bt}\right)$	$V' = V_m bke^{-bt} / \left(1 + ke^{-bt}\right)^2$	bV	$(b / V_m)V^2$	$(bk / V_m)V^2$	e^{bt}
Monomolecular $V = V_m\left(1 - ke^{-bt}\right)$	$V' = V_m bke^{-bt}$	$V_m b$	bV	$(V_m bk)$	e^{bt}
Bertalanffy $V = V_m\left(1 - e^{-bt}\right)^3$	$V' = 3V_m be^{-bt}\left(1 - e^{-bt}\right)^2$	$3V_m^{1/3} bV^{2/3}$	$3bV$	$\left(3V_m^{1/3} b\right)V^{2/3}$	e^{bt}
Chapman-Richards $V = V_m\left(1 - e^{-bt}\right)^k$	$V' = V_m bke^{-bt}\left(1 - e^{-bt}\right)^{k-1}$	$V_m^{1/k} bkV^{(k-1)/k}$	bkV	$\left(V_m^{1/k} bk\right)V^{(k-1)/k}$	e^{bt}
Levakovic I $V = V_m\left(t^d / \left(b + t^d\right)\right)^k$	$V' = bkdV / t\left(b + t^d\right)$	kdV / t	$V_m^{-1/k} kdV^{(k+1)/k} / t$	$V_m^{-1/k} bkdV^{(k+1)/k}$	t^{d+1}

Levakovic III					
$V = V_m\left(t^2/\left(b+t^2\right)\right)^k$	$V' = 2bkV/t\left(b+t^2\right)$	$2kV/t$	$2V_m^{-1/k}kV^{(k+1)/k}/t$	$2V_m^{-1/k}bkV^{(k+1)/k}$	t^3
Korf					
$V = V_m e^{-bt^{-k}}$	$V' = V_m bkt^{-k-1}e^{-bt^{-k}}$	$k\ln(V_m)V/t$	$kV\ln(V)/t$	$(bk)V$	t^{k+1}
Weibull					
$V = V_m\left(1-e^{-bt^k}\right)$	$V' = V_m bkt^{k-1}e^{-bt^k}$	$V_m bkt^{k-1}$	$bkVt^{k-1}$	$(V_m bk)t^{k-1}$	e^{bt^k}
Yoshida					
$V = V_m t^d/\left(b+t^d\right)+k$	$V' = V_m bdt^d/t\left(b+t^d\right)^2$	$bdV/t\left(b+t^d\right)$	$bdk/t\left(b+t^d\right)$	$(bd/V_m)(V-k)^2$ if $d>1$	t^{d+1}
Sloboda					
$V = V_m e^{-be^{-kt^d}}$	$V' = bkdVt^{d-1}e^{-kt^d}$	$kdt^{d-1}\ln(V_m)V$	$kdt^{d-1}V\ln(V)$	$(bkd)Vt^{d-1}$ if $0<d<1$	e^{kt^d}
				$(bkd)V$	$t^{1-d}e^{kt^d}$

Note V is the tree or stand size (height, diameter or volume), V_m is the maximum value of V, t is the age of the tree or stand, V' is the size increment, b, k, and d are parameters of equations, *ln* is the natural logarithmic function and e=2.718.

Source Adapted from Zeide (1993 p. 598).

THE GOMPERTZ MODEL

The main objective of the present study was not to accurately model the growth of *P. radiata* but rather to provide indicative estimates of the marginal costs of reducing emissions from transport by planting trees. The use of the Gompertz model was considered adequate to achieve this objective. It is mathematically tractable, and is accepted as a valid form in forestry literature, even if it is not favoured over alternative yield functions by all researchers.

The Gompertz model is described by equations (3) to (5).

$$V = V_m e^{-be^{-kt}} \quad \text{(Gompertz yield function)} \qquad (3)$$

V is the volume of biomass (m^3 per ha) at any time t (years), V_m (the asymptotic value of V) is the maximum volume of biomass absorbed over the life of the plantation (m^3 per ha)), and b and k are constants.

When $t=0$, $V=V_0$, and

$$b = ln\ (V_m/V_0) \qquad (4)$$

where V_0 is the volume of biomass in the seedlings (m^3 per ha).

Differentiating the Gompertz function twice with respect to time and setting it equal to zero (the condition for a point of inflection) yields

$$k = (ln\ b)\ /\ t_m \qquad (5)$$

where t_m is the year of maximum growth (the age corresponding to point A in figure 2). The asymptotic value of biomass (V_m) was obtained from average yield data (appendix II). Biomass volumes were converted to mass of carbon using conversion factors in appendix II. The initial mass of carbon (equivalent to V_0) was assumed to be 0.05 tonnes per ha (Barson & Gifford 1989, p. 437).

DECAY OF WOOD PRODUCTS

Because trees decay after they are felled, a decay function must also be specified. This function specifies the rate at which the carbon is re-emitted to the atmosphere, depending on the use, and hence the half-life, of the final wood product. Half-life refers to the time taken for half of a given quantity of timber to decay and release its carbon back into the atmosphere in the form of CO_2.

A simple exponential decay function described by equation (6) was used.

$$V_t = V_f e^{-\gamma t} \qquad (6)$$

Where, V_t is the volume of biomass remaining (m^3 per ha) after decaying for time t, V_f is the volume of biomass at the time the forest is felled, and γ is a decay constant.

Incorporating the concept of half life, equation (6) reduces to

$$\gamma t = ln\ 2$$

from which

$$\gamma = 0.693/t \qquad (7)$$

Half lives of wood products used in this study are presented in appendix II.

