Carbon sink potential of radiata pine plantations in Chile

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Summary

The potential amount of carbon (C) accumulated in the bolewood of *Pinus radiata* plantations in Chile was determined using annual information about forest area by age class and administrative region of the country, and by subtracting that removed due to harvesting. A model was generated to estimate the uncertainty in the prediction of the amount of C, using probabilistic distribution functions. The model uses as stochastic variables the coefficient of C of the wood, the length of rotation, the rate of growth and the annual rate of planting. Data were projected until 2060. Accumulated C increases from 67 Mt in the year 2000 to 169 Mt in the year 2060, at an average rate of 1.70 Mt a^{-1}. At the end of the projection date, the maximum value of C accumulated is estimated at 221 Mt and the minimum value 127 Mt. This calculation includes an expansion of the area planted with *Pinus radiata*, from 1.5 to 3.0 million ha, with a maximum projected area of 3.4 million and a minimum of 2.6 million ha. This implies an increase in the area planted ranging from 1.1 to 1.9 million ha. The C removed by harvesting in 2000 was an average of 2.3 Mt which increased to 13.8 Mt in the final projection year, at a rate of 0.19 Mt a^{-1}. An average removal of 0.19 Mt a^{-1} is 11 per cent of the amount accumulated, and implies a removal close to 11 per cent, yielding a positive net balance. The rate of removal of C implies the area to be harvested annually increases from 59 000 ha in 2000 to 113 000 ha in 2060, an increase of 91 per cent.

Introduction

The implications of the increasing concentration of atmospheric CO_2 for climate and the health of the global environment are topics of intense scientific, social and political concern. In contrast to economic globalization, no country can be 'left out' of 'environmental globalization', as its consequences will sooner or later reach all.

The most direct solution to the problem of global change is to drastically reduce CO_2 emissions; however, the costs of this approach may be prohibitive for countries with high levels of development, because of its negative effect on the wealth of the people (Coviello, 2000). Increasing the sequestration of carbon (C) and protecting C already sequestered have been much discussed (Birdsey, 1992; FAO, 2001; IPCC, 2002),

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especially with regard to forests, which cover almost one-third of the Earth's surface and contain nearly 90 per cent of the C stored in terrestrial vegetation (Perry, 1994; FAO, 2001). The potential for sequestering C in forests varies according to geographic locale, forest stocking and composition, growth rate of the species, and the density and age of wood (Gates *et al.*, 1983, cited by Pardos, 1999; ACDI, 2000; FAO, 2001). Rapidly growing young forests store C at very high rates, in contrast to older forests, which store large amounts of carbon but sequester it more slowly (Birdsey, 1992). In plantations, factors such as rotation length, species composition, intensive silvicultural applications (e.g. fertilization, density regulation), genetic improvement, and residue management can significantly affect rates of C sequestration (Liegel, 1991; Murray, 2000; FAO, 2001; Jayawickrama, 2001; Oren *et al.*, 2001; IPCC, 2002; Pussinen *et al.*, 2002). Afforestation, in particular, establishes not only new C sinks, but socio-economic and environmental benefits of great importance to society (van Kooten *et al.*, 1992; Maclaren, 2000; FAO, 2001).

Developing reliable information regarding forest area and productivity, as well as the area with potential to be afforested, is a prerequisite to determining a nation's potential for sequestering and storing C within its forests. In Chile, thanks to a policy that encourages conversion of abandoned or unprofitable agricultural lands to managed forest plantations, the area of commercial forests has increased from 300 000 ha in 1974 to almost 2 million ha in 2000 (INFOR, 2001), 75 per cent of which is *Pinus radiata* D. Don. Although these plantations are not established as 'carbon forests', they sequester and store C until reaching rotation age, after which they are harvested. The harvested area must by law be successfully reforested within 1 year, initiating a new cycle of plantations.

In this paper we address the potential for radiata pine plantations in Chile to sequester and store C. Data collected annually regarding the area of radiata pine by age and administrative region of the country were combined with estimates of growth rate, C content of wood, rotation length and yearly area of afforestation to predict C sequestration in boles to year 2060. Variance in the prediction arising from uncertainties in the parameters was modelled using distribution probabilistic functions (Heath and Smith, 2000; Smith and Heath, 2000). Model predictions of C sequestration are compared with the projected emissions of CO_2 in Chile over the same time period.

