SEQUESTRATION OF ATMOSPHERIC CARBON DIOXIDE IN TREES

Prepared for

AUSTRALIAN NATURE CONSERVATION AGENCY

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EXECUTIVE SUMMARY

The task for this consultancy was to estimate the carbon dioxide absorbed (sequestered) by plantations to be established from the $7.5 million allocated in 1995 as an extension of the "One Billion Trees" Program. The Government's target in the "Greenhouse 21C - A plan of action for a sustainable future" is that, by the year 2000, this and related measures under other Commonwealth programs would contribute to reducing carbon dioxide emissions by up to two million tonnes.

Data on the growth rate of trees were obtained for planted pines in New Zealand and Victoria and for planted eucalypts in Victoria and Wagga Wagga, NSW. Curves were fitted to these data and then extrapolated to other parts of Australia, where tree growth was expected to be slower. The final result was three curves representing three productivity classes for pine trees and five curves, representing five productivity classes for eucalypts. Selections were made from these productivity classes to represent the other two forms of establishment considered, namely seeding and natural regeneration.

Budgets for establishing plantations by planting were obtained from a commercial plantation prospectus and from Greening Australia. These were adjusted firstly to allow for labour to be provided at no cost from either voluntary activity or other Government programs (eg employment). Secondly, alterations were made to these budgets to represent the costs of direct seeding and natural regeneration. Costs per hectare varied from slightly less than $2,000 for planting including labour costs, to less than $500 per hectare for natural regeneration without labour costs.

The amount of carbon dioxide sequestered in the year 2000 by 15,000 hectares established under the $7.5 million extension (at $500 per hectare), 7,500 hectares (at $1,000 per hectare) and 3,750 hectares (at $2,000 per hectare) was then calculated. Among the possibilities considered feasible, the most carbon dioxide absorbed in the year 2000 was 0.144 M tonnes by 15,000 hectares of natural regeneration (Productivity class E3) and 0.128 M tonnes by 7,000 hectares of direct seeding (E1).

Due to the continuing acceleration in the growth rate of these plantations far more carbon dioxide is absorbed per year in years after 2000. For eucalypts planted in the $7.5 million extension program, maximum absorption will be achieved in the period 2009-20 (24 tonnes per hectare per year compared to 21 tonnes per hectare per year in 2000), and for pine plantations, maximum carbon dioxide absorption will be in the period 2019-20 (39 tonnes per hectare per year compared to 19 tonnes per hectare per year in 2000).

Spacing of plants is not considered an important issue. Providing canopy closure occurs within 5-7 years of establishment, many different spacings will achieve the same carbon dioxide absorption.

The results need to be treated with considerable caution since both the data used on tree growth and the data used for plantation budgets were scanty.

There is a considerable amount of work remaining to be performed. This includes making the model user friendly; more attention to deriving suitable budgets; effects of taxation; costs of plantation management; land availability for planting; more data for determining the growth rate of trees across Australia's climatic zones; expanding the capability of the model to cope with other variables; fire; the carbon dioxide contributions to the atmosphere of activities involved in plantation establishment and sensitivity analyses.

1. BACKGROUND

1.1 Tree planting

In 1989, the Prime Minister announced the establishment of the One Billion Trees (OBT) Program. The aim of the Program is to have a billion trees planted by the year 2000, by encouraging the community to re-establish native trees and associated vegetation in a strategic way to achieve sustainable land use and biological diversity. Native vegetation, in particular, is considered to be a key factor in the management of Australia's natural resources - including soil and water quality and the future of Australia's flora and fauna. The Government offered a grant of $4.7 million in the first year of the program, with a commitment to make similar annual contributions for the rest of the decade.

In addition to the OBT program, there are related Government programs:

- Save the Bush, focusing on the protection, management, and study of remnant native vegetation,
- Farm Forestry Program,
- Natural Resources Management Strategy of the Murray-Darling Basin Commission, and
- North Queensland Community Rainforest Reforestation Program.

In 1992, the Prime Minister announced that the Government would be setting aside $4.5 million over the next four years to boost the Save the Bush program. It was also announced that the Government would provide $3.1 million over the next four years to help establish a "National Corridors of Green" along the Murray River, and that the Government would also develop other "National Corridors of Green".

The Farm Forestry Program has a budget of $2 million.

The Australian Government, through the Australian Nature Conservation Agency (ANCA), initially contracted with Greening Australia Ltd to implement most of the OBT program. From 1992, Greening Australia has not been directly responsible for disbursing the OBT community grants, but has continued its role in pre-application assistance, in monitoring outcomes, and managing other parts of the program on behalf of the Government. The OBT community grants are now administered by ANCA and are provided to community groups and local governments.

1.2 Greenhouse Gas Response Strategy

The National Greenhouse Response Strategy, endorsed by the Council of Australian Governments in December 1992, confirmed that, in order to conserve and enhance the sink capacity of Australia's natural environment, it would be necessary to adopt land use and management measures to conserve sinks, including vegetation retention controls, forestry management and creation of conservation reserves, and increase the amount of vegetation, in forests and elsewhere, including through reafforestation, rehabilitation, and expanded plantations.

