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CHAPTER 5

FOREST PLANTATIONS AND CARBON SEQUESTRATION IN CHILE

Gerardo Mery and Markku Kanninen

1. INTRODUCTION

1.1 Climate change and forests

Increases in concentrations of carbon dioxide (CO_2) and other greenhouse gases in the atmosphere have emerged as a major environmental concern because of their impact on global climate and the attendant social and environmental consequences. The alarming increase in the concentration of CO_2—increasing some 25 per cent since the pre-industrial era (IPCC 1992)—has led to a worldwide debate on this issue.

Major reservoirs of carbon are the oceans, the atmosphere, the terrestrial biota, fossil fuels and the soils, and different strategies have been proposed for reducing or controlling atmospheric carbon. Two of these strategies, clearly complementary, are frequently mentioned as efficient ways of tackling the problem: the reduction or limitation of CO_2 emissions and the sequestration of atmospheric carbon dioxide.

The role played by forests in carbon sequestration has been repeatedly highlighted during deliberations on climatic change. Forests are important in the global carbon cycle because they store large quantities of carbon in vegetation and soil, exchange carbon through photosynthesis and respiration with the atmosphere (Brown 1996), and produce products with a high carbon content. However, the carbon stored in forests in the form of wood is released when wood is burned or decays, thus also making forests net emitters of CO_2. Replacing fossil fuels in energy production and using wood in the manufacture of durable products are important approaches to solving the problem (Kanninen 1993). In addition, increasing or at least maintaining permanent forest cover with a high carbon density can contribute to the sequestration of atmospheric carbon into the biosphere. This is especially relevant in view of the fact that above-ground forest ecosystems hold a similar amount of carbon as the carbon content of the earth's atmosphere (Nilsson and Schopfhauser 1995).

Currently, society can adopt different forest management systems that could change the size of terrestrial carbon reservoirs and alter the flow of carbon between vegetation and the atmosphere, and thus have a positive effect on the carbon cycle and climate change.

1.2 Economic role of the Chilean forest sector

Since the beginning of the 1960s, the forest sector in Chile has increased in importance and dynamism, attracting a significant amount of investments. Currently, the sector represents more than 3 per cent of GNP (Cerda *et al.* 1992). The export of Chilean forest products has increased considerably, particularly during the last 15 years, and currently accounts for about 10 per cent of total exports. Total industrial roundwood consumption increased from 4 million m^3 in 1975 to almost 25 million m^3 in 1995 (INFOR 1996). Forest policies implemented in recent decades have mainly supported the establishment of forest plantations for producing industrial roundwood. Fast growing exotic tree species, primarily *Pinus radiata* and *Eucalyptus sp*., have been planted. But the management of natural forests and regulating their rational utilization have been widely neglected.

Several factors confirm the plantation-based forest development approach as an attractive form of land use: i) investments have been highly profitable; ii) risk is confined within acceptable limits; iii) high growth rates for forest plantations of radiata pine and eucalyptus (normally higher than in natural stands) ensure a continuous supply of raw material for the rapidly expanding forest industries; iv) the simplicity of managing and rationalizing the commercial utilization of these artificially created ecosystems introduces important cost reductions; v) good market prospects for products derived from the plantations; vi) forest revenue is realized quickly; and, vii) the government has provided subsidies for forest plantations for more than twenty years. The high rate of carbon sequestration in the plantations could be mentioned as an additional benefit. Accordingly, forest companies can be expected to continue to plant monocultures of fast-growing trees wherever profitable. It should, however, be noted that this approach, which is oriented toward wood production, is mainly motivated by financial and economic issues, disregarding important ecological and social aspects.

The scale of forestry activities and forest industries has rapidly increased during the last thirty years. This was not the result of a unique or specific plan. On the contrary, it was produced by the summation of various, often quite diverse, political decisions. The ultimate result of this development approach is a two-sided forest sector: on one side, we have the dynamic plantation-based forest industries, and on the other side, the backward perception of natural forests and less-than-efficient industry. This dual reality needs to be recognized in the formulation of new forest policies, so that both aspects can be integrated in a balanced manner.

1.3 The purpose of this study

The purpose of this chapter is to analyse the extent of the contribution made by plantations established in Chile during recent decades to the sequestration of atmospheric carbon. While only rough average approximations have been used in earlier papers to determine carbon sequestration, this chapter develops a more detailed approach to estimate the amount of carbon stored in existing radiata pine plantations and the annual flux of carbon sequestration in the Chilean forest plantations. Finally, the role of Chilean forest plantations as a sink of CO_2 is discussed. Consideration is also given to certain social and environmental factors, in particular, the criteria developed internationally to promote sustainable forestry management.

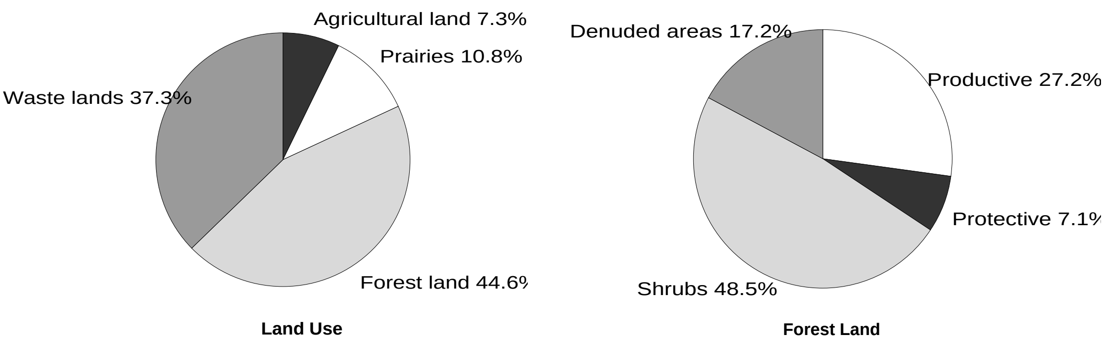
2. FOREST RESOURCES

2.1 Land use

It needs to be mentioned that official figures on forest resources in Chile, particularly those referring to natural forests, should be viewed with some reservation, because a national forest inventory has never been conducted in the country. A national cadastre of the vegetation was initiated in 1994 for the purpose of forest land classification and, to some extent, the evaluation of the state of forests.

Approximately 33.8 million hectares have been classified as forest land, or land suitable for forest growing (Cerda *et al.* 1992). Figure 5.1 indicates the current land-use classification, identifying waste land comprised of mountain peaks, deserts, glaciers, wetlands, and urban areas. Forest land can be classified in four categories (Figure 5.1), one of these being productive forest, which is defined as 'areas dominated by forest tree species which breast high diameter surpass 25 cm and where the solid tree volume exceeds 30 m^3/ha' (INFOR 1990). Productive forests constitute different types of natural forests (81.5 per cent) and forest plantations (18.5 per cent) (INFOR 1996).

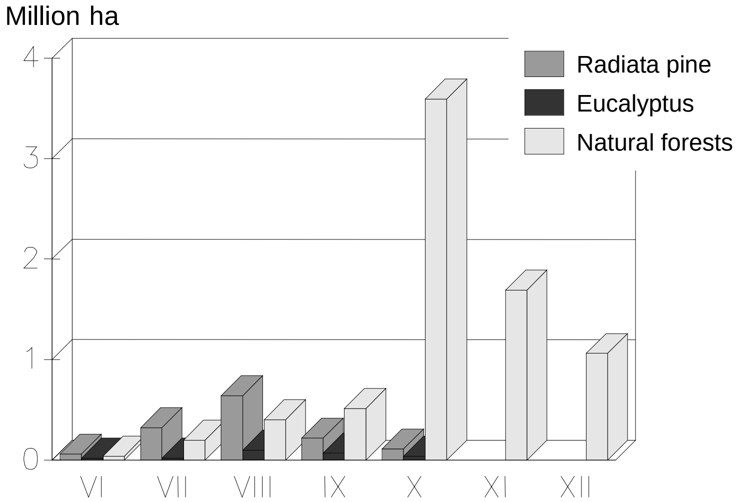
FIGURE 5.1
CURRENT LAND USE AND FOREST LAND CLASSIFICATION



Source: Cerda *et al.* (1992)

The total standing timber volume of potentially productive natural forests in Chile was estimated in 1994 at 891 million m^3 (INFOR 1996). The country also has a rich diversity of natural forests consisting of 12 main forest types and more than 100 tree species (Donoso 1981; Schmidt and Lara 1984). Although several important conifers exist, the most common species are broad-leafed, with the genus *Nothofagus* dominant Donoso 1987; Veblen *et al.* 1981).

