CARBON SEQUESTRATION BY NEW ZEALAND'S PLANTATION FORESTS

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ABSTRACT

Annual carbon uptake by the 1.24 million ha of plantation forest in New Zealand was calculated from detailed information provided to the Government by private owners on the age and volume of the timber resource, a national database of wood density variations, models of the allocation of biomass to tree and forest components other than stems, and estimates of roundwood removals derived from annual Government surveys of sawmills, chip mills, and other wood product mills, as well as export data.

The plantation forests of New Zealand stored approximately 4.5±0.8 million tonnes C in the year between 1 April 1988 and 1 April 1989, increasing total plantation carbon storage to approximately 88 million tonnes C in April 1989. Without harvest, the average annual carbon uptake of the New Zealand plantation estate between 1988 and 1989 would have been approximately 6.4 tonnes C/ha. Plantation roundwood removals were equivalent to 2.7 tonnes C/ha, so that average carbon storage was approximately 3.6 tonnes C/ha. Some harvested carbon is stored in wood products, and additional carbon may be stored in the mineral soil, but these quantities were not included in our estimates. The annual storage of carbon in the New Zealand plantation estate in 1988–89 was equivalent to approximately 70% of total New Zealand fossil fuel emissions, but was <0.1% of total global fossil fuel emissions.

The high annual rate of carbon uptake by the New Zealand plantation estate is a consequence of a large area of new plantings initiated in the 1970s and 1980s. Without continued new plantings, the net annual rate of carbon uptake by New Zealand plantation forests will rapidly approach zero.

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INTRODUCTION

Concern about the consequences of global climate change resulting from increasing levels of carbon dioxide and other trace gases (IPCC 1990) has led to studies of the carbon uptake and storage capacity of planted forests (Dyson 1977; Breuer 1979; Brown & Lugo 1982; Cooper 1983; Marland 1988; Sedjo 1989; Vitousek 1991). These authors concluded that a massive area of land would need to be forested to provide an enhanced global carbon sink that is comparable with present fossil fuel carbon dioxide emissions, and that, moreover, such a sink would exist only for as long as the new forests continued to accumulate biomass. However, if such a forest resource was then used to substitute for fossil fuels, the net amount of carbon dioxide released to the atmosphere could be significantly reduced (Vitousek 1991).

On a more local scale, there is considerable interest in the carbon budgets (sources and sinks of carbon dioxide) of individual countries or states and in the potential of various measures such as growing forests to offset the carbon dioxide emissions of individual corporations. All require reliable and detailed information about the growth of plantation forests. We present here details of a method we used to calculate the carbon uptake and storage of the entire plantation forest estate of New Zealand, and analyse the sensitivity of our calculations to the assumptions we make. Our results show that per hectare, the average carbon uptake of the New Zealand plantation estate is high compared with estimates from other parts of the world (e.g., Marland 1988; Sedjo 1989).

The methodology employed is general and should be applicable to many other plantation estates. We also provide estimates of the carbon storage potential of pasture land in New Zealand that might be converted to new plantation forest. We note, however, that there are other suitable methods for storing carbon that include the natural or assisted reversion of pasture to indigenous forest. Any policies designed to enhance the land-based storage of carbon should consider a range of factors beyond the specifics of carbon accumulation. Our analysis is a direct accounting of carbon storage in plantation forest and does not consider other aspects of the carbon cycle such as fossil fuel use in forest establishment, tending, or harvest.

The quantity of carbon stored in a forest is closely related to the volume of stemwood or growing stock. The amount of growing stock generally increases with increasing forest area and average age-class. Conversely, pests, diseases, excessive harvest, or atmospheric pollution can reduce the growing stock of a forest of static area.

The growing stock of New Zealand's commercial plantation forests is presently increasing. This is attributable to both the planting of new land (mainly pasture or short scrub) and the aging of the plantation estate caused by a high level of planting 5–15 years ago that has not been sustained.