In March 1995, the Minister for Environment, Sport, and Territories, in "Greenhouse 21C A plan of action for a sustainable future", stated that, "The Government will commit a further $7.5 million to the One Billion Trees Program, recognising the substantial contribution already made by this program to enhancing skills". The Action Plan set a target for the OBT expansion measure of 2 million tonnes of carbon dioxide sequestered in the year 2000. The Greenhouse 21C Action Plan also announced the establishment of an Urban Forest Program as part of the expansion measure.

He also indicated that, "The Commonwealth is committed to ensuring that 50,000 hectares are planted this year through the effective combination of Commonwealth programs. Through Working Nation this will be increased over the next two years. By the year 2000 it is expected that these measures will have contributed to reducing greenhouse emissions by up to one million tonnes". Also, that, "By more effectively integrating labour market programs with One Billion Trees, Save the Bush, and Landcare at a regional level, there will be significant employment and environmental benefits."

The goal of the One Billion Trees program is to enthuse, educate, and empower the community to protect and enhance Australia's cover of native trees and associated vegetation, in the interest of biodiversity conservation and ecologically sustainable development for community and private benefit. The Greenhouse 21C OBT expansion measure shares the same catalytic goal.

The Department of Employment, Education and Training (DEET) plans to use its Labour Market Programs to contribute to the Commonwealth program for planting 50,000 hectares of trees per annum. Under existing programs, up to 25,000 participants are engaged in environmental activities, and over the next three years DEET will commit a further 90,000 environmental employment places.

DEET will be expecting to achieve a high level of labour market program participants continuing training or further education in forestry and environmental management and an increase in number of plantations across Australia as a result of planting from labour market programs, including planting on private land.

1.3 This study

The purpose of this consultancy is to determine the likely outcome in terms of carbon dioxide sequestration and area of plantation established from the $7.5 million allocated to the One Billion Trees Program.

2. REQUIREMENTS FOR THE STUDY

The requirements for the study were specified as follows.

The establishment of a rigorous and transparent methodology for the estimation of carbon dioxide sequestration by native and exotic trees at varying life stages from the time of establishment to maturity.

Use of the above methodology to estimate the area of trees which need to be planted or revegetated to reach the Government's target for carbon dioxide sequestration set out in the Government's Greenhouse 21C Action Plan, including:

- whether the government's target of 2 million tonnes of carbon dioxide sequestered per year by 30 June 2000 can be achieved (Section 4.1)
- calculation of the carbon dioxide sequestration by trees (above and below ground) of two broad climatic regions, namely 600-800 mm and 800 mm+ rainfall regions (Section 4.2)
- calculation of the rates of sequestration of carbon dioxide for specified catchment/corridor areas and eight urban forest areas (nominally the capital cities in each State and Territory) (Section 4.3)
- estimates of the amount of sequestration for each of the five years 1995-96, 1996-97, 1997-98, 1998-99, and 1999-2000 based on an establishment program in 1995-96, 1996-97, and 1997-98 at a cost of $1.5 million, $3 million, and $3 million respectively (Section 4.4),
- estimates of the amount of carbon dioxide sequestered from planting under the same program at 30 June 2005, 30 June 2010, 30 June 2020, 30 June 2030, 30 June 2040, 30 June 2050, and so on until average maturity (Section 4.4).

The developed model to include the effect of rainfall, temperature, species type and planting density on carbon dioxide sequestration within the two broad climate regions described above.

The developed model to also include a comparison of the tree planting or revegetation options, with the two broad biogeographic regions of activities including:

- planting with full use of herbicides
- direct seeding with partial use of herbicides, and
- natural regeneration (Section 4.2).

3. APPROACH

3.1 Model development

The rate of carbon dioxide sequestration by forests is influenced by a wide range of factors including rainfall, soils, temperature, species, management styles and the impact of natural disasters such as fire.

Models which predict the growth of forests in terms of merchantable stemwood volume are available for many areas of Australia. Using assumptions relating merchantable wood volume to total biomass it is possible to use these models to calculate biomass accumulation, and hence carbon. The models are commonly region and species specific and, while they could be of great assistance for a detailed examination for later studies, were not considered suitable for the current investigation.

Previous studies (Richards 1969, quoted by Barson and Gifford 1989) proposed an asymmetrical sigmoidal function (the Gompertz Equation) to simulate the time course of net carbon accumulation as a forest grows. The function takes the general form:

$$W = A*\exp(-b*\exp(k*t)) \qquad (1)$$

where

W	is the carbon dioxide sequestered (tonnes/ha)
t	is the time (in years)
A	is the asymptotic value of W
b and k	are constants.

This model was chosen to describe above ground biomass on the assumption that the quantity of carbon accumulation can be directly related to biomass accumulation.