FIGURE 5.2
DISTRIBUTION OF POTENTIALLY PRODUCTIVE NATURAL FORESTS
AND FOREST PLANTATIONS BY ADMINISTRATIVE REGIONS



Source: INFOR (1996)

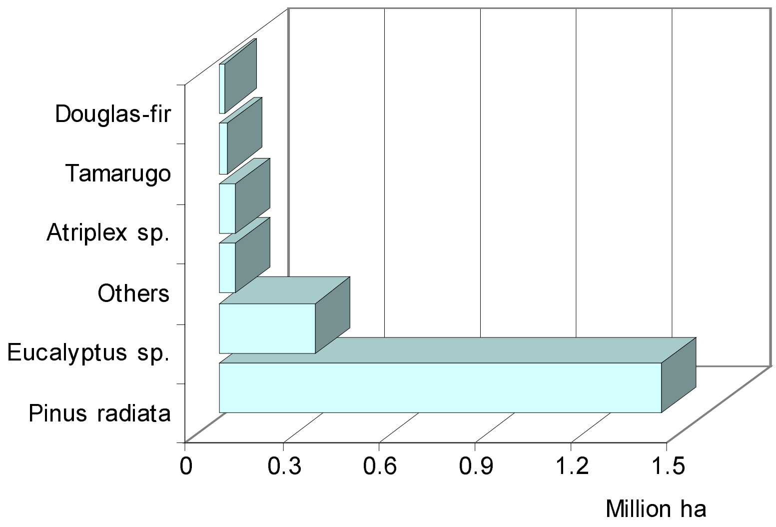
Natural forests vary from arid and semi-arid open sites normally mixed with scrubby vegetation in the northern and central part of the country, to closed rainforests in the south-central and southernmost regions. Over two-thirds of the forests are located in the southern regions (Figure 5.2).

2.2 Forest plantation programmes

Forest plantations began to be established early this century, but large-scale industrial plantations of exotic rapid growing species were not started until the early 1940s. By 1995, about 1.75 million ha of land had been converted to forest plantations with radiata pine (*Pinus radiata*) accounting for 85 per cent of the planted area. Other common species include *Eucalyptus* sp., atriplex (*Atriplex repanda* and *A. numularia*), tamarugo (*Prosopis tamarugo*), Douglas-fir (*Pseudotsuga menziesii*), and poplar (*Populus sp.*) (Figure 5.3). The proportion of non-industrial plantations is quite marginal.

Radiata pine thrives in a broad range of environmental conditions, growing along some 1000 km of Chile's territory, from the sea level up to an altitude of 900 m a.s.l., on soils ranging from sandy to clayish, and with precipitation levels of 400 to 2000 mm yr^{-1}. The adaptability of radiata pine to the climate and terrain conditions prevailing in the central zone of Chile has produced rapid growth that can be roughly estimated to be, on average, 24 m^3 $ha^{-1}yr^{-1}$. Its high yield and numerous uses has resulted in this pine becoming the backbone of the Chilean forest industries and plantations of radiata pine have been established continually over the last twenty years (Figure 5.4). Radiata pine plantations now provide approximately 80 per cent of the total consumption of industrial roundwood. Most pine plantations (more than 98 per cent) are concentrated around the 5th to 10th regions, and region 8 alone contains 47 per cent (Figure 5.2).

FIGURE 5.3
CURRENT AREA COVERED BY FOREST PLANTATIONS (UP TO 1995)



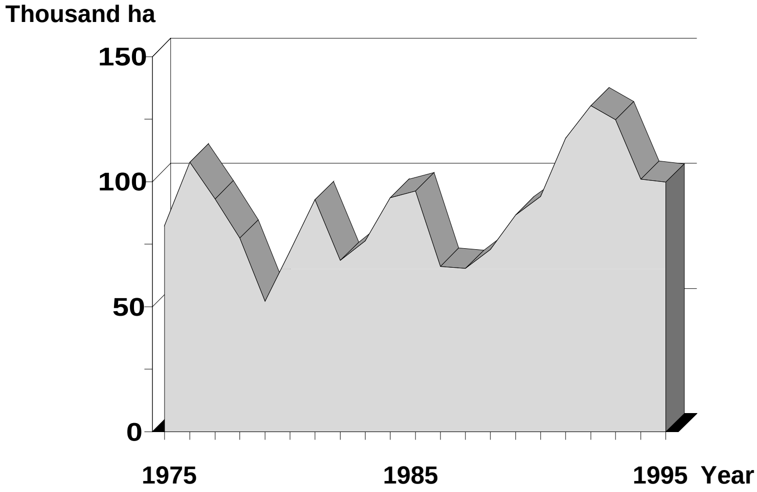
Source: INFOR 1996

Forest plantations have been promoted through subsidies and tax exemptions, and by 1994, close to US$ 150 million had been paid in direct subsidies by the government (INFOR 1996). Legislation introduced in 1974 enabled direct subsidies to be paid up to 75 per cent of the costs for planting, pruning, and miscellaneous managerial expense. As subsidized land was to be re-forested by the recipient, this resulted in significant increases in planted areas over the last twenty years (Figure 5.4), exceeding 65,000 ha annually, mostly in radiata pine. Since 1979, most of the planting operations have been conducted by the private sector, with private companies accounting for over 85 per cent of new plantations (Jélvez *et al.* 1989). Indeed, almost all plantations are owned by private corporations or individuals. The state owns or administers only some 40,000 ha of radiata pine plantations (Cerda *et. al* 1992). More than 40 per cent of the total planted area is owned by three large corporations, each with holdings of approximately 80,000–400,000 ha. Another 40 per cent is in the hands of some 5,000 landowners whose individual holdings range between 50-150 ha, and ownership of the remaining 20 per cent is with medium-sized companies (approximately 30 owners).

Most radiata pine plantations are young, 80 per cent are less than 15 years old (Figure 5.5). As the average rotation age of pine is around 25 years, a considerable proportion of these young stands will mature by 2005-2010. Although different figures on the total volume of harvest becoming available from these pine plantations by the beginning of twenty-first century have been introduced (INFOR 1996 and 1984), an estimate of 23 million m^3 per annum by the year 2005 and 30 million by 2015 seems likely. Even according to a very conservative scenario, future cutting potential for the *Pinus radiata* is enormous. This fact ensures a solid basis for future investments in forest industries.

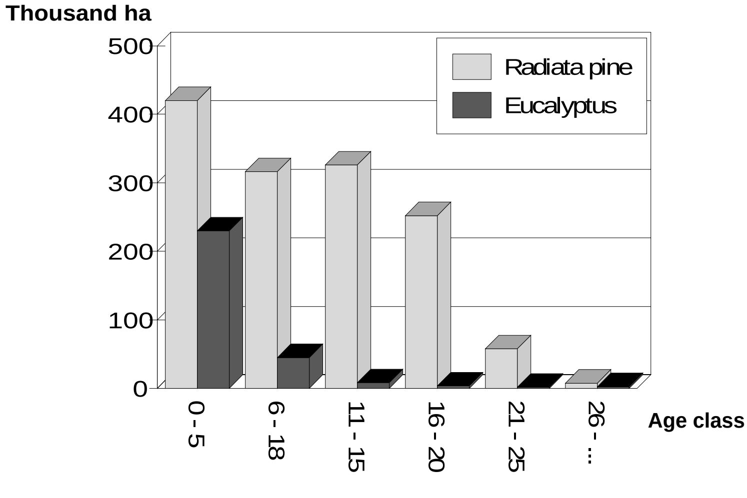
Chile already has the most extensive areas of radiata pine in the world. Moreover, a vast non-productive land area, estimated at 2-5 million ha, has been identified as suitable for forestry operations. It is therefore likely that the total area devoted to forest plantations will gradually increase to 2-3 million ha. In addition, low-yielding farmland currently used for agriculture in the proximity of forest industries is being planted increasingly with forest tree species.

FIGURE 5.4
ANNUAL AREA PLANTED DURING 1975-95



Source: INFOR (1996)

FIGURE 5.5
RADIATA PINE AND EUCALYPTUS PLANTATIONS ACCORDING TO AGE CLASSES, YEAR END 1995



Source: INFOR (1996)

The favourable rate of return on investment in forest plantations is one of the key factors to explain the large investments allocated in Chile for these operations. In a comparative study (1983), Sedjo examined sixteen of the most successful forest plantation cases in different regions of the world. His results showed high profitability for a standard radiata pine plantation in Chile. Also, the special state subsidy programme for promoting forest plantations and increasing knowledge of intensive forestry management have resulted in vast areas being planted annually with radiata pine and eucalyptus.