Previous authors (e.g., Marland 1988; Sedjo 1989) calculated annual forest carbon storage, S, in tonnes of carbon per hectare as:

$$S = \Delta V \cdot \rho \cdot \alpha \cdot k \qquad (1)$$

where ΔV is the average change in wood volume (m^3) from one year to the next,

ρ is the average wood density (oven-dry tonnes/m^3),
α is a dimensionless factor that relates the oven-dry weight of stemwood to the oven-dry weight of stemwood plus other tree and forest components,
and k is the fractional carbon content of the biomass.

The New Zealand plantation estate consists mostly of *Pinus radiata* D.Don (Turland & Neumann 1991). In *P. radiata* and other species, ΔV, ρ, and α all vary with tree age and site characteristics such as climate and fertility (e.g., Turland & Neumann 1991; Cown *et al.* 1991; Madgwick *et al.* 1977). Annual stem volume increment varies by over 50% between growth regions in New Zealand (Turland & Novis 1990) as well as within a region. Wood density at any particular age also varies between regions. For example, wood from *P. radiata* trees growing in warmer locations has a higher mean density than wood from trees growing at cooler sites (Cown *et al.* 1991). To improve the accuracy of our estimates, we extended the basic methodology of Equation (1) by considering the natural variation in tree growth and wood characteristics within the New Zealand plantation estate.

METHOD

The New Zealand Ministry of Forestry maintains a computerised database of the national forest estate (Turland & Novis 1990). This takes the form of forest area and volume of each of 820 "crop types" as at 1 April of each year for each yearly age-class (1 to 80). A "crop type" is an aggregation of stands located in the same territorial authority (county, borough, and city councils) that contain the same species (or species group), are managed according to a similar tending regime, and grow according to similar yield curves. The territorial boundaries are given by Turland & Novis (1990). The 1988 and 1989 area databases were compiled largely from data collected via postal survey from forest growers and managers, with a small proportion of the area estimated from 1985 New Zealand Forest Service records of private forest holdings. The yield table database was constructed from data provided by the major private forest growers and New Zealand Forest Service in 1987.

We stratified Ministry of Forestry data for the New Zealand estate into three wood density regions and 1-year age-classes to account for age-specific and regional variations in growth and wood density. The total quantity of elemental carbon (C_{ij}, in tonnes) in each region, i, for each age-class, j, was calculated according to Equation (2) as:

$$C_{ij} = (V_x \cdot \rho)_{ij} \cdot \alpha_j \cdot k \qquad (2)$$

where V_x is the total standing stemwood volume (m^3) at year x for the appropriate wood-density region and age-class,
ρ is the wood density for each region and age-class (oven-dry tonnes/m^3),
α is the age-specific stemwood to stand biomass conversion factor as defined previously,
and k converts to elemental carbon.

The quantity of carbon in the forest in a given year is therefore ΣC_{ij}, or the sum of all the carbon in each age-class in each wood-density region.

The level of storage between any 2 years is the difference between the total carbon stored in those years, e.g.,

$$S_{88/89} = \Sigma C_{ij(1989)} - \Sigma C_{ij(1988)} \qquad (3)$$

We assumed that the forest estate consists entirely of *P. radiata* and then assessed the sensitivity of our estimates to this simplification.

1988 Volume Estimates

We used the Ministry of Forestry database to calculate the total standing stemwood volume (growing stock) for 1988 as the summation of the area at each age in each crop-type multiplied by the yield at the respective age in the corresponding yield table for each wood-density region:

$$V = \Sigma_{j=1}^{m} \Sigma_{i=1}^{80} (A_{ij} \cdot Y_{ij}) \qquad (4)$$

where A is the net stocked area (ha),
Y is the recoverable yield (m^3/ha),
i is the age class,
j is the crop type,
and m is the maximum number of crop types in a wood-density region.

1989 Volume Estimates

The classification of many forest areas changed significantly in 1989 because of definition changes for silvicultural regimes, and so 1989 wood volume estimates produced by the Ministry of Forestry are not directly comparable with those produced in 1988. We "time-shifted" the 1988 Ministry of Forestry data to more accurately estimate the difference directly attributable to growth between 1988 and 1989. This method involves transferring the 1988 area data for each age-class into the next annual age-class, calculating the estimated growing stock for each age-class, and then deducting estimates of the volume removed by clearfelling between 1988 and 1989 to derive a corrected estimate of the growing stock. Production thinning volumes were not deducted separately because the yield tables reflect production thinning yield changes, and volumes associated with restocking and new planting were not determined because yields are insignificant before age 3 years.