Methods

Description of the model

The content of C in plantations of radiata pine was determined using as a base the planted area by age class and administrative region [The country is divided into 13 administrative regions, from north to south. The radiata pine plantations are concentrated between region V (33° S) and X (41° S)] (Table 1). C accumulated in boles for each year of the projection period was calculated

Table 1: Area (ha) of radiata pine plantations by age class and region as of December 2000

	Age (years)								
Region	0	1–5	6–10	11–15	16–20	21–25	26–30	31+	Total
V	30	2528	3474	3337	2281	2589	511	55	14805
RM	0	6	5	52	406	498	35	0	1002
VI	6694	17959	11970	9564	10050	7837	3246	278	67598
VII	16330	117920	38125	101606	81163	3828	3051	1716	363739
VIII	27985	156760	134762	131108	129431	54852	3154	1896	639948
IX	5859	55576	49940	53912	55285	29707	6525	3638	260442
X	2513	23701	38159	19446	19366	20920	1220	1258	126583
Total	59411	374450	276435	319025	297982	120231	17742	8841	1474117

Source: Data recorded annually by the Servicio Forestal del Estado (INFOR, 2001).

as the product of mean annual increment, area per age class, and coefficients converting bole volume to C content (equation 1). Mean annual increment, rotation length, and carbon content of wood were assumed not to vary across regions, while wood density (kg m^{-3}) was specific to both region and age class.

$$cc_k = cc\mathrm{MAI} \sum_{i=1}^{R} \sum_{j=1}^{E_i} e_{ij} d_{ij} s_{kij} \tag{1}$$

where

cc_k = is the amount of bolewood C content in plantations in the *k*th year of the projection (Mt)
cc = the content of C in wood (kg kg^{-1}).
MAI = the mean annual increment of radiata pine plantations (m^3 ha^{-1} a^{-1})
R = the number of regions with radiata pine plantations (Table 1)
E_i = the rotation age in the *i*th region
e_{ij} = the *j*th age class in the *i*th region, expressed as years; $e_{ij} = 1, \ldots, E_i$
d_{ij} = the wood density of the *j*th age class in the *i*th region (kg m^{-3})
s_{kij} = the area in the *j*th age class of the *i*th region in the *k*th year of the projection (ha).

Description of the model variables

Hollinger *et al.* (1993) concluded, based on data of Baumeister *et al.* (1978) and Houghton *et al.* (1985), that C content in wood varies between 0.47 and 0.53 kg kg^{-1}. This range was therefore used in the present study. We assumed mean annual increment (MAI) to range between 15 and 25 m^3 ha^{-1} a^{-1}, corresponding to the variation in MAI of radiata pine throughout its distribution in Chile (Sedjo, 1999; Toro and Gessel, 1999; INFOR, 2001). There are insufficient sound data to allow calculation of region-specific MAIs. We modelled a range of 20–30 years for rotation age, the age range within which radiata pine plantations are harvested in Chile (Toro and Gessel, 1999). Rotation is determined according to economic criteria; therefore plantations are harvested before reaching the culmination of MAI at ~40 years (Baldini, 1994; Santana, 1998; Acuña, 2001).

Wood density (d_{ij}) was determined by age class and region using a model developed by the authors from studies conducted in *Pinus radiata* plantations throughout the distribution of the species in Chile (not published). In this study, data were divided into three geographical areas: area 1 (regions V–VII) in which $d = 0.20614 + 0.07146\ln(A)$; area 2 (region VIII) in which $d = 0.18334 + 0.07462\ln(A)$ and area 3 (regions IX and X) in which $d = 0.16590 + 0.08464\ln(A)$, where d is the wood density and A is the stand age.

Considering that for more than 25 years the government of Chile has encouraged establishment and management of plantations through a Forestry Encouragement Law, afforestation rate was incorporated as another element of the model. Historically, the country has maintained an annual average afforestation rate of 45 000 ha, varying from 15 000 to 60 000 ha (INFOR, 2001). In this study, we consider an annual afforestation rate between 20 000 and 40 000 ha, distributed among regions in proportion to the area of plantations in each region in year 2000 (equation 2). By using this procedure, each region maintained the same proportional representation of plantations throughout the analysis period.

$$f_{ki} = f_k(s_i/s) \tag{2}$$

where

f_{ki} = is the area afforested in the *k*th projection year in the *i*th region (ha)
f_k = is the total area afforested in the *k*th year (ha)
s_i = is the total area of radiata pine plantations in the *i*th region in year 2000 (ha)
s = is the total area of radiata pine plantations in all regions in year 2000 (ha).