APPENDIX II YIELD DATA, WOOD PRODUCT LIFETIMES AND CONVERSION FACTORS

ESTIMATES OF CARBON YIELD

Individual trees and stands of the same species can differ markedly in growth and yield patterns due to many factors, including differences in climate, environment, soil conditions and density of planting. Data on the proportions of biomass or carbon contained in the different parts of a tree and in forest soils for the same species can also vary considerably depending on the source consulted. This appendix presents data from different sources to illustrate the range of estimates of biomass yield and other parameters per ha. Conservative values of parameters were chosen from these data for use in this study.

Following are estimates of the biomass and carbon content of softwood derived from various sources.

Barson and Gifford (1989)

The study by Barson and Gifford (1989) assessed the potential role of tree planting in Australia as a CO_2 sink. Their study cites Booth (1989) who considers that a typical stem wood growth rate for *P. radiata* in Australia is 10 tonnes dry matter per ha per year (a volume growth rate of 20 m^3 per ha per year) equivalent to about 5 tonnes carbon. Allowing for leaves, fine branches, roots and soil organic matter, Barson and Gifford (1989, p. 438) assume an annual average carbon sequestration rate of 7.5 tonnes carbon per hectare over 40 years. This assumption implies that total biomass is 1.5 times above ground biomass or that about 67 per cent of carbon is stored in the stem wood and the rest in leaves, roots, fine branches and soil organic matter. Barson and Gifford use a value of 390 tonnes carbon per hectare as the asymptotic biomass.

Barson and Gifford (1989, p. 437) note that these growth and yield assumptions may be generous for Australian conditions, as similar average rates of stem volume growth apply to New Zealand state-owned forests at peak plantation growth rate.

Lambert (1979 and pers. comm. 5 October 1995) and Turner (1990)

The estimates of biomass and conversion factors set out below were provided by Marcia Lambert and John Turner of State Forests of NSW. The estimates of biomass relate to average quality 30-year old *P. radiata*.

Biomass has been divided by 1.74 to convert to carbon (Turner 1990, p. 2). If it is assumed that roots represent 30 per cent of above ground biomass (Turner 1990, p. 2), total carbon stored in a 30-year old plantation is 332 tonnes per ha.

(1) Trees		*tonnes per ha*
Foliage		7
Branches		23
Bark		24
Wood		106
Total trees		160
(2) Thinnings and forest floor		
First thinning (12-15 years)	100 m^3 per ha	
Second thinning (18-20 years)	70 m^3 per ha	
Third thinning (24-25 years)	70 m^3 per ha	
Total thinnings	240 m^3 per ha	62
Small trees and understorey		1
Forest floor		14
(3) Organic matter turnover		*tonnes per ha*
Litterfall (4 tonnes per ha per year)		
Accumulation of organic matter (9 tonnes per ha per year)		
Total accumulation of organic matter		270
Total above ground biomass (1) + (2) + (3)		**507**
Total above ground carbon		**291**

Grierson, Adams and Attiwill (1991a)

Grierson, Adams and Attiwill (1991a) carried out a study commissioned by the State Electricity Commission of Victoria to estimate the amount of carbon sequestered in Victoria's forests. Grierson et al (1991a, p. 25) report that *P. radiata* plantations in Victoria have a mean carbon density of 90.5 tonnes per ha (mean biomass density of 181.0 tonnes per ha) in the above ground components. They assumed that below ground components (roots) represent a mean of 20 per cent of total forest biomass (p. 22). This assumption leads to an estimate of 22.6 tonnes per ha as mean carbon density in the below ground components.

Grierson et al (1991a, p. 42) use a mean value of standing litter of 9.3 tonnes carbon per ha taking into account various hardwood and softwood species. They cite estimates of standing litter from five published sources for *P. radiata*. The average of these five estimates is 20.4 tonnes per ha (10.2 tonnes carbon per ha).

Grierson et al (1991a) assumed an average of 5 per cent of organic carbon in forest soil and a bulk density of 1 for a depth of 50 cm. On this basis, Victoria's forest soils contain an average of 250 tonnes of carbon per ha.

The above figures indicate that total carbon per hectare is 373.3 tonnes.

Maclaren and Wakelin (1991)

The study by Maclaren and Wakelin relates to forestry and forests products as carbon sink in New Zealand. They use data from several sources to estimate the quantity of organic components on a forested site.

Non-merchantable volume is assumed to be 15 per cent of total stem volume. Various regression equations and published data were used to estimate other components. The figures given below refer to per cent of oven-dry weight of total stem wood assuming that trees are harvested when they are 35 years old.

	per cent
Bark	6.3
Live branches	2
Dead branches	6.1
Foliage	4
Stumps and coarse roots	23.4
Fine roots	3.07
Cones	2.1
Total	**68 per cent of stem wood**
Forest floor	29.5 tonnes per ha
Understorey and understorey roots	13.0 tonnes per ha

Applying the above figures to 909 m^3 of stem wood per ha (see R. Boardman below) yields 774.3 tonnes of biomass or 310 tonnes of carbon per hectare.

R. Boardman (pers. comm. 9 October 1995)

R. Boardman (Primary Industries, South Australia, Forestry) provided yield data per ha for *P. radiata* of site quality 3 in South Australia. According to Boardman, these figures incorporate improved yields from breeding programs and intensive silviculture and therefore represent future expected average growth rates for *P. radiata* in Australia.

The yields of merchantable wood to 10 cm small end (including thinnings) are 1027 m^3 at 40 years, 909 m^3 at 35 years and 782 m^3 at 30 years.

According to Boardman, if 2200 trees are planted per ha and harvested when they are 35 years old (maximum annual growth occurs at year 8), there could be up to six thinnings. A typical thinning program occurs at 10 years (84 m^3), 16 years (67 m^3), 22 years (75 m^3) and 29 years (110m^3). Thinnings amount to 336 m^3 per ha. At year 35 the amount of standing merchantable wood is 573 m^3 per ha.