The clearfelled volume (F) was calculated as:

$$F = (1 - T) \cdot R \cdot \frac{1}{\beta} \qquad (5)$$

where T is the fraction of wood volume coming from production thinning,
R is the total reported roundwood removals,
and β is the ratio of clearfelled volume to standing volume.

From data of Turland & Neumann (1991) we calculated that 12% of the harvest wood volume comes from production thinning. The volume of roundwood removals was 10 242 000 m^3, based on annual surveys of sawmills, chip mills, and other wood product mills, and on export data (Ministry of Forestry 1991). The ratio of clearfelled volume to standing volume we used was 0.85 (Goulding 1986).

Conversion to Oven-dry Weight

Data for territorial authorities were grouped to form three wood-density classes (Fig. 1). Some approximation was necessary as the territorial boundaries did not always coincide

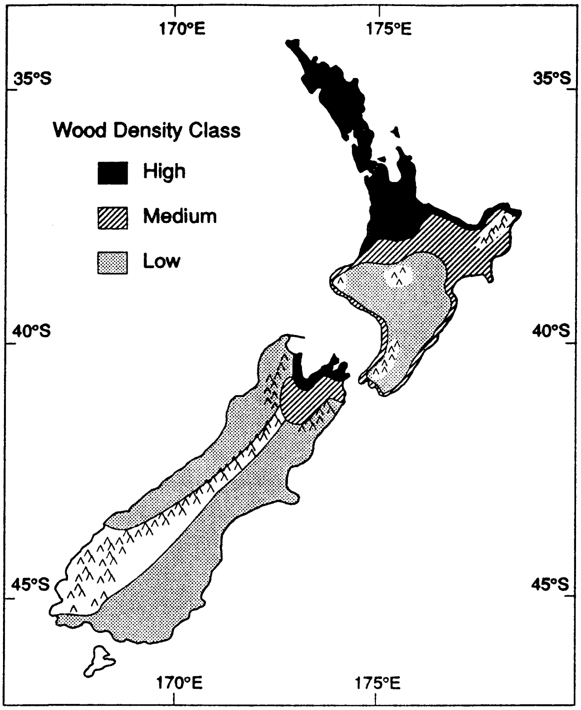

Fig. 1–Location of wood density classes for *Pinus radiata* in New Zealand. Wood density increases with growth temperature in *P. radiata*.

precisely with changes in wood-density class, but consideration was given to known concentrations of existing forest plantations before allocating each territorial authority to a class. There is no evidence to suggest that wood density in *P. radiata* is affected by the number of trees per hectare (Cown *et al.* 1991).

Conversion to Total Forest Biomass

We used a computer model (DRYMAT) to estimate the ratio of the oven-dry weight of needles, branches, stems, live roots, understorey vegetation, and surface litter layers (but not organic matter in the mineral soil) to stem dry weight in *P. radiata* stands over a rotation. This carbon-flow model has been described by Beets (1982) and Beets & Brownlie (1987). Carbon input, as current dry-matter production, is allocated to living tree components and, after mortality, to the forest floor. Carbon leaves the system after decomposition of non-living components. This allocation model is based on forest biomass studies that provided data on the effects of tree age, spacing, and site fertility on stand development parameters (Madgwick *et al.* 1977; Will *et al.* 1983; Madgwick 1985; Baker *et al.* 1986; Beets & Pollock 1987; Beets & Madgwick 1988).

Model inputs include productivity level, initial stocking, timing and intensity of pruning and thinning—either waste or production thinning—and rotation age. Stand development in relation to site and silvicultural regime can therefore be simulated. The ratio of total stand oven-dry weight to total stem oven-dry weight was computed for each annual age-class and applied to the estimate of total stem oven-dry weight for the national forest estate for the respective age-class. The ratio computed by DRYMAT varies with the silvicultural regime. To examine the sensitivity of the carbon estimates to possible errors in assigning the national forest estate to a given regime, we simulated three silvicultural regimes with the model:

Regime 1 (low planting density): Plant 300 stems/ha, prune to 6 m, thin to 225 stems/ha at an early age.