However, there are actual and potential risks involved with monocultures. These include environmental risks such as severe pests already attacking plantations, and social risks such as rejecting plantations of exotic tree species as a substitution for natural forests. Diversification of the plantations should be encouraged by also introducing other species, either in pure or mixed stands (Lara 1992; Mery 1996).

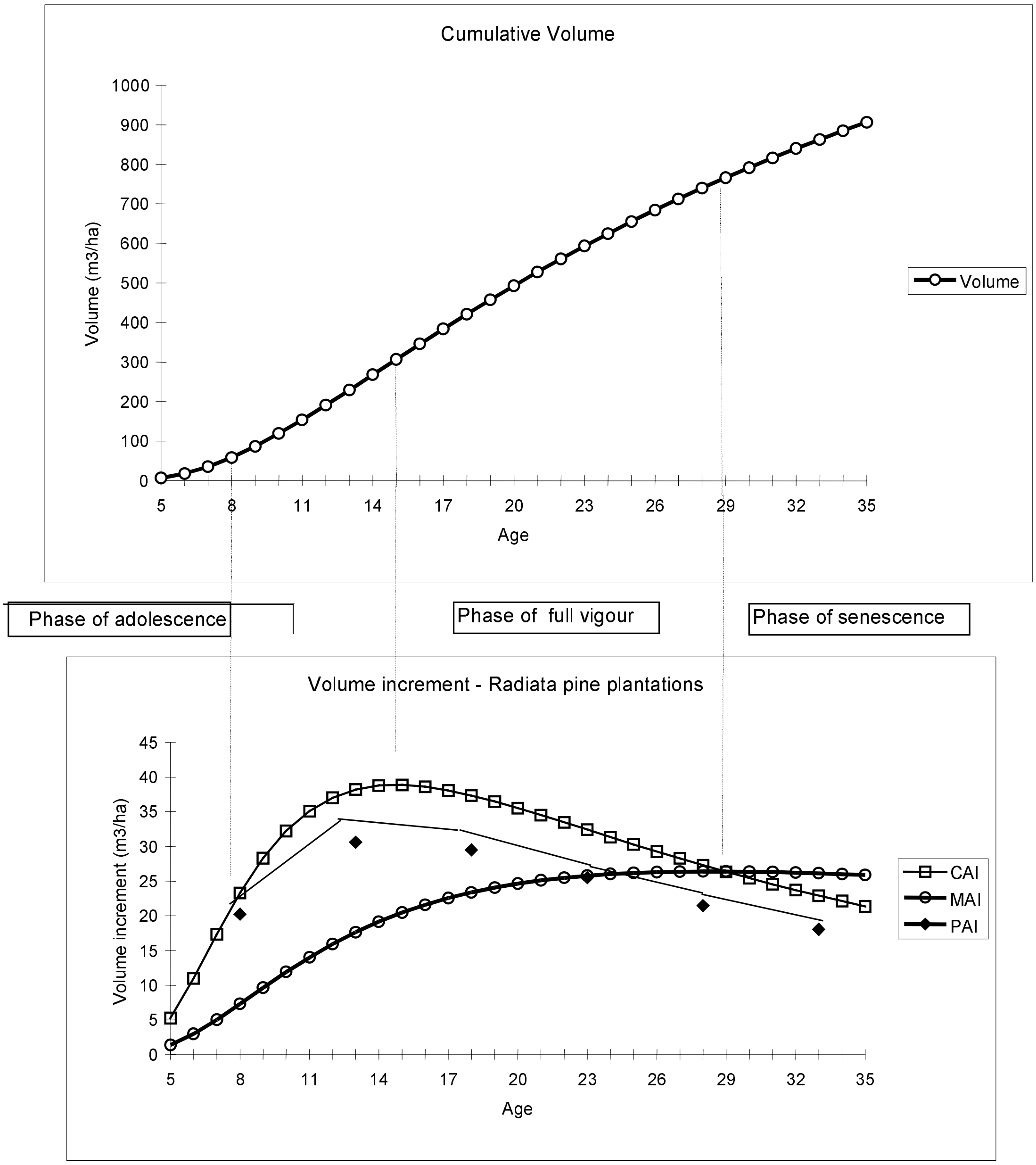
During the last few years, in addition to the popular *Eucalyptus globulus,* different eucalyptus species have been increasingly and successfully introduced to plantations.[1] Auspicious experiences have encouraged private investors to select these new species more often. Also, the exceptional yield of eucalyptus, its demand for many different industrial purposes and its corresponding price on the internal and external markets prophesize rapid expansion for these plantations. Achieving more than 60 m^3 $ha^{-1}yr^{-1}$ in very good sites, the average annual increment of eucalyptus is even higher than radiata pine. Most eucalyptus plantations have been established recently; 95 per cent are less than 15 years old (Figure 5.5). The average rotation age of eucalyptus is often 15-20 years, and a considerable proportion of the current young stands will mature by 2010-15. It is, therefore, expected that by the year 2000, Chile will have close to 400,000 ha in eucalyptus.

2.3 Forest plantations and carbon

The forest plantations of Chile constitute an important source of raw material for the forest industries. Most of the country's man-made forests were established specifically for industrial purposes and most have managed to ensure a steady flow of wood to industrial mills (see section 2.2). Consequently, these plantations are perceived more in terms of crop production than natural ecosystems. They also serve, however, as sinks and reservoirs of greenhouse gases and it should be mentioned that short-rotation forests usually achieve the highest average net annual rates of carbon fixation (Apps and Price 1996).

As of December 1995, Chile had 1.8 million ha of forest plantations, of which 1.4 million in radiata pine, 0.3 million in *Eucalyptus sp.* (INFOR 1996), and 0.1 in other species (Figure 5.3). One of the main aims of the intensive management practice is to achieve full benefit from the forest site by maximizing volume increment. According to common practice, a rotation cycle of 24-28 years for radiata pine and 18 years or less for eucalyptus includes one or two commercial thinnings (at the age of 13-11 and 18-16 years, respectively) and one non-commercial thinning (Hakkila and Mery 1992). Generally, the aim of commonly applied silvicultural management programmes is to produce sawn wood from the last thinning and final cutting, and pulpwood mainly from the commercial thinnings. Obviously a wide variety of management plans adapted to diverse conditions are in operation.

FIGURE 5.6
RELATIONSHIP BETWEEN GROWTH AND VOLUME INCREMENT IN RADIATA PINE PLANTATIONS OF THE IX^TH REGION IN CHILE



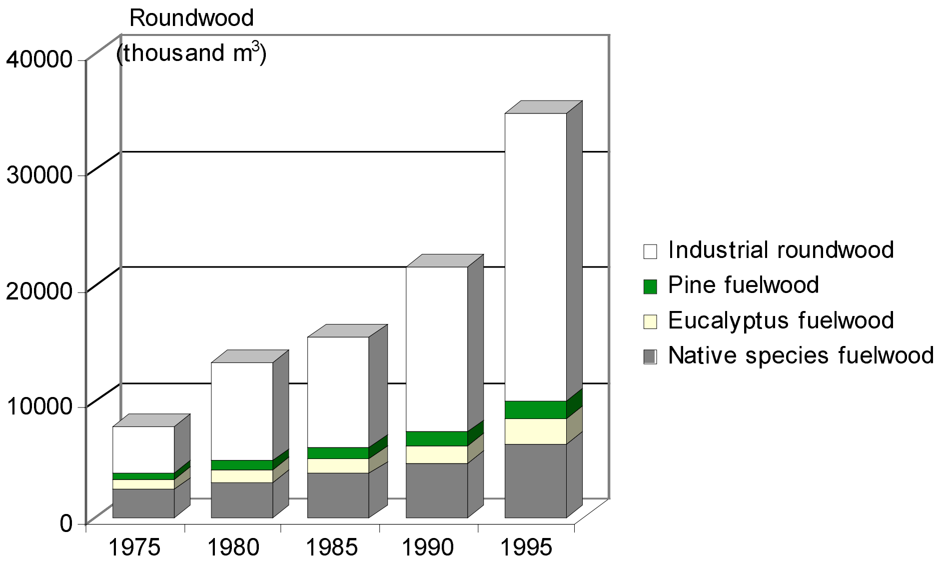
Data source: INFOR 1981

Note: CAI = current annual increment, MAI = mean annual increment, PAI = periodic annual increment.