Plantation area by age class in each projection year was estimated by transforming the values of Table 1 to an annual base, assuming a homogeneous distribution of annual plantation ages within each 5-year age class. Each year, plantations that have reached rotation age are cut, and their C amount deducted from the total amount sequestered. In the following year, harvested plantations are reforested initiating a new cycle with new plantations (equation 3). Reforestation of harvested areas is a legal obligation for all forestry producers.

$$s_{kij} = s_{(k-1)ij} + f_{ki} - c_{(k-1)j} \tag{3}$$

where

s_{kij} = is the area in the *j*th class age of the *i*th region in the *k*th projection year (ha)

$s_{(k-1)ij}$ = the area in the jth age class of the ith region in the $(k - 1)$th projection year (ha). $s_{(k-1)ij} = 0$ when $j = 1$

f_{ki} = is the afforested area in the kth projection year in the ith region (ha). $f_{ki} = 0$ when $k = 1$; $1 < j < E_i$

$c_{(k-1)j}$ = is the cutting area in the $(k - 1)$th projection year (ha). $c_{(k-1)j} = 0$ when $k = 1$.

Total carbon was estimated using afforested area as in equation (1).

Incorporating uncertainty in the model

The ranges in values of the variables were used to generate a model incorporating uncertainty in the prediction of C sequestration. The model uses probability distribution functions to represent uncertainty in estimates of the C content of wood, MAI, rotation age, and annual afforestation rate, assuming values are normally distributed. A similar procedure to estimate uncertainty in the accumulation of C in forests was used by Heath and Smith (2000) and Smith and Heath (2001). Uncertainty values for individual variables are shown in Table 2. Uncertainty in the resulting predictions was determined by constructing the model in the computational program @Risk (Palisade Corp., 2000) using Monte Carlo simulation with Latin Hypercube sampling (Morgan and Henrion, 1990; Vose, 1996; Cullen and Frey, 1999). The resulting model generates a probability distribution function of C sequestration for the different scenarios considered in this study.

Sample size

Mean and variance of C sequestration were determined after 1500 iterations of the model. That number of runs was determined following the two-stage procedure described by Gottfried (1984). The first stage consisted of a preliminary run of 100 simulations, from which the mean and standard deviation were calculated. In the second stage, these values were used to calculate the number of simulations required to achieve the desired level of confidence according to the t distribution (equation 4).

$$n = (ts/xY)^2 \quad (4)$$

where

n = number of observations required
t = t statistic for the desired confidence level (0.05)
s = standard deviation for sequestered C calculated from stage 1 runs
x = desired range as a proportion of the mean
Y = mean of sequestered C calculated from stage 1 runs.

Table 2: Ranges of uncertainty modelled for individual variables

Model variable	Symbol	Uncertainty (%)
Rotation age	E	±17
Mean annual increment	MAI	±20
Carbon content of wood	cc	±5.7
Afforestation rate	f	±25

Results

Net accumulated carbon

The mean predicted value for nationwide accumulated C increased from 67 Mt in 2000 to 169 Mt in 2060, an accumulation rate of 1.70 Mt a^{-1} (Figure 1). Ninety-five per cent confidence intervals (dotted lines in Figure 1) range from 127–221 Mt in 2060.

Projected area

The increased C sequestration results from a predicted doubling of the area planted with *Pinus radiata*, from 1.5 million ha in 2000 to 3 million ha in 2060 (range = 2.6–3.4 million ha; Figure 2).

Carbon removed in harvest

The model determines not only net accumulated C, but also the C harvested annually from plantations that reach commercial maturity. Megatons of harvested C in each projection year are shown in Figure 3. Annual harvest rates are relatively high compared with stocks up to 2012 and low from 2012 to about 2027 because of a current imbalance in age classes. An equal area in each annual age class (a regulated forest) (Davis, 1966) is reached after 2027.