Regime 2 (more typical of present practice): Plant 800 stems/ha, production thin to 250 stems/ha at age 14 and prune remainder to 6 m.

Regime 3 (high planting density): Plant 1000 stems/ha and leave (only natural mortality, no pruning).

The three silvicultural treatments illustrated reflect present intensive tending and more extreme regimes, utilising either high densities without pruning or thinning, or very low initial stocking densities. These treatments bracket the current and anticipated future silvicultural regimes of the New Zealand plantation estate.

Conversion to Carbon Content

The fractional carbon content of dry woody biomass ranges from 0.47 to 0.53 (Baumeister *et al.* 1978; Houghton *et al.* 1985). We used a value of 0.5 which has been adopted in previous estimates of forest carbon storage (Cooper 1983; Sedjo 1989).

Calculation of Carbon Storage of New Plantings

We estimated the potential carbon storage of newly planted land by running a mensuration-based model (STANDPAK) to generate stem volume estimates up to age 30. We used the model DRYMAT (Regime 1) to generate a ratio of oven-dry biomass to total biomass at each age-class and the age-specific density values from the medium-density region. STANDPAK is widely used by the forest industry for forest estate planning in New Zealand. We carried out simulations for sites of different fertility. Site fertility ranged from "medium" (a typical present forest site) through "medium-high" (poor quality pasture) to "high" (average pasture) and "very high" (high quality pasture). Farm sites (medium-high to high fertility) are the land most favoured for future forest expansion (NZFOA 1991). Simulated stands were initially stocked with 800 stems/ha and then thinned to 250 stems/ha at age 5 years. Carbon storage in the forest estate was calculated by summing the biomass at each age-class over the rotation and then dividing by the rotation length.

Sensitivity of Model Calculations

To identify the factors that would most improve our carbon storage estimates and to provide an indication of their precision, we analysed the sensitivity of our results to variation in the input factors. We then attempted to determine the degree of precision of the component values and propagated these precisions as a root mean square. Similar methods have been used in other carbon budget calculations (e.g., Crutzen *et al.* 1986). Many of the values that went into our calculations do not have a readily available estimate of precision. We have estimated the precision in our input values (Table 1) from personal knowledge (e.g., the extent to which forest volume figures are revised each year) or the range of literature values (e.g., wood carbon content).

TABLE 1–Estimated precision of values in calculations

Parameter & description		Value	Units	Precision (%)	Error sources
ΔV	growth increment	21 323 000	m^3	4	Incorrect crop type or yield table
F	clearfelled volume	10 603 000	m^3	5	Reporting errors
ρ	wood density	0.394*	tonnes/m^3	3	Incorrect classification
k	biomass carbon content	0.5	fraction	5	Variation in carbon content
α	total biomass to stem biomass ratio	1.89†	fraction	15	Uncertainties in tending regimes

* 1988 volume weighted, actual values vary by age and region.

† 1988 volume weighted, actual values vary by age and tending regime. The value for the high volume increment age-classes (10–20 years) is higher.

RESULTS

Characteristics of the New Zealand Plantation Estate

Approximately 1.24 million ha were stocked with exotic forest on 1 April 1989 in New Zealand, an increase of approximately 26 000 ha over 1 April 1988 (Turland & Novis 1990). Approximately 89.4% of the forest estate was occupied by *Pinus radiata*, 5.1% by *Pseudotsuga menziesii* (Mirbel) Franco, 3.8% by other exotic softwoods, and the remainder (1.7%) by exotic hardwoods (mostly *Eucalyptus* species). The age structure of the New Zealand plantation forest estate (Fig. 2A) is far from a steady-state where the planted area for all age-classes is equal. Instead, large areas of new land (mostly pasture) were planted in exotic forest in the 1970s and 1980s. Over these two decades, about 40 000 ha of new land was planted each year on average, with peak plantings in the mid 1980s. These plantings are presently driving large annual increases in the growing stock and will lead to a large increase in harvest volumes from the late 1990s.