	Per ha
Total merchantable wood (standing wood and thinnings)	909 m^3
Add 13 per cent of merchantable wood for bark	118 m^3
	1027 m^3
Add tree residue	64 m^3
Total wood, bark and tree residue	**1091m^3**
Assume wood density of 0.44 tonnes per m^3	
Total wood, bark and tree residue	480 tonnes
Add foliage (6.4 tonnes)	486.4 tonnes

The coarse root system and stumps are estimated to account for between 12 per cent and 40 per cent of the total above ground biomass.

If it is assumed that roots account for 25 per cent of above-ground biomass, total biomass would amount to 608 tonnes comprising 243 tonnes of carbon (carbon is assumed to be 40 per cent of biomass).

Summary of estimates

Table II.1 presents a summary of the estimates set out above. The estimate of Boardman (243 tonnes per ha) was used in the analysis.

TABLE II.1 ESTIMATES OF CARBON YIELD IN PINE PLANTATIONS (TONNES PER HA)

Lambert[a] *(1979,1995)*	*Barson & Gifford*[b] *(1989)*	*Grierson et al*[c] *(1991a)*	*Maclaren & Wakelin*[d] *(1991)*	*Boardman*[e] *(1995)*
332	390	373	310	243

a. Average quality *P. radiata* grown in NSW (30 years).

b. Assuming peak plantation growth rate in New Zealand forests (40 years).

c. Average for *P. radiata* grown in Victoria. Includes estimate of soil carbon content.

d. Estimates of tree components (excluding stem wood) applied to the stem wood estimate of Boardman (1995) (35 years).

e. *P. radiata* site quality 3 grown in South Australia (35 years).

Source BTCE estimates based on data from different sources.

CONVERSION FACTORS

Density of softwood

The density of softwood used in various studies is around 0.5 tonnes per m3. In this study a density of 0.44 tonnes of biomass per m^3 (R. Boardman pers. comm. 6 October 1995) has been used.

Carbon content of biomass and wood

Various factors are used to convert biomass and wood to elemental carbon.

Turner (1990, p. 2) divides the weight of wood by 1.74. This is equivalent to wood being 44 per cent carbon.

Barson and Gifford (1989, p. 437) assume that carbon comprises 50 per cent of dry biomass as do Grierson et al (1991a, p. 25).

On the basis that most organic matter in wood fits the formula $C_nH_{2n}O_n$, Boardman (pers. comm., 9 October 1995) suggests that 40 per cent of wood biomass is carbon.

Maclaren and Wakelin (1991) note that various studies have used conversion figures for oven dry weight of wood to weight of elemental carbon of 0.42 to 0.53. They conclude that 0.496 is an appropriate figure for *P. radiata* in New Zealand.

For the purpose of this study, carbon is conservatively estimated to account for 40 per cent of biomass by weight.

ESTIMATES OF LIFETIMES OF SOFTWOOD PRODUCTS

The few available estimates of the lifetimes of the components of trees vary substantially. Information on wood product lifetimes is sparse. Some estimates that have been used in previous studies are set out below.

Barson and Gifford (1989)

Barson and Gifford (1989, p. 437) considered that paper products have half lives of 1 to 5 years, pallets, posts and form work 5 to 10 years, and treated and structural timber and furniture, 10 to 100 years. They did not use separate decay rates for each wood fraction, choosing instead an average rate of decay for total biomass.

In their study, Barson and Gifford conducted scenario analysis using half lives of 1, 2, 5, 10 and 100 years for total biomass.

Maclaren and Wakelin (1991)

Maclaren and Wakelin (1991, p. 13) used separate decay functions for each forest by-product of the form:

> Residues at year A = initial residues times $(1-A/9)^{0.5}$, where A is the number of years since harvest.

Maclaren and Wakelin categorised harvested wood volume in accordance with data in a New Zealand Ministry of Forestry report (MOF 1988) relating to the quantity of wood harvested during the year ended 31 March 1987 and its usage. The wood products were classified into three types: long term (posts and poles), medium term (sawn timber and panel products) and short term (wastage, form work and packaging). The figures used for these three types of wood product are summarised in table II.2.

TABLE II.2 LIFETIMES OF WOOD PRODUCTS

Type of wood product	*Proportion of wood harvested(per cent)*	*Lifetime (years)*
Long term	2.2	80
Medium term	20.5	50
Short term	77.3	1

Source Maclaren and Wakelin (1991, p. 14).

Grierson, Adams and Attiwill (1991b)

Grierson et al used harvest data from the Victorian Department of Conservation and Environment for a 35 year old *P. radiata* plantation. Sawlogs comprised 77 per cent, pulp wood and round wood 13 per cent, and residue 10 per cent. The decay fractions assumed in the study are shown in table II.3.

TABLE II.3 TYPICAL PROPORTIONS AND LIFETIMES OF PRODUCTS FROM A PINE PLANTATION

Product	*Proportion of carbon (per cent)*	*Life (Years)*
Bark	*8–10*	*100*
Sawn Timber	*30*	
Fencing		20
Pallets and packaging		5
Construction and furniture		100
Sawdust	*6*	*0.5*
Pulp	*26*	
Paper		1–5
Particle board		15
Litter	*30*	*n.s*

n.s. Not stated.

Source Grierson, Adams and Attiwill (1991b, p. 23-24).

Forest industry sources (pers. comm. 12 October 1995) indicated that typical use of merchantable pine wood fibre is as shown in table II.4.