In view of the fact that the increment curve corresponds to the adolescent and full vigour phases of growth and in view of the typical management programmes described above, it is apparent that silvicultural practices are applied at a time when the physiological activity of trees requires a high amount of carbon sequestration (Figure 5.6). It should be remembered that a forest acts as a carbon sink whenever total harvesting and mortality do not exceed volume increment. Therefore, forest plantations administered according to sound management regimes will constitute a significant and efficient carbon sink. Sustainable logging, by definition, does not have a decreasing impact on carbon reservoirs (Kauppi 1996). Legislation in Chile stipulates that logged-over areas be successfully reforested. Consequently, harvesting and thinning operations result in a temporary reduction of carbon stores—some of which is transferred to forest products—but forests resume carbon accumulation once the stands recuperate from their interrupted development or are regenerated.

Another relevant consideration is the range of products generated from the wood of these fast growing trees. Radiata pine and eucalyptus have been—and still are—mainly used as basic raw material, providing in 1995, for instance, 75 per cent and 14 per cent, respectively of the demand (INFOR 1996). A large proportion of this is consumed by the pulp and paper industry, which as the most important segment of the country's forest industries, constitutes the major bulk of production, investments, and technological input. Annual pulp production in 1995 totalled 2.1 million tons and the paper production 0.6 million tons. On the other hand, the rapidly expanding sawwood industry produced 3.8 million m^3 and production of wood-based panels was 0.6 million in 1995 (INFOR 1996). Other important products are wooden chips and lesser volumes of timber for houses, furniture, agricultural and mining constructions, fruit crates, etc. Moreover, in recent years the range of products manufactured from radiata pine and eucalyptus has been increasing. This is an important development because the production of diverse forest products normally yield a greater potential for carbon storage.

FIGURE 5.7
ROUNDWOOD UTILIZATION IN CHILE, 1975-95



Source: INFOR (1996)

On the other hand, the proportion for fuelwood consumption of the total amount of roundwood (35 million m^3 in 1995) is diminishing in relative terms but is still high (exceeding 10 million m^3 in 1995; Figure 5.7). Forest plantations provide approximately 37 per cent of the total demand for fuelwood (22 per cent eucalyptus and 15 per cent radiata pine) (INFOR 1996). Thus, it can be concluded that radiata pine and eucalyptus plantations are mainly used for producing medium- and long-life products, subsequently preventing the rapid release of sequestered CO_2 into the atmosphere.

It is a fact that carbon sequestration is not the primary aim of forest planting nor the specific goal of the management plans usually applied to forest plantations. It should, nevertheless, be recognized that human beings, through forest management, have the opportunity to increase carbon reservoirs and to modify carbon flows, subsequently contributing to the stabilization of the carbon cycle and to averting climatic change (Brown 1996). Consequently, the carbon issue is becoming a vital element of sustainable forest management.

3. CARBON SEQUESTRATION

3.1 Forests and carbon sequestration

Carbon dioxide is removed from the atmosphere by the photosynthetic activity of terrestrial vegetation and phytoplankton. The two major terrestrial reservoirs are carbon in the soil and carbon in living forest vegetation (Kauppi 1996). Forests, as the most important ecosystem component of vegetation, can be carbon sinks, deposits or sources of CO_2. Forest ecosystem components can be grouped into three major carbon reservoirs: live biomass, detritus, and soils (Apps and Price 1996; Kauppi *et al.* 1996). The dynamics of carbon exchange among—and between—these components and the atmosphere is a basic problem that needs to be understood (Kauppi 1996). In addition, the importance of forest products should also be considered even though they represent only a small fraction of the fixed carbon.

Trees act as a carbon sink when, through photosynthesis, they absorb CO_2 from the atmosphere, subsequently releasing oxygen but retaining carbon. The bulk of the stored forest carbon is in the form of wood (Dabas and Bhatia 1996). Carbon is mainly fixed in the wood as lignin and cellulose. But, the soils and undergrowth vegetation also contain substantial quantities of fixed carbons (Nilsson and Schopfhauser 1995).

The ability of a forest to sequester atmospheric carbon depends on its composition, structure of the stand, genetic characteristics of the trees and plants, and climatic and edaphic factors. Age is another crucial factor. Carbon sequestration and the accumulation of organic carbon in detritus and soil reservoirs change as the stand matures or decays, or whenever natural or man-made disturbances occur. Consequently, the stage of development of a particular forest stand is one of the crucial factors affecting its structure, composition and cumulative biomass volume, and thereby also affecting carbon dynamics. Once a stable distribution in terms of age has been established and if growth conditions remain unchanged, the biomass carbon pools reach a point of steady state when average net biomass C accumulation effectively becomes zero (Apps and Price 1996). The point of the steady state is attained only if the periodic carbon sequestration of forest ecosystems is not exceeded by carbon releases from forest fires and other disturbances over the same period (Brown *et al.* 1996b).

The growth of a tree or stand follows a characteristic S-shaped curve (Figure 5.6). The section between the origin and the first inflection point represents the adolescent age of the plant with a rapid growth rate. The section between the two inflections points represents a faster growth phase of the plant (full vigour phase) when CAI (current annual increment) reaches its maximum. Finally, the section beyond the second inflection point corresponds to the senescence stage when growth gradually declines. At this phase, the mean annual increment (MAI, the ratio of the final growth quantity divided by the number of years) diminishes (Loetsch *et al.* 1973). A stand composed of fast growing young trees will absorb an important amount of CO_2 from the atmosphere, but a younger forest contains less biomass and therefore its carbon pool is smaller. In an old-growth forest, the absorption achieved through growth is largely off-set by wood decay. Left undisturbed, mature forests no longer sequester atmospheric carbon but are able to retain a fixed amount of carbon within the vegetal tissues, acting as carbon deposits (Kanninen 1993; Apps and Price 1996).

Forests and other types of vegetation covers become sources of CO_2 when disturbed and the carbon appropriated earlier is released into the atmosphere. Natural or anthropogenic in origin, disturbances include deforestation or the conversion of forests to non-forest uses such as agriculture land and pastures; unsustainable logging or degradation that occurs from damage to residual trees and to the soil through wild fires, poor logging practices, overgrazing, excessive fuelwood gathering and other events; diseases and decay. Even though logging reduces the amount of carbon stored per unit area, logged forests can be regenerated under sound management regimes to accumulate carbon again (Brown 1996).

At the global level, it is estimated that forests are the basic net source of carbon dioxide and other greenhouse gases like methane (CH_4), carbon monoxide (CO) and nitrogen oxides (NO_n) to the atmosphere (IPCC 1995). The forest also constitutes a vital link in the plant-to-soil sink mechanism, acting as a pump which discharges some of the carbon contained in the litter into deeper soil layers where it is finally stored (Kauppi 1996). The carbon pump phenomenon varies widely according to the inherent characteristics of the different ecosystems. But the vast areas being deforested and degraded every year (FAO 1997) cannot be compensated adequately with new forest plantations and/or increased quantities of biomass per unit area as proposed by current management programmes.

3.2 Estimation of carbon pools, fluxes and balance

3.2.1 Estimation procedure

To estimate the carbon sequestration of forest plantations in Chile, two basic assumptions have to be taken into consideration. An important amount of carbon is already stored in the existing radiata pine and eucalyptus plantations that had been established prior to December 1995. The increment of this stored carbon pool is a cumulative phenomenon. See section 3.2.3 for an estimation of this carbon pool.

The annual flow of carbon is calculated on the basis of both existing and new plantations. The plantation volumes reduced by harvesting, forest fire, or disease are subtracted from the respective volume of growing stock. However, thinnings have not been taken into consideration nor the amount of carbon stored in the soil and forest products. See section 3.2.2 for this estimation.

3.2.2 Estimation of the stand volume and volume increment

The total volume of the growing stock was estimated on the basis of the total area of forest plantations as of December 1995 (Table 5.1) and the mean cumulative volume which for radiata pine plantations was estimated with the yield functions (see equation 1 and Table 5.2) developed by Instituto Forestal (INFOR 1981) for each administrative region. These functions estimate the average values of a stand's stemwood volume, and have been calculated on the basis of numerous sample plots. The dependent variable of these models is the cumulative stand volume (V, $m^3\ ha^{-1}$) and the independent variable is the stand age (E, years). (For the values of parameters ***a*** and ***b*** see the Table 5.2):

(1) Ln V = a - b (1/E), where V = stand volume ($m^3\ ha^{-1}$), and E = stand age (years).