Carbon Uptake and Storage in the New Zealand Plantation Estate

The total stem volume in 1988 was estimated as 221 505 000 m^3 (Table 2). About 25% of this volume was in the low wood density region, 40% in the medium-density region, and 35% in the warmest high-density region. Most of the standing volume was in the 10- to 25-year age-classes (Fig. 2B), although there was also an appreciable volume in the ~60-year age-classes. Shifting the 1988 data to 1989 suggested that total volumes before harvest would have increased to 242 828 000 m^3 (Table 2). The volume increment between 1988 and 1989 estimated by time-shifting the 1988 data is 28% less than the volume increment reported by the Ministry of Forestry (1991) but is a much more accurate method of assessing annual change than comparing the 1988 and 1989 composite figures. The 1989 Ministry of Forestry volume data were distorted by the reclassification of large areas of forest into different types with the consequent use of new yield tables. The changes in volume resulting from the

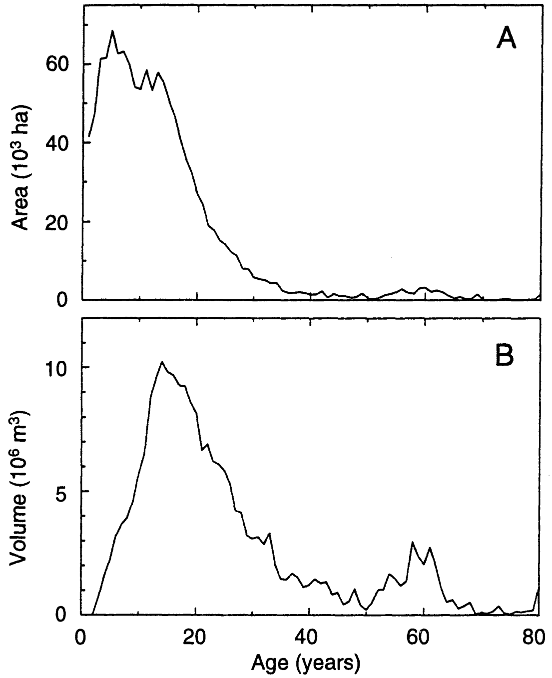

FIG. 2–Age structure of plantation forest area (A) and wood volume (B) in New Zealand on 1 April 1988.

TABLE 2–Summary calculations of 1988–89 New Zealand plantation estate growth

	Stem volume (m^3)	Stem dry weight (tonnes)
1988 stock	221 505 000	87 332 000
Grown on to 1989	242 828 000	95 695 000
Felled	10 603 000	4 373 000
1989 stock	232 225 000	91 322 000
Net increment	10 720 000	3 990 000

reclassification thus relate to the precision of the total volume estimates rather than the volume increment.

Plantation forest roundwood removals in 1989, including production thinnings, were 10 242 000 m^3 (Ministry of Forestry 1991). Using Equation (5), we estimated that clearfelled volume in the year to 1 April 1989 was 10 603 000 m^3; this was assumed to come from all age-classes over 30 weighted by the wood volume in each age-class over 30. We estimated, therefore, that 232 225 000 m^3 remained in the forest on 1 April 1989, yielding a difference (net annual increment) of 10 720 000 m^3.

Pinus radiata wood density increases with age in all three regions (Fig. 3). At any particular age the variation in wood density among the three regions is low, averaging about

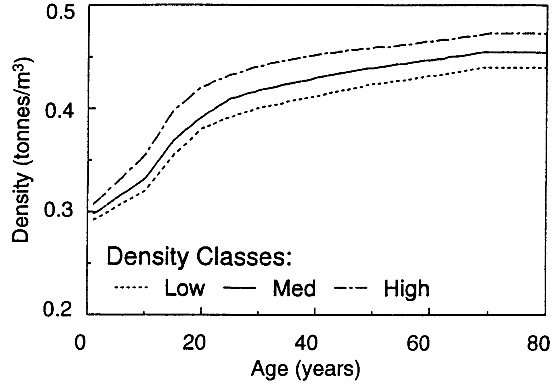

FIG. 3–Change in wood density with tree age for three growth regions in New Zealand (data from Cown *et al.* 1991).

