THE CARBON-SEQUESTRATION POTENTIAL OF A GLOBAL AFFORESTATION PROGRAM

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Abstract. We analyzed the changes in the carbon cycle that could be achieved with a global, large-scale afforestation program that is economically, politically, and technically feasible. We estimated that of the areas regarded as suitable for large-scale plantations, only about 345 million ha would actually be available for plantations and agroforestry for the sole purpose of sequestering carbon. The maximum annual rate of carbon fixation (1.48 Gt/yr) would only be achieved 60 years after the establishment of the plantations – 1.14 Gt by above-ground biomass and 0.34 Gt by below-ground biomass. Over the period from 1995 to 2095, a total of 104 Gt of carbon would be sequestered. This is substantially lower than the amount of carbon required to offset current carbon emissions (3.8 Gt/yr) in order to stabilize the carbon content of the atmosphere.

1. Background and Objectives

The world's forests currently cover about 3,417 million ha, approximately 26% of the total land area. The distribution of forests by continent and main ecological zone in 1990 is presented in Table I. Other wooded areas where the tree stand density is less than 10% to 20% are classified as open woodland or brush. This category also includes woody fallow land generated by the clearance of existing forests; currently about 13% of the world's land area falls into this category. The rate of deforestation in the Tropics has increased significantly in recent decades; the Food and Agriculture Organization of the United Nations (FAO) (Lanly *et al.*, 1991) estimates that 16.8 million ha were cleared each year during the 1980s, corresponding to an average annual loss of 1.2% of total tropical forest cover.

The above-ground forest ecosystems contain an estimated 500 Gt to 800 Gt of carbon (Winjum *et al.*, 1992), approximately the same amount as is present in the earth's atmosphere in the form of CO_2. Living forests sequester CO_2 from the atmosphere; therefore, any increase in forest biomass will reduce the buildup of atmospheric CO_2. A number of forestry options are available for the mitigation of carbon buildup, including slowing the rate of tropical deforestation, increasing the productivity of existing forests, and increasing afforestation. The Noordwijk Declaration (1989) called for an annual net increase in global forest cover of 12 million ha by the year 2000. Given that about 17 million ha of tropical forests are lost each year, this implies an afforestation target of 30 million ha per year.

Several studies have attempted to estimate the magnitude of the forestry measures that would be required to stabilize CO_2 at current levels. A summary of these estimates of the area of forest plantations that would be required to offset various

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TABLE I

The world's forested areas in 1990, by continent and ecological zone. Based on Allan and Lanly (1991) and FAO (1991a, 1991b)

Ecological zone		Africa	America	Asia[a]	Pacific	Europe[b]	TOTAL
Temperate (incl. boreal, mediterranean, sub-temperate)	Temperate and boreal forests (million ha)	8.1	511.4	188.4	47.3	904.3	1659.5
	% of temperate land area	1.1	22.8	10.6	5.9	32.3	19.9
Tropical	Tropical forests (million ha)	600.1	839.9	274.9	42.6		1757.5
	% of tropical land area	26.7	50.1	30.7	78.6		36.3
Total	Total forested area (million ha)	608.2	1351.3	463.3	89.9	904.3	3417.0
	% of total land area	20.5	34.7	17.3	10.8	34.4	26.1

[a] Includes the Middle and Near East but excludes the Asian part of the former Soviet Union.

[b] Includes all of the former Soviet Union.

CO_2 emission levels is presented in Table II, which shows a range of 3.4 to 700 million ha needed to offset 0.05 to 5 Gt/yr of fossil-fuel use.

Centeno (1992) argues that to offset the net contribution of tropical deforestation to the greenhouse effect, a total of 115 million ha of fast-growing tree species or 460 million ha of slow-growing species are required; to offset the current net global carbon emissions (3.8 Gt/year), a total of 475 million ha of fast-growing species or 1,900 million ha of slow-growing species are required (Table III).

Hasenkamp (1992) calculates that the global climate problem could be solved by planting a total of 500 million ha of plantations, even without parallel efforts to minimize carbon emissions from fossil-fuel combustion. Hall *et al.* (1990, 1991) suggest that a total of 600 million ha of biomass plantations with an average yield of 12 dry tons/ha/yr could offset 50% of 1985 emissions by the year 2050, if the biomass is used instead of fossil fuels for energy production. Thus, any discussion of the total effects of large-scale plantations on greenhouse gas emissions should include both carbon sequestration and the substitution of biomass for fossil fuels for energy production.