Radiata pine

Biomass studies for tree plantations are relatively limited with the greater proportion of studies having been undertaken on radiata pine. Madgwick *et al* 1977 presented data for above ground biomass accumulation for eight sample stands of radiata pine ranging in age from 2 to 22 years. These data were fitted to the general form of function (1) and a set of constants for A, b and k derived. It was assumed that these data represented the best growth that could be achieved under optimal conditions.

Grierson *et al* (1992) made estimates of above ground biomass accumulation for Victoria's forests. The data for radiata pine (a. Central Gippsland and Otways regions; and b. All other regions) were fitted to the general form of function (1) and two sets of the constants A, b and k derived.

The general form of the functions derived were compared with other biomass data including the CSIRO Biology of Forest Growth data (Myers et al 1991) and additional data for New Zealand presented by Madgwick (1994).

From an examination of the data and the fitted curves, it became apparent that the addition of an extra term in the function would better describe the relationship.

The function then takes the general form:

$$W = A*\exp(-b*\exp(k*t)) + z \qquad (2)$$

where

W	is the carbon dioxide sequestered (tonnes/ha)
t	is the time (in years)
A	is the asymptotic value of W
b and k	are constants
z	is equal to -A*exp(-b).

Three curves were then generated using smoothed constants and these were taken to represent three productivity classes; the best growth (P1), good growth (P2), and average growth (P3). No curves were generated for below average growth.

The curves were developed primarily from stem volume models which were then used as a basis to predict above ground biomass. When extrapolated to young ages, inconsistencies were found. While these are not of consequence to the project, the advisory group indicated a preference for functions which provided consistency over the whole range of ages. By adding the variable z, this could be achieved and a set of smooth curves was able to be generated.

The values of the constants for each pine productivity class are shown in Table 1 below:

Table 1. Values for Constants for Pine Productivity Classes

Constant	P1	P2	P3
A	700	495	310
b	4.85	4.3	3.7
k	0.077	0.079	0.08
z	-5	-7	-8

The declining values of A from P1 to P3 indicate that the maximum carbon that can be accumulated per hectare, declines with the productivity of the land.

Eucalypts

Biomass studies for tree plantations are relatively limited with the lesser proportion of studies having been undertaken on eucalypts. Grierson *et al* (1992) made estimates of above ground biomass accumulation for Victoria's forests. Regression equations relating above ground forest biomass to forest age were presented for a number of eucalypt types. Data were calculated from the regressions for some typical forest types and the data fitted to the modified asymmetrical sigmoidal function (2) described for radiata pine.

The growth for E. regnans was taken to represent the very best eucalypt productivity class (E1), the growth data for coastal eucalypts were taken to represent average productivity (E3) and the box ironbark the lowest productivity (E5).

The general form of the functions derived were compared with other biomass data including CSIRO Wagga Effluent Plantation Project (Myers et al 1994) and the Wodonga effluent study (Hopmans *et al* 1990).

Five curves were then generated using smoothed constants and these were taken to represent the best growth (E1), average growth (E3) and poor growth (E5); productivity curves E2 and E4 were intermediate.

The values of the constants for each eucalypt productivity class is shown in Table 2 below:

Table 2. Values of Constants for Eucalypt Productivity Classes

Constant	E1	E2	E3	E4	E5
A	700	575	450	310	185
b	2.4	2.3	2.2	2.1	2.0
k	0.049	0.044	0.040	0.035	0.030
z	-64	-58	-50	-38	-25

Again, the values of A represent the maximum amount of carbon that can be accumulated per hectare in each productivity class.

By adding the constant (z), curves which provide a good fit to the data and provide a logical transition at young ages were developed. These curves are illustrated in Figure 1.

There was a distinct difference in the form of the biomass accumulation curve between pine and eucalypt data, with the eucalypts growing faster in the early years and then the pine trees growing faster for the rest of the 40 years modelled.

This is best illustrated by Figure 2, which shows the annual increment of carbon dioxide for the first ten years.

Predicting carbon dioxide sequestration

This methodology allowed above ground biomass to be calculated from a set of curves generated for each species group and for a range of productivity classes. Intermediate values can also be calculated by scaling the constants accordingly. The methodology provides the tool to be able to predict carbon dioxide sequestration over time from a variable tree establishment program over a wide range of sites and with a wide range of management approaches.

Data for root biomass are scarce. Data for 4-year-old irrigated eucalypts and pine at Wodonga (Stewart *et al* 1988) showed the mass of roots as a proportion of total biomass ranged between 16% and 19%. Data for radiata pine (Madgwick 1994) shows a wide variation; 20% for 42-year-old stand, 34% for a 28-year-old stand, and 12% for an 18-year-old stand. In the absence of broad data sets, increasing above ground biomass by 20% to estimate total biomass appears to be a reasonable compromise. Higher than 20% root biomass could be possible. (The model would readily allow the impact of assuming, say, a 30% root component by changing the conversion factor shown below.)