0.04 tonnes/m^3 (~10%) difference between low- and high-density regions. Age and regional variations in wood density of other New Zealand plantation species are less well-known. Generally, however, wood density values for other species are equal to or higher than those of equivalently aged *P. radiata* (e.g., Frederick *et al.* 1985). Based on the assumption that the forest estate in 1988 consisted entirely of *P. radiata*, the average wood density of the estate was 0.394 tonnes/m^3.

Using the *P. radiata* age-specific volumes from the three wood density regions to convert to oven-dry tonnes of stemwood, we estimated that there were 87 332 000 tonnes of stemwood in the New Zealand plantation estate on 1 April 1988 and 91 322 000 tonnes on the same date in 1989 (after fellings), with a difference of 3 990 000 tonnes (Table 2).

The ratio of total biomass to stem biomass varies with age and silvicultural treatment in *P. radiata* (Fig. 4). Most of the biomass in young trees is contained in the non-stem

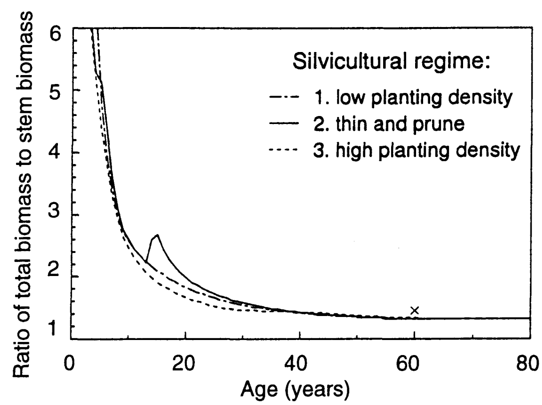

FIG. 4–Variation in age-specific ratio of total biomass to stem biomass for three silvicultural regimes generated by the allocation model DRYMAT. The peak after age 14 for Regime 2 is associated with stand thinning and pruning. The "x" represents the allocation ratio for 60-year-old *Pseudotsuga menziesii* (Harmon *et al.* 1990).

components, but this reverses in older trees so that by age 25 years, ~60% of the total tree, litter, and understorey biomass is contained in the stem.

Converting the three density and age series estimates to tonnes of carbon by summing and multiplying by 0.5, and converting age-specific ratios of total biomass to stem biomass in the three different silvicultural regimes yielded estimates of carbon uptake for each management regime (Table 3). Because many forests that contribute to the present New Zealand estate are most similar to Regimes 2 or 3, we adopted the mean of these values, $4.5 \cdot 10^6$ tonnes C, as our best estimate of the amount of carbon sequestered by the growth of New Zealand plantation forests between 1 April 1988 and 1 April 1989.

TABLE 3–Carbon sequestration in the New Zealand exotic forest estate (10^6 tonnes C)

	Regime 1*	Regime 2	Regime 3
1988	84.0	89.2	78.6
1989	88.5	94.4	82.5
Difference	4.5	5.2	3.9

* Regime 1: plant 300 stems/ha, prune to 6 m, thin to 225 stems/ha at an early age
Regime 2: plant 800 stems/ha, production thin to 250 stems/ha at age 14 and prune remainder to 6 m
Regime 3: plant 1000 stems/ha and leave (only natural mortality, no pruning).

Treating all of the plantation estate as *P. radiata* may have slightly inflated our estimates. The volume yields of *Ps. menziesii*, exotic hardwoods, and exotic softwoods are typically only 50–75% that of equal-aged *P. radiata* (Turland & Novis 1990). If we assumed that over the forest estate an average yield of these species is 60% that of *P. radiata*, our carbon storage estimates would be ~5% too high. In general, however, wood density and the ratio of total biomass to stem biomass are higher in these other species than in *P. radiata*. This will reduce the error in treating all of the plantation estate identically to below 5%.