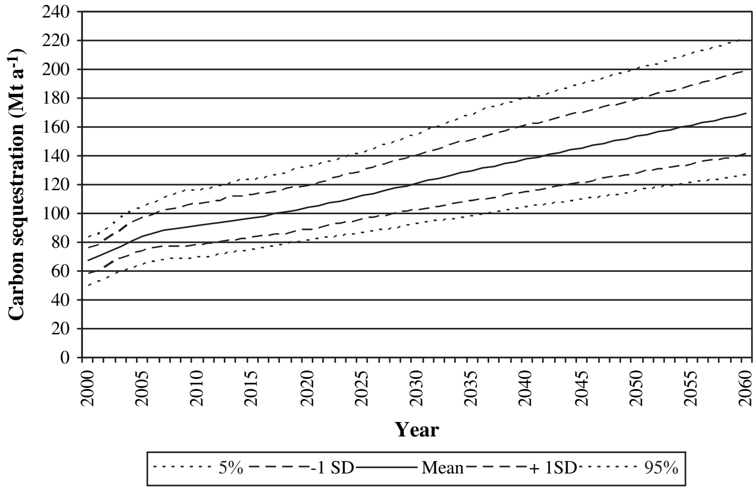

Figure 1. Mean predicted annual sequestration of C by *Pinus radiata* plantations in Chile (solid line) projected to year 2060. The probability bands represent the influence of uncertainty in parameter values (dashed lines = standard deviation of the mean; dotted lines = 5 per cent and 95 per cent percentile of predicted values distribution).

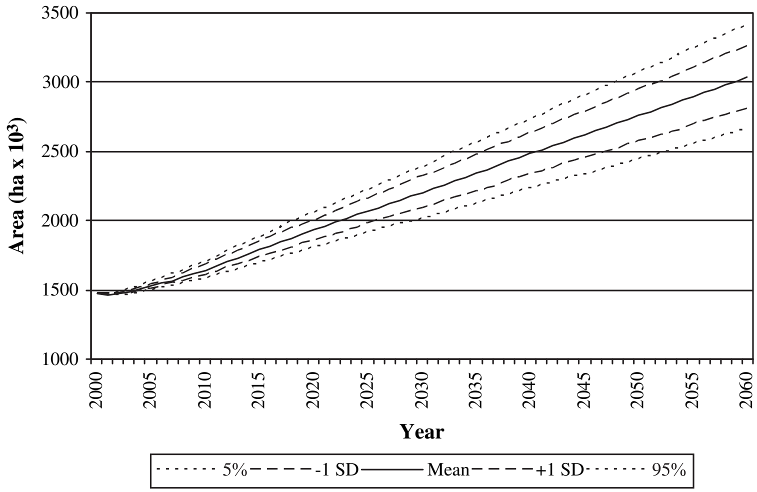

Figure 2. Annual area projected for *Pinus radiata* plantations (solid line). The probability bands represent the influence of uncertainty in parameter values (dashed lines = standard deviation of the mean; dotted lines = 5 per cent and 95 per cent percentile of predicted values distribution).

We estimate that 2.3 Mt of C were removed by harvesting in 2000, increasing to 13.8 Mt in the last year of the projection, an average increase of 0.19 Mt a^{-1}. Carbon harvested in 2060 is projected to be ~11 per cent of the total sequestered. The increasing rate of harvest results from afforestation and the consequent increase in area harvested. We project the area eligible for harvest each year will grow from 59 thousand ha in 2000 to 113 thousand ha in 2060, an increase of 91 per cent.

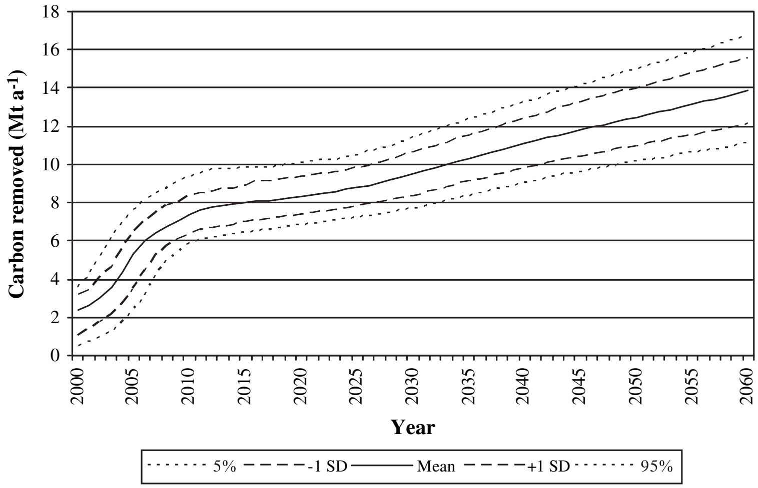

Figure 3. Carbon removed annually due to harvesting *Pinus radiata* plantations (solid line) projected to year 2060 (dashed lines = standard deviation of the mean; dotted lines = 5 per cent and 95 per cent percentile of predicted values distribution).

Correlation coefficient

The importance index of each of the four model variables with carbon sequestration to year 2060 is shown in Table 3. All variables correlate positively with C sequestration, with rotation age having the strongest effect.