The conversion factor used from biomass estimates to carbon was 0.45 (DEST 1994). Other workers have adopted 50% (eg Barson and Gifford 1989), but Farquhar (personal communication) believes 45% to be a more accurate factor.

Thus to convert above ground biomass estimates to total (above and below ground) carbon equivalent, the figures were multiplied by 0.45*1.20 = 0.54 (biomass to carbon x multiplier to account for root biomass as well). To convert carbon to carbon dioxide equivalent, the result is multiplied by 3.67 (see page 9).

3.2 Modelling the impact

The impact of selecting a variety of choices of climate, species, and establishment style on carbon dioxide sequestration has been undertaken using an interactive model. This model uses the carbon dioxide sequestration functions developed above and incorporates factors such as budget availability, price for tree establishment, year established and productivity class.

Management type

Each approach to forest management results in a different outcome in terms of carbon dioxide sequestration. Table 3 attempts to place each potential forest type into a productivity class.

Table 3. Allocating Growth Classes by Characteristics

Rainfall	Species	Establishment Style	Productivity Class
400-600	Best growing species	Planting	E4
		Direct Seeding	E4
		Natural Regeneration	n/a
	Local provenance	Planting	n/a
		Direct Seeding	E5
		Natural Regeneration	E5
600-800	Best growing species	Planting	E2 or P2/P3
		Direct Seeding	E3
		Natural Regeneration	n/a
	Local provenance	Planting	E3
		Direct Seeding	E4
		Natural regeneration	E5
800+	Best growing species	Planting	E1 or P1/P2
		Direct Seeding	E2
		Natural Regeneration	E2
	Local provenance	Planting	E2
		Direct Seeding	E3
		Natural Regeneration	E3/E4

The study requirements stated that "the developed model to include the effect of rainfall, temperature, species type, and planting density in carbon dioxide sequestration within the two broad climatic regions ..." The table above provides our approach to all but temperature.

Plant response to temperature is quite complicated, since higher temperatures increase both photosynthesis and respiration. So maximum plant growth is obtained with warm days and cold nights. *Ceteris paribus,* tree growth should be faster on the Atherton Tablelands than at Cairns and at Dorrigo than Bellingen. To model tree growth and temperature we would need to model the interaction of rainfall with day and night temperature, or divide Australia up into bioclimatic regions and provide separate growth curves for those bioclimatic regions. Not including temperature in the model would not affect the outcomes developed within this paper. Including temperature effects will be needed where land allocation choices are to be made on a regional basis, such as between the tablelands and the coast.

Cost classes

Budgets for the different styles of management and different subsidy rates were established using commercial budgets for plantation establishment and then modifying these with additional information supplied by Greening Australia (NSW) from the North Coast Regional Office at Lismore (costs of up to $10,000 per hectare for cabinet timbers were presented) and the South West Plains Regional Office at Deniliquin. The final budgets are summarised in Table 4 and presented in detail in the Appendix. They include fencing, land preparation, plants (or seeds), planting (or seeding) costs, fertiliser, weed pest and disease control, pruning, thinning, maintenance (fire control), supervision, and contingency costs.

The budgets covered six possible alternatives in a three-by-two matrix. Firstly, from the commercial plantation budget the full cost of planting trees including full labour and materials costs were included. No cost was attributed to the rental cost of the land, as it was assumed that land for planting would have no rent attributed to it, or that this would be part of the community's contribution, or that the benefits of tree planting in ameliorating degradation would compensate for the rental value of land forgone for tree planting. Then, allowing for community input and additional government programs (eg., Department of Employment, Education, and Training) labour and materials costs were subtracted. Each of the three budgets was then adapted for direct seeding by replacing planting costs with seeding costs and then for natural regeneration by removing seeding costs.

Each budget has an expenditure estimate for the first ten years and a maintenance budget thereafter. Since the funds supplied by the Billion Trees Extension are solely for establishment, only the first year's costs have been included as the establishment cost of plantations. These full budgets are presented in the Appendix. The first year costs are presented in Table 4.

Table 4 First year costs per hectare of plantation establishment

	Planting	Direct Seeding	Natural Regeneration
Including labour	$1944	$1157	$680
Not including labour	$1544	$872	$419

The range of costs varied from $1,944 for planting with labour costs included to $419 for natural regeneration with labour costs met by the community or other government programs. As stated later, the budgets are first approximations only and should be checked against costs incurred by those using both the different methods of establishment and the different government programs.

The model has been set up so that the amount in the budget can be varied and the impact on the program assessed. The cost of preparing plans and fencing are highly dependent on size and shape. Long narrow strips could easily involve costs exceeding $500 per hectare. Large areas could involve substantially less.

In order to simplify the costs of establishment, three levels of costs, $2,000 (C1), $1,000 (C2), and $500 (C3), have been used in Section 4, with the exception that planting costs of less than $1,000 per hectare were not explored for classes E1-3 and P1-3, as these were not considered feasible. $2,000 represents the upper end of the range for planting; $1,000 represents what can normally be achieved using direct seeding; and $500 represents the approximate costs per hectare for natural regeneration.