TABLE 5.1
TOTAL PLANTED AREA ESTABLISHED BY THE END OF 1995
BY AGE CLASSES AND ADMINISTRATIVE REGIONS ('000 HA)

	Age classes (in years)						
Region	0 -5	6-10	11-15	16-20	21-25	26-...	Total
Radiata pine							
V and RM	4	3	3	3	2	1	17
VI	21	10	11	15	4	0	60
VII	78	90	92	36	24	1	320
VIII	192	135	147	147	19	3	640
IX and X	125	78	73	52	9	2	337
Sub-total	420	316	326	253	58	7	1374
Eucalyptus							
All regions	229	44	7	3	3		286
Total	649	360	333	256	61	7	1660

Source: INFOR (1996)

TABLE 5.2
PARAMETER VALUES OF EQUATION (1) Ln V = a - b (1/E)
BY ADMINISTRATIVE REGIONS

Region	Parameter values	
	a	***b***
V and RM	6.909100	26.7026
VI	7.294867	29.3753
VII	7.608300	32.1089
VIII	7.282900	23.8646
IX and X	7.621200	28.4121

TABLE 5.3
MEAN CUMULATIVE STEM VOLUME (M^3 HA^{-1}) IN FOREST PLANTATIONS
ACCORDING TO AGE CLASSES AND ADMINISTRATIVE REGIONS

Region	Mean cumulative stem volume (m^3 ha^{-1}) Age classes (in years)					
	0-5	6-10	11-15	16-20	21-25	26-...
Radiata pine						
V and RM	5.0	35.6	128.4	227.2	313.6	411.2
VI	5.0	37.5	153.7	288.0	410.6	553.2
VII	5.0	36.4	170.4	338.5	498.8	690.9
VIII	6.0	73.7	232.1	386.5	515.6	656.8
IX and X	5.0	58.5	229.4	421.1	593.4	791.7
Eucalyptus						
All regions	2.0	35.3	135.4	285.7	517.0	N.A.

TABLE 5.4
TOTAL STANDING STEMWOOD VOLUME OF THE GROWING STOCK BY YEAR END, 1995
ACCORDING TO AGE CLASSES AND ADMINISTRATIVE REGIONS (MILLION M^3)

Region	Age classes (in years)						
	0-5	6-10	11-15	16-20	21-25	26-...	Total
Radiata pine							
V and RM	0.02	0.11	0.41	0.66	0.66	0.48	2.34
VI	0.10	0.38	1.66	4.23	1.51	0.22	8.10
VII	0.39	3.27	15.61	12.11	12.07	0.79	44.23
VIII	1.15	9.95	34.21	56.64	9.90	1.72	113.56
IX and X	0.62	4.59	16.72	21.90	5.27	1.59	50.70
Sub-total	2.28	18.3	68.61	95.54	29.41	4.8	218.93
Eucalyptus							
All regions	0.46	1.56	0.99	0.78	1.41	0.0	5.19
Total	2.74	19.86	69.60	96.32	30.82	4.79	224.12

The functions were applied for calculating the cumulative volume of radiata pine (Table

5.3). The total stemwood volume of radiata pine plantations was 219 million m^3 by the end of 1995 (Table 5.4).

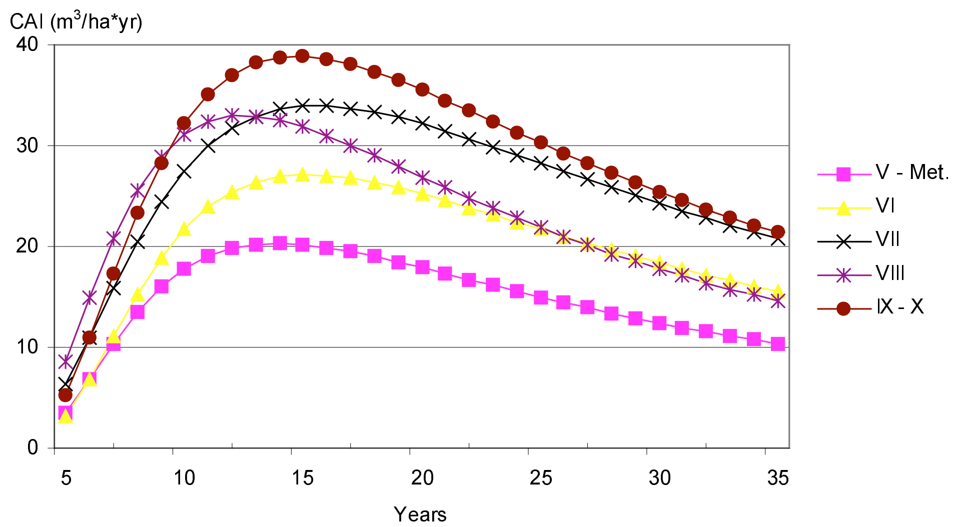
Unfortunately, it was not possible to apply the same methodology to eucalyptus plantations, because yield functions by administrative regions were not available. Instead, the mean cumulative volume (Table 5.3) was estimated, using a growth model developed for the *genus eucalyptus* in Chile (INFOR 1994). We assumed that in an 'average site' and with an 'average management regime', an eucalyptus stand reaches an average height of 28 metres in 20 years and that the stand has a density of 1,600 seedlings ha^{-1}. The total standing volume of eucalyptus plantations in 1995 was 5.2 million m^3 (Table 5.4).

<u>Volume increment:</u> The yield functions explained above (Equation 1) were applied for calculating the current annual volume increment (CAI) (m^3 ha^{-1} yr^{-1}) for radiata pine

TABLE 5.5
CURRENT ANNUAL VOLUME INCREMENT (M^3 $HA^{-1}YR^{-1}$) BY THE MEAN VALUE OF THE AGE CLASSES AND ADMINISTRATIVE REGIONS, 1996

	Age classes (in years)					
Region	5	8	13	18	23	28
Radiata pine						
V and RM	3.5	13.5	20.2	19.0	16.1	13.4
VI	3.2	15.3	26.4	26.4	23.2	19.7
VII	6.3	20.5	32.9	33.3	29.9	25.8
VIII	8.6	25.6	32.9	29.0	23.8	19.3
IX and X	5.3	23.3	38.2	37.3	32.4	27.3
Eucalyptus						
All regions	2.0	11.7	25.3	32.0	33.4	n.a.

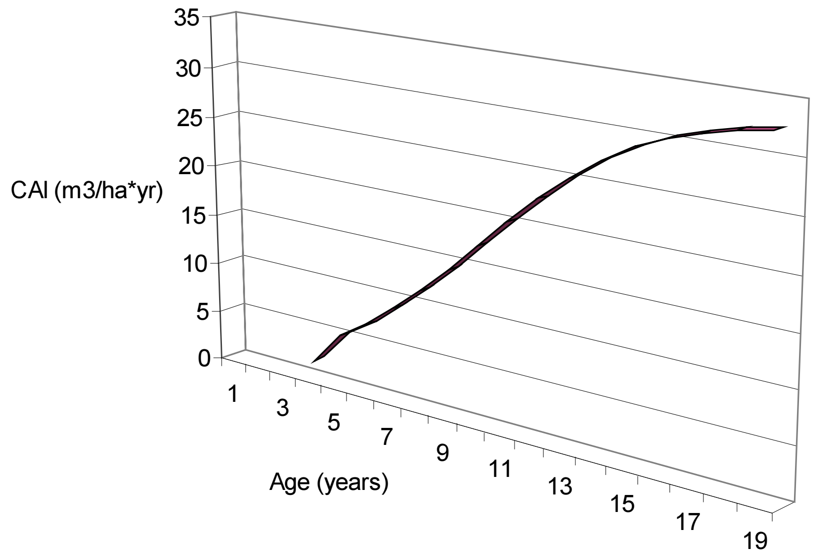
FIGURE 5.8
CURRENT ANNUAL VOLUME INCREMENT (CAI) (M^3 HA^{-1} YR^{-1}) OF *PINUS RADIATA* PLANTATIONS IN CHILE BY ADMINISTRATIVE REGIONS



and the mean annual volume increment (MAI) (m^3 ha^{-1} yr^{-1}) by age groups and by administrative regions. As was explained above, estimation by administrative regions and age is relevant because important differences in the figures for volume growth and volume increment exist between regions, as Table 5.5 and Figure 5.8 indicate.

Due to the lack of data, the above method was not applied to eucalyptus plantations. Instead, the current volume increment given in Table 5.5 and Figure 5.9 was calculated with the 'average site' and 'average management regime' method explained above. It is possible that this may be an under-estimation of growing stock for plantations exceeding 15 years, because the growth functions used were defined for plantation maturity less than 15 years only.