Discussion

We used Monte Carlo simulation and probability density functions to estimate the probability distribution of net C sequestered in bolewood of *Pinus radiata* plantations in Chile. Other studies have used Monte Carlo simulation and probability functions to analyse uncertainty in C sequestration (Heath and Smith, 2000; Smith and Heath, 2000, 2001).

Table 3: Importance index of model variables with carbon accumulation to year 2060

Model variables	Importance index
Rotation age	0.68
Mean annual increment	0.47
Carbon content of wood	0.42
Afforestation rate	0.39

The 67 Mt of C we estimate sequestered by growth of *Pinus radiata* in Chile during year 2000 is four times greater than the 16.4 Mt of C emissions projected for Chile during that year (CONAMA, 1999). CONAMA (1999) projected C emissions in Chile of about 26.2 Mt for year 2020, ~25 per cent of the amount that our model predicts will be sequestered in net plantation growth (104 Mt). Assuming a constant trend in increasing C emissions within Chile, these will reach 52 Mt by 2060. For the same year our model predicts a net sequestration of 169 Mt of C, an amount sufficient to compensate the emissions and maintain a surplus greater than 300 per cent. These values do not include the mitigation measures agreed to by Chile at the Río Summit.

Brown *et al.* (1996) cited by FAO (2001) estimated that between 1995 and 2050, 30.6 Gt of C could be absorbed through afforestation and reforestation on a global basis, 11.78 Gt of this in the temperate zones. During the next 50 years *Pinus radiata* plantations in Chile could contribute 1.3 per cent of the temperate zone value.

The projected increase in net sequestration over the study period results from afforestation. We estimate a planted area at the end of the projection period of between 2.6 and 3.4 million ha, implying an expansion of 1.1–1.9 million ha between 2000 and 2060. Unda and Ravera (1994) determined that 4.4 million ha could be afforested in Chile, much higher than that projected by our study. The available area could be increased if, from the country's total 2.7 million ha in farming, more marginally profitable agricultural lands were afforested (Unda and Ravera, 1994).

Although afforestation is clearly important, in our model net sequestration correlates more strongly with rotation length. This is largely due to the fact we maintained a constant annual harvest rate regardless of rotation length, which results in fewer hectares being harvested each year and more accumulated C stored on the stump as rotation lengths are increased.

The net C sequestration estimated by our model represents only a portion of the potential C accumulated by the plantations for at least two reasons. First, a more complete accounting would include accumulations in soil, forest floor understorey, and tree components other than boles (Krankina *et al.*, 1996; Bouwman, 1990, cited by Heath and Smith, 2000; Richter and Markewitz, 2001). Birdsey and Heath (1997) estimate that, in forest ecosystems in the United States, only 29 per cent of C is in trees, and of that in trees only 50 per cent is in timber. Their relatively low estimate for the proportion contained in trees reflects the large amounts of C stored in soils.

When one looks at sequestration over a given time period the relative amounts are somewhat different. For example, a loblolly pine forest in South Carolina planted on old agricultural land sequestered 165 Mg of C in 40 years, about 51 per cent of which was in stems, 13 per cent in branches and foliage, and 37 per cent in forest floor, roots and soil (Richter and Markewitz, 2001). Based on that study, our model has accounted for about one-half of the C sequestered in radiata pine plantations. C stored in soil will have variable turnover times, but at least some will represent a long-term storage pool. The fate of C stored in the forest floor depends on techniques used for site preparation following harvest. Standard practices in Chile include subsoiling and windrowing, with fire seldom used. The effects of these practices on soil C have not been studied in Chile.

The second reason our model underestimates C storage is that we have assumed all harvested C is deducted from the storage pool, which is not the case. Harmon *et al.* (1996) estimated that 45–60 per cent of the C harvested in Oregon and Washington is lost to the atmosphere during manufacturing, with the remainder going into pools of varying stability depending on product, recycling and means of disposal (e.g. landfills *vs* incineration for paper). It is beyond the scope of this paper to quantify the various pathways of harvested C in Chile.

The C sequestration potential of *Pinus radiata* in Chile compares favourably with the annual C sequestration rates from other forest types, such as evergreen rainforest, evergreen forest, mixed deciduous in central Europe and broadleaf forests on old agricultural land (IPCC, 1996, cited by Wright *et al.*, 2000). Even without considering their potential economic value as carbon sinks, *Pinus radiata* plantations in Chile are economically feasible. Afforestation not only creates new economic opportunity, but takes economic pressure off native forests and restores degraded agricultural land. The potential for net C sequestration adds significantly to these benefits, and places Chile in a position to offer C credits to industrialized countries that must reduce CO_2 emissions according to the Kyoto Protocol.

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