Fund Allocation

The number of hectares that can be allocated to carbon dioxide sequestration is limited by the cost per hectare of establishment and the funds allocated by Government. The model is built to allow any amount of funds (in $M) to be input for a 10 year period.

Preferences

Given that priorities for tree planting for the particular mix of productivity classes will be defined by a number of sociological or other factors, the model allows preferences for the particular mix of productivity classes to be input for each year in a matrix. Using the budget constraints, the model then calculates the area of each class that can be established for each year.

Once the productivity classes are defined, the establishment costs set, the budget for each year set and the preferences chosen by year, the model calculates carbon dioxide accumulated each year. Carbon dioxide is obtained by multiplying the carbon accumulated by 44/12 or 3.67.

4. OUTPUT

4.1 What can be achieved with the current budget

Table 5 presents the model's results for carbon dioxide accumulated for a range of species types by a range of establishment costs for the budget of $7.5 million as currently proposed.

Table 5. Area Planted/Regenerated and Carbon Dioxide Absorbed in the Year 2000 and Accumulated over the Project Period to 2000 for a Budget of $7.5 Million Over the Next Three Years

	C1, $2,000			C2, $1,000			C3, $500		
Productivity Class	Area (ha)	Total CO2 absorbed to year 2000 (Mt)	CO2 absorbed in 2000 (Mt)	Area (ha)	Total CO2 absorbed to year 2000 (Mt)	CO2 absorbed in 2000 (Mt)	Area (ha)	Total CO2 absorbed to year 2000 (Mt)	CO2 absorbed in 2000 (Mt)
E1	3,750	0.167	0.064	7,500	0.334	0.128			
E2	3,750	0.129	0.049	7,500	0.258	0.098			
E3	3,750	0.097	0.036	7,500	0.193	0.072	15,000	0.386	0.144
E4	3,750	0.061	0.022	7,500	0.122	0.045	15,000	0.244	0.090
E5	3,750	0.033	0.012	7,500	0.066	0.024	15,000	0.132	0.048
P1	3,750	0.069	0.028	7,500	0.138	0.056			
P2	3,750	0.067	0.029	7,500	0.134	0.058			
P3	3,750	0.061	0.026	7,500	0.123	0.052			

(shaded) These combinations were not considered possible. See section 3.2.

If planting costs are in the region of $2,000, direct seeding $1,000, and natural regeneration $500, independent of productivity class, then natural regeneration over the 15,000 hectares that can be funded for this activity will absorb more carbon dioxide (0.144 tonnes) than the area that can be seeded (7,500 hectares absorbing 0.128 tonnes/year) or the 3,750 hectares per year that can be planted (0.064 tonnes/year).

If the planting strategy concentrates solely on achieving the maximum carbon dioxide absorption in the year 2000, then eucalypts will be preferred to pines.

4.2 Budget required to Achieve the Target

On the basis of the information in Table 5, the question can then be asked, "How many dollars need to be allocated to achieve the greenhouse target of 2 million tonnes of carbon dioxide per year by the year 2000?" The assumption is made that the funds will be provided in the ratio 1:2:2 for the years 1995-96, 1996-97, and 1997-98. The answers are provided in Table 6.

Table 6. Areas of Plantations Required and Budget ($ million) to Achieve the Target of 2 Million Tonnes of Carbon Dioxide Absorbed in the Year 2000

Productivity Class	Area (ha)	Funding Required		
		C1 ($2,000)	C2 ($1,000)	C3 ($500)
E1	117,300	$234,600,000	$117,300,000	
E2	153,750	$307,500,000	$153,750,000	
E3	208,122	$416,25,000	$208,130,000	$104,060,000
E4	333,685	$667,370,000	$333,680,000	$167,840,000
E5	630,705	$1,261,400,000	$630,700,000	$315,350,000
P1	265,506	$531,000,000	$265,500,000	
P2	258,299	$516,600,000	$258,300,000	
P3	286,673	$573,350,000	$286,700,000	

(shaded cells) These combinations were not considered possible. See section 3.2.

At an establishment cost of $500 for Productivity Class 3, $104.06 M (fourteen times the current budget) would be needed. At an establishment cost of $1,000 for Productivity Class 1, $117.3 M (sixteen times) would be needed, and for an establishment cost of $2,000 for Productivity Class 1, the cost of achieving the target is $234.6 M (thirty one times).

4.3 Rainfall, regions, species, and style of establishment

Table 7 provides the data on carbon dioxide absorbed per hectare (tonnes per hectare per year) for the different rainfall regions, species, and establishment styles as given in Table 3 for a planting in 1995-96.