FIGURE 5.9
CURRENT ANNUAL VOLUME INCREMENT (CAI)(M^3 $HA^{-1}YR^{-1}$)
OF *EUCALYPTUS SP*. PLANTATIONS IN CHILE



3.2.3 Estimation of the current carbon pool and annual flux

Total carbon pool: To estimate the total amount of carbon stored in the stemwood of trees (Cpool) the total standing volume is multiplied by the average wood density and by the estimated carbon content of the biomass (Hollinger *et al.* 1993). However, carbon is stored not only in the stemwood, but also in branches, foliage, roots, forest floor litter and in the vegetation growing in the understorey. Various studies have been carried out for estimating the conversion of stemwood biomass to total biomass. Here, we use the models developed by the New Zealand Forest Research Institute for their local *Pinus radiata* stands. The model is based on studies on forest biomass and it takes into consideration the effect of tree age, plantation density and site fertility (Ministry for the Environment 1994; MacLaren *et al.* 1994) (Equation 2). Thus, the carbon pool fixed in the total biomass of radiata pine and eucalyptus plantations, Cpool, is given by

(2) $$Cpool = V \bullet \rho \bullet c \bullet \alpha$$

where:

$V =$ total standing volume as estimated in Table 5.4 (m^3)

$\rho =$ 4.29 10^5 g m^{-3} for radiata pine, average wood density (dry matter) (Perez 1983)

$\rho =$ 6.23 10^5 g m^{-3} for *Eucalyptus globulus*, average wood density (dry matter) (Perez 1983)

$c =$ 50 per cent carbon content of the biomass (Hollinger *et al.* 1993)

$\alpha =$ 1.89 the ratio of total biomass to stem biomass (Hollinger *et al.* 1993).

Annual fluxes of carbon are usually calculated on the basis of the increment of the carbon pool and its decrease due to removals and mortality. In our case, available data included the net area of forest plantations. A rough estimate of the annual flow of carbon to forest plantations in 1996 is obtained by summing the carbon flux to existing plantations (S1, Equation 3) and the flux to newly established plantations (S2, Equation 4). Thus, S = S1 + S2. In 1996, the total planted area increased by 64,000 ha, a figure which also includes reductions due to final cuttings and forest fires. S1 and S2 were calculated for both species as:

(3) $S_1 = (CAI \bullet \rho \bullet c \bullet \alpha \bullet a_o)$

(4) $S_2 = (CAI \bullet \rho \bullet c \bullet \alpha \bullet a_n)$

where:

$S_1 =$ annual carbon sequestration in the area planted up to the end of 1995

$S_2 =$ annual carbon sequestration in the new planted area in 1996

$CAI =$ current annual increment in m^3 ha^{-1} yr^{-1} for radiata pine and eucalyptus (Table 5.5)

$\rho =$ 4.29 10^5 g m^{-3} for radiata pine, average wood density (dry matter) (Perez 1983)

$\rho =$ 6.23 10^5 g m^{-3} for *Eucalyptus globulus,* average wood density (dry matter) (Perez 1983)

$c =$ 50 per cent carbon content of the biomass (Hollinger *et al.* 1993)

$\alpha =$ 1.89 the ratio of total biomass to stem biomass (Hollinger *et al.* 1993)

$a_o =$ planted area up to the end of 1995 (ha)

a_n = planted are during the year 1996 (ha).

The values of current annual increment given in Table 5.5 have been applied for estimating the annual carbon sequestration (S) during 1996. It should be stressed that *CAI*, ρ, c and α may vary with species, tree age, forest location and edaphic factors, and silvicultural regimes.

3.3 Carbon pools, fluxes, and balance

Using the Equation 2, we obtain a total carbon pool of approximately 88.8 Tg (tera-gram or million tons) in radiata pine plantations or 64.6 ton ha^{-1}. The carbon pool estimated in *Eucalyptus sp* plantations is 3 Tg. Therefore, forest plantations established in Chile up to December 1995 constitute a carbon pool close to 92 Tg (Table 5.6). This is equivalent to 48.8 tons ha^{-1} of carbon stored in forest plantations.

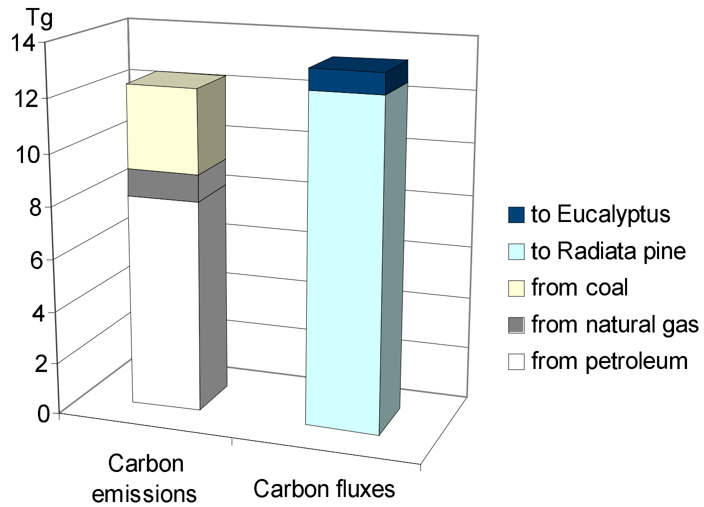
TABLE 5.6
CARBON POOLS AND FLUXES IN CHILEAN FOREST PLANTATIONS

	Age classes (in years)						
	0-5	6-10	11-15	16-20	21-25	26-...	Total
Cpool (Tg)							
Radiata pine	0.93	7.42	27.82	38.73	11.92	1.94	88.75
Eucalyptus	0.27	0.92	0.58	0.46	0.83		3.06
Total	1.20	8.33	28.40	39.19	12.75	1.94	91.81
Flux S1(Tg yr-1)							
Radiata pine	1.17	2.97	4.46	3.17	0.64	0.06	12.47
Eucalyptus	0.27	0.30	0.11	0.05	0.05		0.79
Total	1.44	3.27	4.57	3.22	0.70	0.06	13.26

Applying Equations 3 and 4, we have S1 = 12.5 Tg yr^{-1}. S2 is negligible because the value of CAI is close to 0 during the first year. So, S2 can be excluded from the table of results. Thus, we estimate that the total carbon flux is 12.5 Tg yr^{-1} for the radiata pine plantations in 1996. This is equivalent of 9.1 ton ha^{-1} yr^{-1}. In the case of eucalyptus plantations the total carbon flux (S1) for the year 1996 is 0.8 Tg yr^{-1} (Table 5.6), which is equivalent to 2.8 ton ha^{-1} yr^{-1}. Consequently, the total flux of atmospheric carbon for forest plantations in Chile was approximately 13.3 Tg yr^{-1} in 1996. The values obtained here for the annual carbon sequestration are higher than the values reported by other researchers (Mellillo *et al.* 1993, Dixon *et al.* 1994). Considering that the carbon content in the molecule of CO_2 is 27.3 per cent, our calculations indicate that 48.7 Tg yr^{-1} of atmospheric CO_2 is sequestered annually by the Chilean forest plantations.

In comparing the estimates presented above with the carbon dioxide emissions in Chile for 1996, one can conclude that annual carbon fluxes to forest plantations exceeded annual carbon emissions which were estimated as 12.33 Tg (EIA) (Figure 5.10) in that year. The emissions are estimated from fossil fuel consumption of petroleum, coal and natural gas. Therefore, forest plantations have a positive role in the carbon balance of the country because they contribute to absorbing excessive CO_2 emissions moving into the atmosphere, and thus preserve the equilibrium between different components of the carbon cycle. Carbon balance is crucial for maintaining the ability of the earth's biological ecosystems to provide the goods and services that are essential for sustainable economic development.[2]

FIGURE 5.10
BALANCE BETWEEN CARBON EMISSIONS FROM FOSSIL FUEL CONSUMPTION AND CARBON FLUXES TO FOREST PLANTATIONS IN CHILE, 1996