For the purpose of analysing the precision of our estimate, we treated the quantity of carbon sequestered as the product of the net volume increment, mean wood density, allocation factor, and carbon content. The net volume increment is the difference between growth and felled volume. Errors in our values for density, allocation, or carbon content will have proportional effects on the final value of carbon sequestration (e.g., an error of 5% in our carbon value will result in a 5% error in our sequestration value). The least precise of these factors is the value of the ratio of total biomass to stem biomass (α).

The precision in the net volume increment depends on the size of the difference between ΔV and F as

$$\frac{\sqrt{\Delta V_{err}^2 + F_{err}^2}}{(\Delta V - F)} \tag{6}$$

where ΔV_{err} and F_{err} are the uncertainties (= precision • value) in the estimates of the growth increment, ΔV, and felled volume F (Table 1). The precision estimate of the net volume increment is thus 9.4% and the root mean square precision estimate of plantation carbon storage is 19% ($\sqrt{9.4^2 + 3^2 + 5^2 + 15^2}$) or 0.8 million tonnes C. The precision of the overall carbon storage estimate is dominated by the uncertainty in α. Halving the uncertainty in α improves the total precision to ~13%. Halving the uncertainty in k, by contrast, results in essentially no improvement in the precision of the carbon storage estimate.

Carbon Storage of Newly Planted Production Forest

Newly planted *P. radiata* stands on fertile farm sites accumulate carbon at an almost constant rate until at least age 30 (Fig. 5). After 25 years a stand would accumulate ~190 tonnes C/ha and after 30 years, ~225 tonnes C/ha. Carbon storage in a forest of *P. radiata* that contains an equal area in each annual age-class (a "normal" forest) also increases approximately linearly with length between harvests. For the example in Fig. 5, after age 15 approximately 4.5 additional tonnes C/ha are stored for each year's increase in rotation length. Thus, with a 25-year rotation on a highly fertile ex-pasture site, the mosaic of stands in a normal forest would store on average ~78 tonnes C/ha in perpetuity. Extending the rotation length in the forest estate to 30 years increases carbon storage about 30%. Carbon storage in these forests is not very sensitive to site fertility. For a 30-year rotation, carbon storage on medium, medium-high, and very high fertility sites would be 96%, 98%, and 103% of that on a high fertility site.

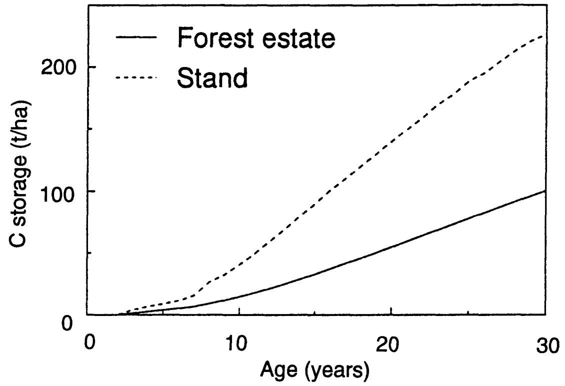

FIG. 5–Typical increase in carbon storage with age for a newly planted *Pinus radiata* stand and for a forest estate that consists of an equal area of each age-class up to the specified age, planted on a fertile ex-pasture site in New Zealand.

DISCUSSION

New Zealand's plantation forests are acting as a powerful carbon sink. Carbon storage between 1988 and 1989 averaged around 3.6 tonnes C/ha. An additional 2.8 tonnes C/ha was removed in wood harvests and at least some of this will end in storage. Without harvest, carbon uptake of the New Zealand plantation estate would therefore have averaged 6.4 tonnes C/ha. This supports suggestions that fast-growing forest stands might realistically accumulate 4.4–6.2 tonnes C/ha annually (Sedjo 1989; Harmon *et al.* 1990). The annual rate of carbon storage in New Zealand forests managed for production is still substantial, and the advantage of establishing plantation forests for production purposes is that they are economically viable without carbon storage arguments.