Table 7. Allocating Growth Classes by Characteristics

Rainfall	Species	Establishment Style	Productivity Class	Carbon Dioxide Absorbed in Year 2000 (tonnes per hectare per year)	Carbon Dioxide absorbed to Year 2000 (tonnes per hectare)
400-600	Best growing species	Planting	E4	6	16
		Direct Seeding	E4	6	16
		Natural Regeneration	n/a	-	
	Local provenance	Planting	n/a	-	
		Direct Seeding	E5	3	9
		Natural Regeneration	E5	3	9
600-800	Best growing species	Planting	E2 or P2/P3	13 7	35 17
		Direct Seeding	E3	10	26
		Natural Regeneration	n/a	-	
	Local provenance	Planting	E3	10	26
		Direct Seeding	E4	6	16
		Natural regeneration	E5	3	9
800+	Best growing species	Planting	E1 or P1/P2	17 8	46 18
		Direct Seeding	E2	13	35
		Natural Regeneration	E2	13	35
	Local provenance	Planting	E2	13	35
		Direct Seeding	E3	10	26
		Natural Regeneration	E3/E4	8	21

Not surprisingly, the highest amount of carbon dioxide absorbed is from E1 at 17 tonnes per hectare per year, while the lowest is from E5 at 3 tonnes per hectare per year. So, the highest achievement of carbon dioxide absorption per hectare will come from E1 sites.

4.4 Capitals and corridors

On page 14 of "Greenhouse 21C A plan of action for a sustainable future", there is a commitment to Urban Forests. In his Media Release of 15 June 1995 the Minister stated that funds from the $7.5 M OBT expansion would be used on "new corridor projects". In order to deal with these two issues we have tabulated the rainfalls for both the urban areas to be forested and the corridors to be forested. Since rainfall can vary across capitals, and along the corridors, we have taken a representative site for each, where there is known to be open space available for forestation. For Adelaide and Melbourne we have taken two sites to represent these capitals, since rainfall varies considerably across them.

Table 8. Rainfalls for Representative Capitals and Corridors

Place	Classification	State	Rainfall (mm/yr)	Productivity Class
Todd River	Corridor	NT	268	E5
Murray River (Echuca)	Corridor	NSW/Vic	400	E5
Rocky River	Corridor	SA	400	E5
Elizabeth (Adelaide)	Capital	SA	500	E4
Werribee (Melbourne)	Capital	Vic	500	E4
Hobart	Capital	Tas	600	E3
Macquarie River	Corridor	NSW	600	E3
Hopkins River	Corridor	Vic	600	E3
Canberra	Capital	ACT	700	E3
Fairfield (Sydney)	Capital	NSW	750	E3
Blackwood River	Corridor	WA	800	E3
Hunter River	Corridor	NSW	800	E3
Derwent River	Corridor	Tas	800	E3
Upper Murrumbidgee River	Corridor	ACT/NSW	800	E3
Gumeracha (Adelaide)	Capital	SA	800	E3
Perth	Capital	WA	850	E2
Dandenong (Melbourne)	Capital	Vic	1,000	E1
Mary River	Corridor	Qld	1,000	E1
Brisbane	Capital	Qld	1,100	E1
Darwin	Capital	NT	1,600	E3

Most carbon dioxide absorption will come from planting activities in the highest productivity class zones, E1. If costs are approximately those given earlier, then the sites where returns in carbon dioxide sequestered per dollar invested are not so clear.

4.5 Sequestration through time

The rates of sequestration of carbon dioxide over the period to 2050-51, by representative species and establishment style scenarios, are shown in Table 9.

Table 9. Carbon Dioxide Absorbed in the year (t/ha), by Productivity Class using the planting budget ratio 1.5 : 3 : 3, 1995-96 to 2050-51

Year	E1	E3	P1
1995-96	0	0	0
1996-97	14	9	6
1997-98	15	9	6
1998-99	16	9	6
1999-2000	17	10	8
2005-06	21	11	19
2009-10	24	12	31
2019-20	24	13	39
2129-30	20	12	29
2139-40	15	10	17
2149-50	10	7	8

The table illustrates that, even though the targets set for the year 2000 will not be met by the current budget, in the year 2019-20, 24 tonnes of carbon dioxide will be absorbed per hectare by E1 plantations - which compares to 17 tonnes in 1999-2000. With P1 (pines), a peak of 39 tonnes/hectare/year is achieved in 2019-2020 compared to 8 tonnes/hectare/year in 1999-2000.

4.6 Spacing

The issue of the number of stems per hectare has been omitted as there are a wide range of tree densities which will produce a very similar outcome. It has been assumed that each class would typically reach a closed canopy early in the life of the forest, typically age 2-5 for eucalypts (depending on class) and 4-5 for pine.

A forty year old pine forest, for example, will have a closed canopy with around 250 stems per hectare. Regular, but light thinning will remove carbon in the biomass but will have little impact on the amount of carbon dioxide sequestered by the forests, and this can be used as a technique to enhance sequestration. This aspect is not covered in the model.

The rate at which a closed canopy is achieved would depend on initial spacing and forest type. Higher productivity eucalypt (E1) will achieve closed canopy at around age 3 for an initial density of 1,000 stems per hectare; closed canopy may be delayed until age 4 for 500 stems per hectare. A lower productivity eucalypt (eg., E3) at 1,000 stems per hectare may not develop a closed canopy until age 5.