4. THE CHALLENGES OF SUSTAINABLE FORESTRY AND CARBON SEQUESTRATION

4.1 Scenarios for carbon sequestration in radiata pine plantations

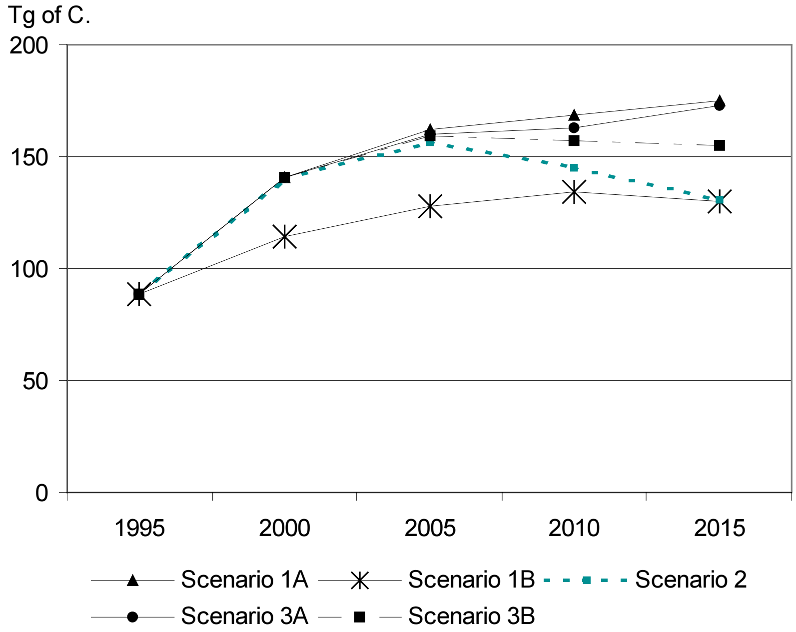
Forests have the potential to contribute to climate change through their influence on the global carbon cycle. In particular, the importance of local measures to promote carbon sequestration and conservation has been emphasized (Brown 1996). Here, we present some scenarios on the potential development of carbon pools in the radiata pine plantations up to the year 2015. Unfortunately, the lack of forestry statistics, especially for cuttings, makes the development of these scenarios difficult. Eucalyptus plantations could not be included in these scenarios, due to lack of reliable data and uncertainties regarding the future development of these plantations.

The five scenarios developed in this study belong to three 'groups': Group 1 (scenarios 1A and 1B) in which future plantations (both reforestation and afforestation) are established at the rate attained in recent years, i.e. approximately 63,500 ha yr^{-1}, resulting in a 10-20 per cent increment of total plantation area by the year 2015. Group 2 (scenario 2) assumes that the current plantation area is maintained, and only the harvested areas are reforested; no afforestation is carried out. Group 3 scenarios (3A and 3B) is based on the assumption that future plantations (both reforestation and afforestation) are established at approximately 31,750 ha yr^{-1}, which is half of the initial rate of recent years, and later at a rate to compensate areas harvested. This would mean an increment of 35-46 per cent of the total plantation area by 2015, based on the assumption that the government is willing to continue its support for creating new areas through subsidies for afforestation, but not for reforestation.

For two groups (1 and 3), we developed different sub-scenarios (A and B) to illustrate the impact of different forest management options on carbon pools. In subclass 1A, all plantations older than 26 years and 50 per cent of plantations in the age group 21-25 years are harvested. In subclass 1B, all plantations older than 21 years and 50 per cent of plantations in the age group 16-20 years are harvested. Thus scenario 1A represents a 'conservative forest management' option with rather long rotations, and 1B an 'aggressive management' alternative with very short rotations that promote an immediate supply of raw material from the plantations. In scenario 3A, all plantations older than 21 years are harvested, and in scenario 3B, all plantations older than 26 years and 50 per cent of plantations in the age group 21-25 years are harvested (similar to scenario 1A). Thus, 3A can be considered 'silvicultural optimum' scenario, while 3B represents a 'conservative forest management' scenario.

The results (Figure 5.11) show that in all cases (except scenario 2), the carbon pool of the radiata pine plantations increases with the maturity of the forest stands and increment of total plantation area. The 'aggressive management' scenario (1B) yields the

FIGURE 5.11
THE FIVE SCENARIOS FOR SIMULATING THE CARBON POOL IN RADIATA PINE PLANTATIONS BETWEEN 1995 AND 2015



lowest (130 Tg), while the scenarios for 'conservative management' (1A) and the 'silvicultural optimum' (3A) indicate the highest carbon pool at 175 and 173 Tg, respectively by the year 2015. The carbon pool in scenario 2 increases until the year 2005,

FIGURE 5.12A
TOTAL HARVESTED AREAS ACCORDING TO DIFFERENT SCENARIOS, 1995-2015

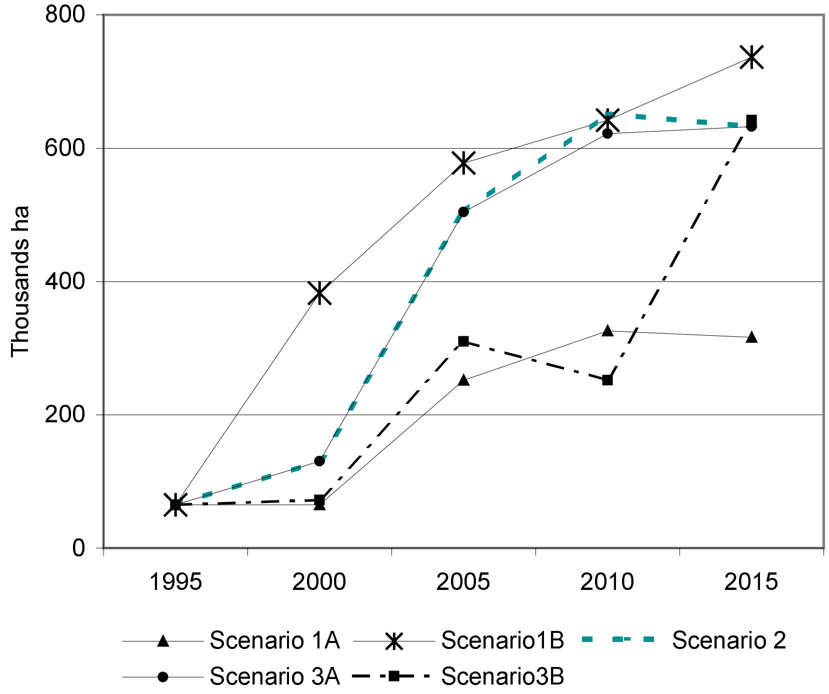
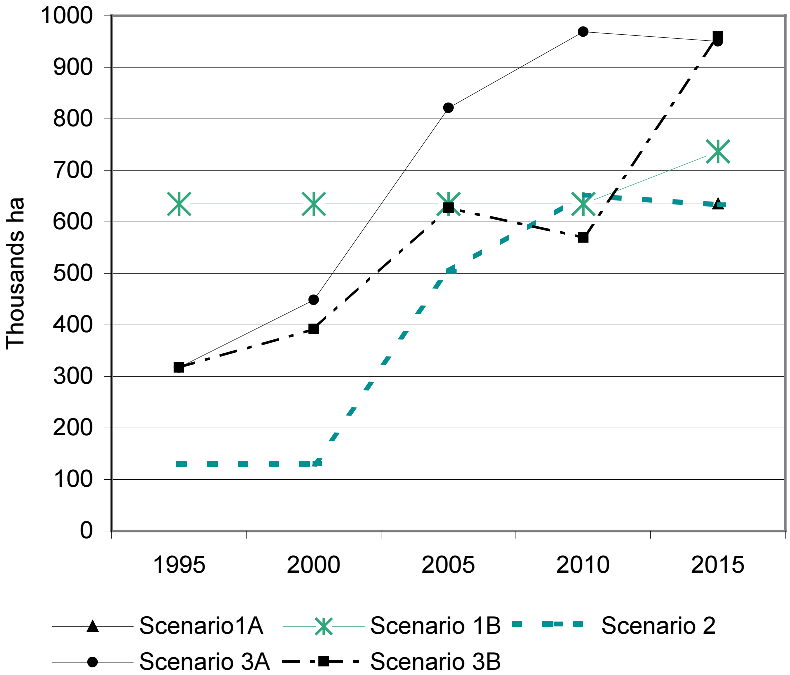


FIGURE 5.12B
PLANTED AREAS ACCORDING TO DIFFERENT SCENARIOS, 1995-2015



and decreases thereafter. This is explained by the fact that in scenario 2, only harvested areas are reforested and no afforestation is carried out. Consequently after 2005, plantations are dominated by young age groups, which have low carbon density per unit area. In scenario 1B, rotation is sub-optimal, and despite total plantation area increasing by 10 per cent, it is not sufficient to compensate the low carbon density of young plantations established after harvesting. The above scenarios also have differentiated consequences and impacts on the total plantation area, and areas harvested and planted annually (Figure 5.12A and 5.12B respectively). The 'silvicultural optimum' scenario, which is based on a net annual plantation area of approximately 32,000 ha in 1995, produces after the year 2006 the highest annual rate of plantation establishment (approximately 90,000 ha), yielding a 46 per cent increment in the total area of plantations by 2015.