TABLE II.4 ESTIMATES OF TYPICAL PROPORTIONS AND LIFETIMES OF MERCHANTABLE PINE WOOD USED FOR DIFFERENT PRODUCTS

Product	*Proportion (per cent)*	*Life (years)*
Sawn timber (house frame construction)	24	100
Exported wood chips (paper production)	10	5
Particle board	14	40
Medium density fibreboard	5	40
Paper (newsprint, tissues etc)	36	1-5
Waste (usually burnt on site)	11	0

Source Forest industry sources (pers. comm. 13 October 1995).

A substantial proportion of short term product (mainly paper and cardboard) is recycled, thereby extending its effective half life.

BTCE assumptions

For the purpose of this study, the total carbon accumulated by a plantation at year 35 was assumed to comprise three categories. Table II.5 sets out the proportions of carbon per ha in each category and the corresponding half lives which have been estimated by the exercise of judgement and with due regard to the data presented in this appendix.

TABLE II.5 ESTIMATES OF HALF LIVES OF PINE PRODUCTS USED BY THE BTCE

Product	*Proportion of total carbon per ha (per cent)*	*Half life (Years)*
Long term[a]	24	10
Medium term[b]	29	5
Short term[c]	47	1

Source BTCE assumptions based on various sources.

a. Long term product is mainly sawn timber for house frame construction, treated timber for exterior use such as poles and also includes some root matter.

b. Medium term product includes manufactured wood products such as particle board and fibreboard.

c. Short term product includes paper products and foliage.

APPENDIX III PLANTATION COST DATA

A major component of the analysis of marginal costs of carbon sequestration involves estimation of the costs of establishing and maintaining a softwood plantation. Costs have been derived from RAC (1992) and indexed to 1996 dollar values using timber price indexes (ABARE 1994).

TABLE III.I PLANTATION ESTABLISHMENT[a] COSTS

Operation	*Cost ($ per ha)*
Pre-planning management	68
Clearing	27
Ploughing	137
Seedlings	164
Planting	185
Fertilising	82
Grass control	110
Vermin control	14
Tracks and firebreaks	55
Fencing	14

a. Does not include land costs. Land costs used in this study are set out in appendix IV.

Source RAC (1992).

TABLE III.2 ANNUAL PLANTATION COSTS

Cost item	*Cost ($ per ha)*
Rates	4
Firebreaks	3
Fire insurance	38
Management	27

Source RAC (1992).

It is assumed in this study that the trees are sold on a stumpage basis. Harvesting and transportation costs are not included in the analysis.

Planting cycles are assumed to continue in perpetuity. As loss of soil nutrients is likely to reduce yields over successive planting cycles, the application of fertiliser after each planting cycle is assumed (in addition to the fertilising carried out during establishment of the plantation as set out in table III.1). After each harvest, ACT Pine (N. Byatt, ACT Forests, pers. comm. 21 November 1995) uses a heavy roller to crush residual organic matter on the forest floor to speed up its absorption into the soil and then applies fertiliser. The cost of these two operations is $465 per ha ($240 per ha for the rolling operation and $215 per ha for fertiliser application). A cost of $465 has therefore been included as a recurring cost for each planting cycle (excluding the first cycle).

APPENDIX IV LAND DATA

CLASSIFICATION OF LAND

In 1991, the National Plantation Advisory Committee (NPAC 1991) published a study which contained data on areas of land in Australia with good growth potential for hardwood plantations. The identification of suitable land in the study was done in collaboration with the CSIRO Division of Wildlife and Ecology. In order to draw on CSIRO databases on land availability, the NPAC study formulated the following set of eleven decision rules to identify land suitable for plantations:

- Exclude areas with six or more consecutive months of rainfall less than 40 mm.
- Exclude areas with mean annual rainfall below 600 mm.
- Exclude areas with no vegetation (for example, lakes).
- As far as possible give preference to areas with higher mean annual rainfall.
- Avoid national parks, nature reserves, military areas, cities, aboriginal areas which include parks or nature reserves and give preference to remaining areas.
- Give preference to areas which have fertile soils and good water holding capacity.
- Give preference to areas which have been cleared and areas where minimal preparatory clearing would be required.
- Give preference to areas of low to moderate relief.
- Rate grazing density into three classes.
- Rate cropping index into three classes.
- Give preference to areas which have shrubs over 10 per cent of the cover.

On the basis of these rules, NPAC produced a three by three matrix of plantation capability versus agricultural intensity with nine classes as shown in table IV.1.

TABLE IV.1 METHOD OF LAND CLASSIFICATION

	Agricultural intensity		
Plantation capability	*Low*	*Medium*	*High*
Low	11	12	13
Medium	21	22	23
High	31	32	33

Note For an explanation of the meaning of the numbers see the text below.
Source NPAC (1991).