In a more sophisticated model, the issue of initial spacing and stocking density over time for a range of productivity types can be included. At a planning level, the model can be used to estimate the impact of, say, adopting an agroforestry regime which has a 50% canopy occupancy by multiplying the amount of carbon dioxide sequestered by 50%.

4.7 Establishment costs

If instead of using standardised rates of $2,000, $1,000 and $500 per hectare for establishment costs, the costs given in Table 4 are used, then areas that can be planted with the $7.5 M budget allocated over the three years in the ratio 1.5:3:3 are given in Table 10, along with the carbon dioxide absorbed in the year 2000.

Table 10. Carbon Dioxide Absorbed in 1999-2000 if Budgeted Plantation Costs Are Used

Labour included	Establishment method	Cost of establishment (per hectare)	Productivity class	Area (hectares)	CO2 absorbed in 1999-2000 (million tonnes)
No	Planting	$1,544	E1	4,858	.083
	Direct seeding	$872	E2	8,601	.112
	Natural regeneration	$419	E2	17,943	.244
Yes	Planting	$1,944	E1	3,858	.066
	Direct seeding	$1,157	E2	6,482	.084
	Natural regeneration	$680	E2	11,029	.144

Under these assumptions spending all the available funds on natural regeneration in places where a growth curve of E2 (rainfall above 800 mm) can be achieved will absorb more carbon dioxide in 1999-2000 than either direct seeding or planting. This is because of the lower costs of natural regeneration. Whether land is available in these quantities in these areas for natural regeneration of trees was not determined.

These numbers should be used with considerable caution, as not only are the costs first approximations, but the curves for natural regeneration and direct seeding are based on limited evidence.

5. CONCLUSIONS

5.1 Caveats

It is important to state the limitations of the study to date.

The models have been developed from data collected in New Zealand, Victoria and Wagga Wagga, NSW, and then applied to a very wide range of climatic and species types. The models thus provide a framework for evaluation, but further work using more comprehensive data sets would be required to develop more specific models.

The models are based on growth models which describe stem volume over time. Biomass studies have been used to estimate above and below ground biomass. As forestry models rarely estimate stem volume for trees less than age 10, the basis for biomass estimates in younger stands is weak.

5.2 Output

The results for carbon dioxide accumulated for a range of species types, by a range of establishment costs, for the budget of $7.5 million as currently proposed, have been presented. The results indicated that the best possible outcome within the range of probable combinations, using the current budget of $7.5 million over the next three years, is an annual increment in the year 2000 of 0.144 million tonnes of carbon dioxide (eucalypt class E3 at $500 per hectare establishment cost). The least favourable outcome among those analysed was an annual increment in the year 2000 of 0.012 million tonnes.

With their faster growth in the early years, eucalypts are preferred to pines, but over a longer time frame pines (39 tonnes per hectare per year in 2019-20) will accumulate more carbon dioxide per year than eucalypts (25 tonnes per hectare per year in 2019-20). There are many issues (biodiversity, soil acidification, etc.) which need to be considered if a full assessment of pines versus eucalypts is to be made.

The model is predominantly derived from plantation/commercial forestry information and community plantings may not be able to achieve the same results.

The most efficient allocation depends on establishment costs and productivity class, and no definite statement can be made at present as to where these will be obtained. More work is required, especially on the establishment costs per hectare, to determine the most efficient allocation of limited funds.

5.3 More economic plantings

An overall objective of commercial production of wood from plantings would be desirable, in order to avoid a situation where a large expenditure of funds on plantation establishment and maintenance resulted in a poor rate of return on the use of those resources from the standpoint of the national economy.

Dargavel and Semple (1990) stated that "setting commercial production as the primary objective entails choice of species, establishment sites and general location based on economic criteria, careful and detailed evaluation of establishment and maintenance costs, growth rates, product outputs, projected timing and magnitude of resources, cash flows, total investment and focus on resource aggregations sufficient to achieve economies of scale in management, and to attract commercially viable industries capable of using the full range of forest products."

They also pointed out that "there is limited expertise at present for establishment of plantations of other conifers or eucalypts (particularly on land formerly used for agriculture). Mistakes have occurred in the past due to suitable land at reasonable cost not being available - scattered areas and consequent increased costs, establishment costs not well known, inadequate funding (supervisory personnel), economically desirable standards of site preparation and level of herbicide, fertiliser and rodenticide were uncertain, non-availability of labour, leakage of chemicals into groundwater. General field application of the results of research trials of species site suitability, growth rates, treatment responses and product output often (if not usually) results in markedly poorer growth rates or treatment responses than were predicted, due to inadequate knowledge of the response of a particular species to specific environmental variables, site quality, establishment techniques, or fertiliser, herbicides, insecticide in thinning treatments, failure to match site-specific variable with those associated with the research trial (eg., soil parent material, structure, and drainage), aerial methods of broadcasting, inadequate site preparation, inadequate management control of intensified treatment, and inability to accurately estimate stem defects."