Given the public good of such commercial plantations, a strong case could be made for incentives to encourage their continued establishment. Other incentives or regulations designed to lengthen the average rotation of such forests would further enhance carbon storage. In our example in Fig. 5, each year of increase in rotation length beyond 25 years increases carbon storage by ~4.5 tonnes C/ha. On the conservative assumption that forest value is increasing at the same rate as biomass, the cost to a forest company in lengthening a rotation is the difference between the increase in value and the applied discount rate. The marginal cost of increasing the rotation length beyond the optimum by a few years is small (Clark 1976) and would be a cost-effective way of increasing carbon storage.

In our estimates we ignored carbon storage in mineral soils or wood products. Generally, studies suggest that there is little change in forest soil carbon storage over a rotation (Cooper 1983). The quantity of carbon stored in wood products depends on the lifetime of the product and these lifetimes are poorly known (Row & Phelps 1990). Dewar & Cannell (1992) used an exponential model and assumed that 95% of wood product carbon was lost over the next rotation. At an equilibrium over many rotations, ~16% of total storage carbon was in wood products. Over the shorter timespan considered here and with the present New Zealand forest product mix (high in short-lived products such as pulp), total carbon storage in wood products would be substantially less.

The calculations presented here were for the year ending 1 April 1989 because this was the latest year for which reliable data were available. New calculations will need to be made for subsequent years as it is incorrect to assume a constant change in growing stock from year to year. There is scope for increasing the precision of the calculations because the area and yield databases are improving in precision and because proposed surveys will enable the national estate to be classified more precisely by silvicultural regime. This would allow improved estimates of the ratio of total biomass to stem biomass.

Approximately 6.4 million tonnes of fossil fuel carbon (including that used for international transport) were emitted by human activities in New Zealand in 1988 (Hollinger & Hunt 1990) and about 5.9 billion tonnes C were emitted globally (Marland *et al.* 1989). New Zealand plantation forest carbon uptake in 1988–89 was thus 70% of the carbon in New Zealand carbon dioxide emissions, but less than 0.1% of global emissions.

If new land is not continually planted, eventually total forest biomass will no longer increase from one year to the next and the volume of wood harvested will equal the volume grown by the forest. The forest itself will then be "greenhouse neutral". However, some carbon will continue to be sequestered in durable wood artifacts.

The stage of greenhouse neutrality can be postponed by continually expanding the forest estate through planting new land. If the new forest is on fertile farmland, and is cut and replanted after 25 years, each new hectare will eventually store, on average, ~78 tonnes C in perpetuity. This figure enables us to estimate the quantity of farmland needed to sequester a specified amount of carbon, based on the establishment of typical new production forest. If we assume that the New Zealand Government wished to reduce annual carbon dioxide emissions of, for example, 6.4 million tonnes C by 20%, they would need to offset 1.28 million tonnes C. This could be done by establishing 16 400 ha of commercial pine forest on pasture with a rotation length of 25 years or 12 800 ha of forest with a rotation length of 30 years. To offset the same quantity of emissions in a second year, a further 16 400 (or 12 800) ha of new land would have to be planted, and so on for emissions in future years.

A changing climate may also affect forest productivity. The particular impacts will depend on just how the climate changes. Although the exact response of *P. radiata* to increasing temperatures and atmospheric carbon dioxide is not known, over the near-term the expected changes are more likely to enhance than inhibit productivity (Hollinger 1990; Whitehead *et al.* 1992). Over the longer term, higher temperatures would almost certainly inhibit productivity.

CONCLUSIONS

The New Zealand plantation forest estate stored a substantial amount of carbon in 1988–89. The positive carbon balance in 1988–89 resulted from biomass growth that exceeded the amount harvested. The reason for this is that the present forest is still expanding and maturing, and has not yet reached an equilibrium state where the volume of wood harvested equals the volume grown. Planting new land will ensure that the plantation forests continue to sequester carbon.

There are many other ways of fostering terrestrial carbon storage such as allowing land to regenerate in native forest or by planting carbon storage forests. Any scheme that does not require sustained yield from forests, in fact, will store on average far more carbon per unit land area than plantation land (Cooper 1983). The carbon storage potential of plantation forests should be considered as just one of many tools in efforts to deal with the problem of increasing atmospheric carbon dioxide.

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