4.2 Sustainable forestry and carbon policies

The development path followed by Chile has led to a two-faceted forest sector: on one side are the dynamic plantation-based forest industries, and on the other side, the backward perception of natural forests and the less-than-efficient industry based on these natural forests. Thus, it is a matter of debate whether this development strategy constitutes a sustainable approach. In recent years, development has been clearly unsustainable at least on the part of natural forests.

The above scenarios for radiata pine (Figure 5.11) show that plantation forestry—with its main objective of producing raw material for related industries—can play a diverse role in contributing to Chile's carbon balance. Under the 'silvicultural optimum' and 'conservative management' scenarios with relatively long rotation cycles, the carbon pool in 2015 is estimated to be approximately twice the 1995 level. Even under the 'aggressive' forest management scenarios with shorter rotations and large quantities of raw material being extracted for industrial use, the carbon pool increases by approximately 50 per cent.

It is also interesting to compare these scenarios in terms of areas planted annually and the total plantation area. High carbon pool values under the 'silvicultural optimum' scenario are obtained through the expansion of the plantation area by 46 per cent, whereas equally high pool values under 'conservative management' scenarios are obtained using long rotations and a 20 per cent increase in the plantation area. Low carbon pool values by 2015 are obtained when the current plantation area is maintained (scenario 2) or with 'aggressive' forest management approach with a 10 per cent increase in the plantation area.

The forest sector offers major opportunities for sustainable development. The first priority should be to adopt a more balanced approach in which the potential of plantation forestry, the rational management, and utilization of natural forests complement each other. A carbon policy for the mitigation of atmospheric CO_2 build-up needs to be integrated in the sustainable development strategy of the forest sector. This integration is indispensable because it is unrealistic to assume that forests will be managed solely for the purpose of carbon sequestration. On the contrary, it is vital that forests continue to be managed for their traditional economic benefits, but in a sustainable way (Apps and Price 1996). Sustainable forestry contributes to increasing the carbon sink effects, but also to halting significant net additions of carbon to the atmosphere that result from deforestation and mismanaged forestry practices.

Consequently, the criteria introduced by the Montreal Process (1995) for assessing sustainable forest management have to be taken into consideration in the formulation of forest policies which endeavour to promote carbon sequestration. Accordingly, due attention should be given to other issues like the conservation of biological diversity, maintenance of productive capacity of forest ecosystems, maintenance of forest ecosystem health and vitality, and the conservation and maintenance of soil and water resources. In addition, recognition must be given to issues such as the maintenance and enhancement of long-term multiple socioeconomic benefits to meet the needs of the society; legal, institutional, and economic framework for forest conservation, and sustainable management. The findings of the analysis on the limitations and rewards of sustainable forestry management in Chile could provide a solid foundation for dictating a new forest policy on a rational basis, and for launching new forestry programmes. A similar approach is recommended for other developing countries.

To enhance the maintenance of carbon pools in forest ecosystems and to increase the flux of CO_2 to forest biomass, several forest policy programmes should be adopted and implemented. The most important policy considerations are the promotion of plantations; the preservation of natural forests; the adoption of management regimes based on sustainable forestry; the rehabilitation of eroded land or degraded forests; the prevention of deforestation, and the production of industrial wood and fuelwood. The following relevant measures need to be included in such programmes (Brown *et al.* 1996a; Nilsson and Schopfhauser 1995; Kanninen 1993):

i) measures to prevent carbon emissions by conserving existing carbon pools in forest vegetation and soil through deforestation control, increasing the area of protected forests, changing harvesting regimes and the final utilization of wood, and controlling anthropogenic destructive actions like forest fires;

ii) measures to expand the storage of carbon in forest ecosystems by increasing the area and quantity of biomass and soil carbon density, and increasing carbon storage in durable wood products;

iii) measures to transfer forest biomass carbon into long-life products, substitute fossil fuel-based energy and substitute cement-based products with wood.

In Chile, of the three options mentioned above, only measures to expand carbon storage through the expansion of forest plantations have been partially adopted. Other elements, such as substituting fossil fuels with biomass energy, have future potential, but so far have not been considered. Natural forests and their management have been largely neglected and have, to some degree, been converted to other land uses, including plantations. The CO_2 emissions caused by this conversion and the low priority given to sustainable management of carbon pools in natural forests have only recently been off-set by the carbon sequestration of forest plantations.

4.3 Discussion

Without a doubt, the expansion of forest plantations, frequently over the last 20 years surpassing 100,000 ha of annually planted areas, has promoted the development of forest industries in Chile. The share of forest products of total exports of the last two decades has increased from 7.9 to 15.7 per cent (INFOR 1996). However, forest policies have mainly supported the establishment of plantations of fast growing exotic tree species to meet industrial needs. In contrast, promoting sustainable management and utilization of natural forests have been widely neglected. If one takes into consideration the high quantities of biomass and large carbon pools existing in these natural forests, this policy is inadequate from the point of view of carbon management.

Annual amount of carbon dioxide removed from the atmosphere by Chile's forest plantations, 49 Tg yr^{-1}, is substantial indeed and highlights their importance for carbon sequestration. Our scenarios show that both the carbon pool and carbon density will increase considerably in the future because biomass will increase as forest plantations mature. Currently, the forest plantations are characterized by a skewed age distribution in which young stands are dominant.

Data availability is the most important constraint in defining a method for estimating the carbon pools and fluxes in the Chilean forest plantations. In an ideal situation, estimations are conduced with detailed data on stand volume, increment and yield (distribution by age groups, site classifications, altitudinal variations, etc.). Currently, however, numerous GIS-based (geographical information system) methods are available, and this type of detailed spatial analysis can be implemented, but also accentuates the need for modern forest inventories to provide the basic stand and spatial data (Brown *et al.* 1996b). Unfortunately, as national-level forest inventory data are not available for Chile, detailed spatial information is also unobtainable. However, in the case of radiata pine plantations, application of the yield models by administrative regions at least partially takes latitudinal variations into consideration. In the case of eucalyptus plantations, data availability is even poorer and the volume estimation is carried out by using a simple growth model.

Monitoring changes in the carbon reservoirs is important for tracing the net flux of carbon between forests and the atmosphere. Forest inventories provide the best sources of data on tree volume and biomass because the data are generally collected in a statistically sound manner, but this also implies that national forest inventories are conducted at frequent intervals or on a permanent basis.

Soils are important reservoirs of carbon—their carbon content is often larger than in the terrestrial vegetation—and this fact should be taken into consideration in similar types of estimation (Kauppi 1996). Unfortunately, another limitation in the study is the paucity of data on the quantities of carbon fixed in forest soils. Several studies on this issue have been performed in other countries, but we considered it wiser to omit these calculations. The same criterion was applied in relation to avoid estimations on the amount of carbon stored in forest products, their average life, and the effect on the carbon balance of recycling material used in the industrial processes.

Future studies are needed to provide detailed estimations on the amount of carbon sequestered in forest plantations and also in natural forests. Natural forests, due to their larger standing volume and biomass, usually contain larger reservoirs of carbon than forest plantations. Thus, the conservation of natural forests has a positive effect on the national carbon balance. Currently, there are some 9 million hectares of national parks, 5.5 million hectares of forest reserves, and some minor areas declared as natural monuments. Although only a fraction of these protected areas is covered by closed forests, it is a clear fact that the policy of conservation has contributed to maintaining the existing carbon pools.

In Chile, plantations are in a key position in the formulation of carbon policies. Currently, only 28 per cent of the land considered suitable for forest growing is covered by different types of forests. At the moment, there is clear potential to increase forest resources through forest plantations, particularly by establishing plantations for rehabilitating degraded forest ecosystems, eroded and/or denuded lands, and for afforestation of marginal agricultural and grazing lands. Nevertheless, most of these areas are located in remote places where the creation of plantations is not economically feasible. In spite of their potential, new planting investments are constrained by land availability. However, if the current subsidies for establishing forest plantations are maintained, no significant reduction in the annually planted area is to be expected in the near future.

NOTES

1 These include, among others, *E. globulus*, *E. nitens*, *E. delegatensis*, *E. fastigata*, *E. regnans*, and *E. camaldulesis.*

2 The emission statistics were obtained from the internet page of the Energy Information Administration (EIA: http://www.eia.doe.gov/) and include emissions from fossil fuel consumption, from the consumption of petroleum, natural gas, coal, and the flaring of natural gas in 1996.

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