6. FURTHER STUDIES

On the basis of the above study, areas where further work is required include the following: -

6.1 Making the model more user friendly

As it is currently constructed, the model requires someone familiar with the issue and the contents of the model to operate it. There appears to be demand for this model to be used to determine "Greenhouse credits" to compensate for greenhouse gas emissions. The task is relatively simple and Hassall & Associates would be pleased to perform this task.

6.2 Budgets

Budgets for tree planting activities from applications to the OBT are available as a data source. These and other data could be used to further validate the cost of plantation establishment per hectare.

These data will probably indicate that the cost of establishment will vary between regions (as rainfall drops, property sizes become larger, the size of plantations will increase, cost of fencing will drop, but so too will the amount of carbon dioxide absorbed per hectare).

In any case, with cost of establishment being a major parameter in determining how much carbon dioxide is accumulated per dollar expended, it is useful to all calculations to find out the true cost of plantation establishment.

6.3 Taxation

Changes to the tax law in recent years, particularly in relation to the taxation of grants received from Government, will have impacts on the establishment of plantations, and this aspect should also be investigated.

6.4 Plantation Management

So far, nearly all attention in the Government's tree planting strategy has been on the planting component. Management strategies for these plantations need to be considered.

If these plantations grow to maturity and are then left as standing timber (mass of carbon) they will not be sequestering carbon dioxide, because photosynthesis and respiration will come into balance. If they are to be harvested, then part of the harvest will be destined for short term storage, like firewood, part for medium term storage, like paper, and part for long term storage, like structural timber. The greenhouse consequences of carbon storage have been discussed by Barson and Gifford (1989). The fate of these carbon storages could easily be tracked in the model.

6.5 Land availability

More detailed consideration could be given to factors influencing land suitability for plantations, including whether there is cleared land to plant, soil type (particularly depth and nutritional status), prior land use, rainfall, altitude (in relation to snowfall), topography, exposure, site accessibility and location.

Should the marketing of the timber from and land degradation benefits of these plantations be important considerations, then a more detailed search for suitable sites and areas would be needed.

6.6 More data for model building

Chris Borough, the forestry consultant to Hassall & Associates for this study, performed a consultancy to collect a large quantity of data on tree growth curves in 1991. The data need to be updated, so that the many decisions being made on tree planting and forestry today are based on a better data set. In addition, the FARMTREE model could be used to validate the model used in the above study for places such as Victoria, where FARMTREE has been validated against data.

6.7 Expanding the capabilities of the model

To cope with frequently encountered situations, variables should be added to the model to take into account such factors as:

- tree growth patterns, with and without "mining" of groundwater, where the increasing scarcity of the groundwater has caused tree growth to rapidly decline;
- above and below ground carbon accumulation, allowing for variations in prior carbon level of the soil as a consequence of varying periods since clearing; and
- climate variability (eg., drought), variations in predicted rainfall due to Greenhouse effects, variations in water use efficiency due to higher levels of carbon dioxide.

6.8 Fire

Both controlled burning, to avoid wildfires, and wildfires themselves put carbon dioxide back into the atmosphere. Controlled burning is likely to have a small but noticeable effect on carbon accumulation; uncontrolled burns are likely to have a large effect on carbon accumulation on the hectares that are burnt.

To examine fire in more detail, figures could be obtained of the current situation of the occurrence of fire in Australia and the proportion of different types of fire in different types of plantation and forest each year. Then the effect of controlled burning and other fire management practices could be examined for the effects on carbon accumulation.

Currently, bushfire contribution to carbon dioxide emissions are not counted in the National Greenhouse Gas Inventory, the IPCC assumption being that the carbon dioxide is taken up by regrowth.

6.9 Net benefits in terms of carbon dioxide sequestration

Establishing plantations involves the use of materials, labour and fuels which will all emit carbon dioxide to the atmosphere. The more materials that are used the more carbon dioxide will be produced. If these releases of carbon dioxide are included in the absorption curves of the established plantations then the graphs would start at year zero with carbon dioxide emissions. The year when cumulative contributions are positive is hard to estimate until some budgeting of the carbon dioxide emissions has been performed, but including these emissions in the curves will give an advantage to natural regeneration, because emissions will be lowest with this form of establishment.

6.10 Other benefits of reforestation

Currently, nearly all plantations are being established for other purposes - timber production, erosion control, windbreaks, groundwater management, biodiversity, etc. So carbon accumulation benefits are being obtained as a fringe benefit, rather than a direct benefit of the planting activities. This being the case then most of the costs attributable to the planting should be debited to its major purpose, and only the marginal costs, such as fertiliser should be debited against the greenhouse benefits.

6.11 Sensitivity analyses

Although the major effects of cost of establishment, rainfall, species, and method of establishment have been presented above, sensitivity analyses are a critical step for validating factors in the model and should be incorporated in any further studies, eg., to cope with the availability of land, climate variability, removals, and fire.

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