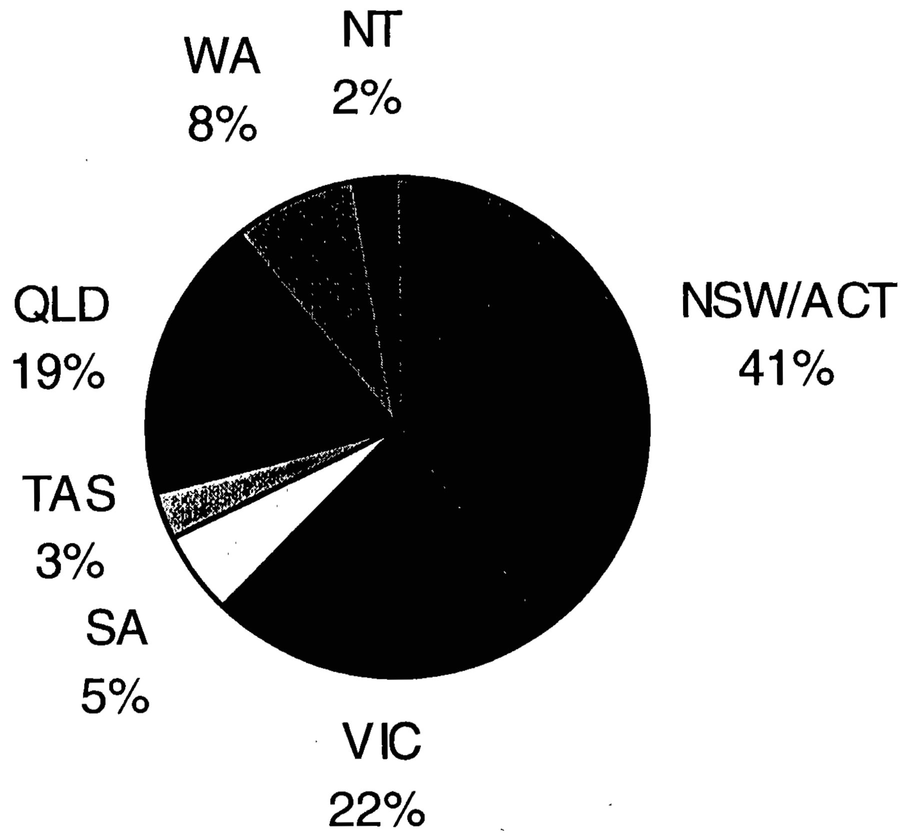
The first digit in any cell in the table indicates plantation capability and the second digit represents agricultural intensity. For example, class 33 represents areas which are highly suitable for plantations but also have a high degree of agricultural activity. Class 31 represents areas which are also highly suitable for plantations but have low agricultural activity.

The NPAC study did not provide information on the area of land available in each category in the table for individual states and territories. For the purpose of this study, the BTCE contracted the CSIRO Division of Wildlife and Ecology to provide the areas of land for each of the categories in table IV.1 by state, territory and islands. These data are set out in table IV.2. Table IV.2 also contains data on total land area in each state and territory as estimated by the Geographical Information System (GIS) used by the CSIRO and the Australian Bureau of Statistics (ABS). Although these data and the decision rules from which they are derived refer to land suitable for hardwood plantations, it can be assumed that they would not differ appreciably for softwoods such as pine (T. Booth, pers. comm. 26 April 1995).

Table IV.2 shows that land suitable and available for plantations in Australia amounts to 18 409 000 ha. Figure IV.1 shows the distribution of this land by state and territory. Most of the land is located in NSW (41 per cent) and Victoria (22 per cent). Figure IV.2 shows the degree of agricultural intensity of land available for plantations. Much of the land suitable for plantations has a high (32 per cent) or medium (56 per cent) level of agricultural intensity.

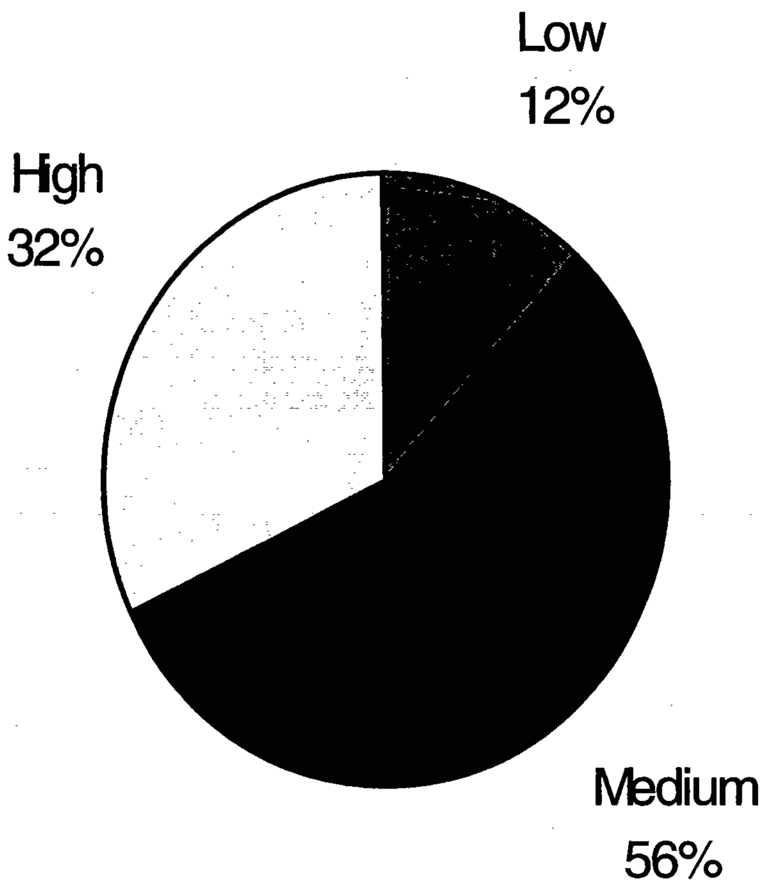
Land with low plantation capability and high agricultural intensity (categories 11, 12, 13, 23 and 33) was not considered commercially attractive and has therefore been omitted from the analysis. This leaves a potential plantation area in Australia of 9 627 000 ha. Table IV.3 shows the distribution of this land by state and territory. Land which is suitable for planting would not necessarily be available for use immediately, as it may currently be used for other purposes such as grazing. A range of land prices was used to take account of the different grades of land suitable for plantation forestry.

FIGURE IV.1 DISTRIBUTION OF LAND SUITABLE FOR PLANTATIONS BY STATE AND TERRITORY



Source Based on data provided by the CSIRO Division of Wildlife and Ecology under contract to the BTCE.

FIGURE IV.2 AGRICULTURAL INTENSITY OF LAND SUITABLE FOR PLANTATIONS



Source Based on data provided by the CSIRO Division of Wildlife and Ecology under contract to the BTCE.

TABLE IV.2 CLASSIFICATION AND DISTRIBUTION OF LAND FOR PLANTATIONS IN AUSTRALIA

('000 hectares)

State/Territory	Land categories 11	12	13	21	22	23	31	32	33	Total (11 to 33)	Total land (GIS)	Total land (ABS)	Per cent error
NSW	146	775	324	141	2 428	730	170	2 052	578	7 344	78 934	80 143	1.5
VIC	158	639	427	87	627	954	107	255	779	4 033	22 713	22 760	0.2
QLD	32	275	183	103	911	147	225	1 105	448	3 429	169 820	172 700	1.7
SA	110	81	454	10	65	195	0	3	39	957	95 839	98 438	2.6
WA	74	168	62	49	536	5	159	167	290	1 510	247 817	252 550	1.9
TAS	188	30	156	4	12	129	11	3	24	557	6 671	6 830	2.3
NT	82	7	0	0	0	0	355	13	0	457	132 941	134 620	1.2
ACT	0	0	0	0	27	0	0	0	0	27	241	243	0.9
Islands	31	62	0	2	0	0	0	0	0	95			
Total	821	2 037	1 606	396	4 606	2 160	1 027	3 598	2 158	18 409	754 976	768 284	1.7

Note The first digit in the land categories represents the degree of plantation capability (1=low, 2=medium, 3=high) and the second digit represents the degree of agricultural intensity (1=low, 2=medium, 3=high).

Source CSIRO Division of Wildlife and Ecology under contract to the BTCE.

TABLE IV.3 LAND SUITABLE FOR PLANTATIONS IN AUSTRALIA

('000 hectares)

	Agricultural intensity	
	Low	*Medium*
NSW		
Medium	141	2 428
High	170	2052
Victoria		
Medium	87	627
High	107	255
South Australia		
Medium	10	65
High	0	3
Tasmania		
Medium	4	12
High	11	3
Queensland		
Medium	103	911
High	225	1 105
Western Australia		
Medium	49	536
High	159	167
Northern Territory		
Medium	0	0
High	355	13
ACT		
Medium	0	27
High	0	0
Islands		
Medium	2	0
High	0	0
Australia		
Medium	396	4 606
High	1 027	3 598
Total	**1 423**	**8 204**

Note In the notation of table IV.2, low =1, medium = 2 and high = 3.

Source CSIRO Division of Wildlife and Ecology under contract to the BTCE.

For this study, due to the small areas involved, all islands belonging to Australia were excluded from the analysis and land in the ACT was combined with land in NSW (although shown separately in table IV.3).

LAND VALUES

Land values vary widely, depending on a number of factors such as location. Values depend on the degree of proximity of the land to major population centres and timber marketing and processing sites. For example, Margules and Partners (1990) reported a high upper range of land values for Victoria ($10 000 per ha) because they identified land suitable for plantations close to Melbourne where competing land uses and population have increased the price of land.

Land values can also be affected by the value of adjacent land and competing uses of the land. Land suitable for forestry competes with agricultural uses such as cattle and sheep grazing and the growing of crops. Various agricultural subsidies can also distort land values, raising values relative to land used for forestry.

New uses for land which require large plots can also affect prices considerably. For example, in the south east of South Australia, land previously planted with pine, as well as land suitable for pine is being increasingly used for vineyards, resulting in upward pressure on prices. Government policies that require a substantial increase in the area under plantations, such as the policy instrument discussed in this study, are also likely to drive up land prices.

Other factors that affect land values include particular land characteristics (such as drainage and the quality of soil) and the size of plots offered for sale (large areas generally fetch lower prices per ha because of the relatively greater demand for small plots).

Several sources were consulted to determine a range of land values, predominantly the Valuer General's offices in each state and territory, as well as forestry authorities, ABARE, and Margules and Partners (1990). The estimates used by the BTCE on the basis of these sources are set out in table IV.4.

A major part of the approach to costing forestry as a means of carbon sequestration was to assume that fuel sellers would seek to minimise costs. If land were to become prohibitively expensive, or forest yields were to fall to low levels, forestry would no longer be an attractive method of reclaiming carbon. Fuel sellers could resort to alternative means of sequestration such as underground storage of CO_2. Another option would be to establish plantations overseas where costs (particularly land) were cheaper—an alternative consistent with the terms of the 1992 Framework Convention on Climate Change. Possible increases in land values over time due to factors such as

TABLE IV.4 LAND VALUES FOR SOFTWOOD PLANTATIONS IN AUSTRALIA

State/Territory	*Lower bound $*	*Upper bound $*
New South Wales	1 000	3 000
Northern Territory	500	1 500
Queensland	800	2 500
South Australia	1 300	3 000
Tasmania	1 000	1 500
Victoria	1 300	3 000
Western Australia	2 000	3 000

Source BTCE estimates predominantly based on information provided by Valuer General's offices in each state and territory.

increased demand for land for tree plantations, have not been taken into account in this study.

Land values in table IV.4 were used to estimate a planting order (together with yield data in appendix I) for the land identified in table IV.3. The categories in table IV.3 can be represented as shown in table IV.5.

TABLE IV.5 CATEGORIES OF LAND USED TO DERIVE PLANTING ORDER

	Agricultural intensity	
Plantation capability	1 (low)	2 (medium)
Medium (2)	21	22
High (3)	31	32

Source BTCE.

The lower bound figures in table IV.4 were assigned to the land with medium plantation capability and low agricultural intensity (21). The mid point of the range of land values in table IV.4 was assigned to land with high plantation capability and low agricultural intensity (31). The upper bound figures in table IV.4 were applied to land with medium plantation capability and medium agricultural intensity (22). Finally, the upper bound figures in table IV.4 increased by an arbitrary premium of 30 per cent were applied to land with high plantation capability and medium agricultural intensity (32). For example, land with high plantation capability and low agricultural intensity (31) in Victoria would be valued at $2 150 per ha.

A planting order was derived by taking account of both yield potential and land value. The available land was classified into two productivity groups. The yield of carbon in a 35-year old plantation used in the analysis (243 tonnes) is based on yield data for class 3 pine in South Australia (appendix II). Better quality land was assumed to have a higher yield and a premium of 14 per cent was therefore added to the yield relating to yield class 3. This was done with reference to yield tables for South Australia (Lewis, Keeves & Leech 1976, p. 76) by averaging yields for classes 4 to 7. The addition of this premium resulted in a yield of 277 tonnes of carbon after 35 years. The two values of 243 tonnes and

277 tonnes were then applied to different categories of land in each state and territory together with associated lower and upper bound land values (table IV.4) to estimate the cost per tonne of carbon sequestered. The values obtained (in dollars per tonne of carbon sequestered) were arranged in ascending order thereby providing the planting order shown in table IV.6.

The table suggests that category 21 land in Queensland should be planted first, followed by category 31 land in the Northern Territory down to category 32 land in Victoria.

TABLE IV.6 PLANTING ORDER

Location	Land category[a]	Land available '000 ha	Land value $/ha
Qld	21	103	800
NT	31	355	1 000
Tas	21	4	1 000
NSW	21	141	1 000
Tas	31	11	1 250
Tas	22	12	1 250
SA	21	10	1 300
Vic	21	87	1 300
Tas	32	3	1 500
NT	32	13	1 500
Qld	31	225	1 650
Qld	22	911	1 650
NSW	31	170	2 000
Vic	31	107	2 150
WA	21	49	2 000
NSW	22	2 455	2 000
SA	22	6 5	2 150
Vic	22	627	2 150
WA	31	159	2 500
Qld	32	1 105	2 500
WA	22	536	2 500
SA	32	3	3 000
WA	32	167	3 000
NSW	32	2 052	3 000
Vic	32	255	3 000
Total		**9 625**	

a. The first digit represents plantation capability (2=medium, 3=high) and the second digit represents agricultural intensity (1=low, 2=medium).

Source BTCE estimates based on data from various sources.

APPENDIX V FEEDBACK EFFECTS IN FORESTRY

The build up of greenhouse gases in the atmosphere gives rise to biological feedback effects which can either increase (positive feedback) or decrease (negative feedback) the concentration of these gases in the atmosphere. Some of these feedback effects are relevant to forestry.

A possible negative feedback effect of increased CO_2 concentrations in the atmosphere is an increase in the rate of growth of plants. This CO_2 fertilisation or stimulation effect tends to reduce the amount of CO_2 in the atmosphere and thereby slow the rate of global warming. The greater concentrations of CO_2 accelerate the process of photosynthesis causing plants to absorb C at a faster rate.

Recent work by researchers at Duke University in North Carolina and Brookhaven National Laboratory in New York involved CO_2 enrichment of an experimental plot of loblolly pine in the University's experimental forest (Holmes 1995, p. 14). The experiment is reportedly the first to study the effect of CO_2 enrichment in a free standing forest as opposed to studying saplings in an enclosed chamber. Using an elaborate system of pipes, the researchers pumped computer-controlled doses of CO_2 into the air near the trees to maintain the concentration at 550 parts per million, which is the forecast level about the middle of the next century based on current trends. An adjacent plot without pipes was studied at the current concentration of 355 parts per million.

The pine trees with enriched carbon dioxide were found to photosynthesise 65 per cent faster than their neighbours over an entire summer. However, there are other factors that also affect plant growth such as availability of soil nutrients and water, and it is not clear whether enhanced growth can be sustained as the availability of these are reduced.

There are also some positive feedback effects. One effect is the warming-enhanced decay of organic matter in forests and soils. Due to increases in temperature, the rate of respiration tends to increase, resulting in higher CO_2 emissions. Another possible effect is reduced forest growth caused by the stress of climate change. Due to the state of scientific knowledge, the magnitudes of these individual feedback effects are difficult to quantify and so is the net effect.

APPENDIX VI NET PRESENT VALUE OF A STREAM OF OUTLAYS AND RETURNS THAT VARY CYCLICALLY

PRESENT VALUE

The concept of present value refers to the notion that a dollar received today is worth more than a dollar that will be received at some future time. This is because the dollar received today can generally be invested to produce a greater return in the future.

If the interest rate is r, then, after a period of time t, an initial investment I plus accumulated interest will amount to

$$\text{Total future value} = I\,(1 + r)^t$$

as this is to be equal to the future payment F due at time t,

$$F = I\,(1 + r)^t$$

so that

$$I = F \,/\, (1 + r)^t$$

By definition, I is the net present value of F due at time t.

As long as the interest rate is positive, the present value of any future income will be less than its nominal value, and the net present value of any cost will be less in absolute value than its nominal value. This is why the procedure is generally referred to as 'discounting future outlays and returns'.

There are two important points to note about discounting.

(I) Although it is usual to quote annual interest rates, and measure time in years, this formula does not depend on such annual accounting. It is valid to use a monthly interest rate and time in months, or a daily interest rate and time in days.

(ii) If a future payment is expressed in nominal (dollar) terms, it can be discounted using the nominal interest rate (that is, the normal interest rate not adjusted for inflation.) If the payment is expressed in real terms, so that it will be increased or decreased in line with price changes, it is possible to adjust the interest rate to allow for inflation. The adjusted interest rate is called 'the real interest rate', and is roughly equal to the nominal interest rate minus the rate of inflation.

NET PRESENT VALUE OF A FINITE STREAM OF FUTURE OUTLAYS AND RETURNS

If a project is expected to entail some immediate outlays and others in the future, and to bring in some immediate returns and some returns in the future, the project itself will have a net present value (*NPV*) equal to

NPV = immediate returns

- immediate outlays
+ present value of future returns (discounted separately and added up)
- present value of future outlays (discounted separately and added up)

So long as there is only a finite number of outlays and returns, and so long as each of them is due after only a finite delay, calculating net present value involves the application of the above formula.

PRESENT VALUE OF AN INDEFINITE UNIFORM STREAM OF PAYMENTS

An indefinite stream of equal annual payments beginning immediately, each of A\$, is equivalent to an immediate payment of A\$, plus a stream of future payments equal to the interest on a lump sum of A\$/*r*, (where *r* is the annual interest rate). The lump sum is never returned, but earns interest indefinitely. Therefore the present value of the infinite stream is

$$P = A + A/r$$
$$= A\,(1 + 1/r)$$

It is possible to confirm that this formula is the same as would be obtained if an infinite number of separate payments are discounted and added together. The result can also be generalised to periodic payments that are not annual.

Discounting at an interest rate of r makes the present value of a payment of A to be received in i periods equal to

$$NPV_i = A\,/(1 + r)^i$$

Therefore the value of a stream of n payments of A paid at regular periods is

$$NPV = A + A/(1 + r) + A/(1 + r)^2 + A/(1 + r)^3 + ... + A/(1 + r)^n$$

where r is the interest rate per period

$$NPV = A\,[1 + A/(1{+}r) + 1/(1{+}r)^2 + 1/(1{+}r)^3 + ... + 1/(1{+}r)^n]$$

By mathematical induction it can be proved (Spiegel 1968) that this simplifies to

$$NPV = A\,\{\,[1 - 1\,/(1 + r)^n]\,/[1 - 1\,/(1 + r)]\,\}$$

The limit of this expression as n increases without bound is

$$\begin{aligned} NPV_\infty &= A\,/[1 - 1/(1 + r)] \\ &= A\,/\{[(1 + r) - 1]/(1 + r)\} \\ &= A\,/\,[\,r/(1 + r)] \\ &= A\,(1 + r)/r \\ &= A\,(1 + 1/r) \end{aligned}$$

NET PRESENT VALUE OF A REPEATING CYCLE OF RETURNS AND OUTLAYS

Suppose an indefinite series of outlays and returns were expected which follow a pattern that repeats itself on a cycle of fixed length. For example, consider the annual cycle of outlays and returns involved in preparing land for planting, establishing plantations and maintaining, harvesting and selling the crop. It is straightforward to calculate the net present value of a complicated pattern such as this in two steps.

First, all of the outlays and returns of a single cycle are discounted back to the beginning of the cycle. This is the lump sum that, if received at the beginning of the cycle, would be equivalent to the outlays and receipts of the cycle. So the outlays and receipts of the cycle, repeated indefinitely, are equivalent to an infinite stream of uniform periodic payments, where the period between the payments is equal to the length of the cycle.

If the net 'present' value of the outlays and returns of a single cycle (at the beginning of the cycle) is NPV_c then the net present value of the cyclical stream of outlays and returns is

$$NPV_\infty = NPV_c\,(1 + 1/r)$$

where r is the interest rate for a period equal to the length of the cycle.

It remains only to show how to calculate the interest rate of a given period.

If the annual interest rate is r_a, a sum on deposit will be multiplied by a factor $(1 + r_a)$. If this is repeated n times, the sum will grow to $(1 + r_a)^n$ times its original value. If the original capital is subtracted, what remains is the interest over a period of n years. So the interest rate for a period of n years is given by r_n, where

$$r_n = (1 + r_a)^n - 1$$

Therefore, the net present value of a stream of payments that repeats itself over a cycle of n years, with annual interest rate r_a, each cycle having a net present value of NPV_c at its beginning, is NPV_∞, where

$$NPV_\infty = NPV_c \{1 + 1/ [(1 + r_a)^n - 1]\}$$

In the notation of equation (10) on page 11 and substituting the value for n, this equation is equivalent to

$$PVS = PVC + \frac{PVC}{(1+r)^{35} - 1}$$

However, the value of land V_l must be included because it is an initial capital cost. Hence,

$$PVS = (PVC + V_l) + \frac{PVC}{(1+r)^{35} - 1}$$

REFERENCES

Abbreviations

ABARE	Australian Bureau of Agricultural and Resource Economics
AGPS	Australian Government Publishing Service
BTCE	Bureau of Transport and Communications Economics
CSIRO	Commonwealth Scientific and Industrial Research Organisation
HMSO	Her Majesty's Stationery Office
MOF	New Zealand Ministry of Forestry
NSW	New South Wales
NPAC	National Plantations Advisory Committee
RAC	Resource Assessment Commission

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ABBREVIATIONS

ABARE	Australian Bureau of Agricultural and Resource Economics
ABS	Australian Bureau of Statistics
ACT	Australian Capital Territory
AGPS	Australian Government Publishing Service
BTCE	Bureau of Transport and Communications Economics
C	Carbon
CAI	Current Annual Increment
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
CSIRO	Commonwealth Scientific and Industrial Research Organisation
GIS	Geographical Information System
GJ	Gigajoule (10^9 joules)
H	Hydrogen
ha	hectare
MAI	Mean Annual Increment
MOF	New Zealand Ministry of Forestry
mm	millimetre
NPAC	National Plantations Advisory Committee
NPV	Net Present Value
NSW	New South Wales
NT	Northern Territory
O	Oxygen
P. radiata	*Pinus radiata*
PVC	Present value of a single planting cycle
PVS	Present value of infinite planting cycle
Qld	Queensland
RAC	Resource Assessment Commission
SA	South Australia
Tas	Tasmania
Vic	Victoria
WA	Western Australia