Most of the above-mentioned studies do not, however, address the technical, economic, or political feasibility of establishing such plantations. The objective of this paper is to examine the potential increases in carbon fixation rates that could be achieved through a feasible afforestation program.

1.1. PLANTATIONS, AFFORESTATION, REFORESTATION

Plantations are defined as forest stands that have been established artificially, either on land that has not supported forests in the last 50 years (afforestation), or on land that has supported forests in the past, but where the original vegetation has been replaced by forests (reforestation) (Brown *et al.*, 1986). From statistics on land suitable for plantations, it is difficult to distinguish land that is suitable for afforestation from that which is suitable for reforestation. The latter includes land that has been clear-cut and left fallow, producing only brush and scrub ('backlog' land). Therefore, the following discussion deals with plantations established on land that is both suitable and available for afforestation and reforestation. Land that is reforested immediately after clear-cutting in a sustainable forestry system has been excluded.

Several large-scale reforestation programs have already been implemented, as can be seen from Table IV.

According to Pöyry (1992), the area of accumulated pure industrial plantations by 1985 (39 million ha) is expected to increase from its 1985 level of 39 million ha to 50 million ha by the year 2000, driven by socioeconomic and technological developments. Pandey (1994) reports that the area of accumulated tropical industrial and nonindustrial plantations was 43.9 million ha at the end of the year 1990. The annual average tropical plantation rate is estimated to be 2.6 million ha. Pandey also estimates the accumulated plantations at the end of the 1990s to

TABLE II

Estimates of the areas of plantations required to offset various CO_2 emission levels (*Source:* Andrasko, 1990)

Estimate	Location	Carbon-sequestration rate assumed (t/ha/yr)	Offset goal	Area (million ha)
Dyson and Marland (1976)	Temperate zone	7.5	5 Gt C (total annual fossil-fuel use)	700
Marland (1988)	Tropics	9.6	5 Gt C (total annual fossil-fuel use)	500
Myers (1988)	Tropics	10.0	2.9 Gt C (net annual C increase)	300
Sedjo and Solomon (1989)	Tropics or temperate zone	6.2	2.9 Gt (net annual C increase)	465
Woodwell (1987)	Tropics	5.0	1–2 Gt (net annual C increase, tropics)	200–400
Postel and Heise (1988); Brown *et al.* (1988a)	Tropics	6.8	0.7 Gt (C benefits from new fuelwood plantations and restored forests)	110
Dudek (1988)	U.S.A.	10–12	0.05 Gt (1987–1996 new electric plant C)	3.4–4.5
Andrasko (1989)	U.S.A.	3.5–10	0.05 Gt (1987–1996 new electric plant C)	4.5–13.0
Andrasko and Tirpak (1989)	U.S.A.	4.4	0.12 Gt/yr	10.5[a]
USFS/EPA (1989)	U.S.A.	5.7;5.7	0.06 Gt/yr;0.12 Gt/yr	8.1[b];15.0[c]

[a] Assumes 10.5 million ha planted and 23.5 million ha intensively managed.

[b] Assumes 8.1 million ha planted and 4.3 million ha intensively managed.

[c] Assumes 15.0 million ha planted and 10.8 million ha intensively managed.

TABLE III

Area of plantations needed to offset net carbon emissions from tropical deforestation, and net global carbon emissions, at average 1980s emission levels. Based on Centeno (1992)

Scenario	Rate of forest growth (t C/ha/yr)	Area of plantations necessary (million ha) to offset carbon contributions due to		Cost ($ billion)[c]
		Tropical deforestation[a]	Net global carbon emissions[b]	
A	8.0	115	475	285
B	5.3	174	717	430
C	3.2	287	1187	712
D	2.0	460	1900	1140

[a] Assuming an average loss of tropical forests of 17 million ha/yr during the 1980s (65% dense forests, 35% open forests).

[b] Assuming net global carbon emissions of 3.8 Gt/yr.

[c] Based on an average cost of US$600/ha to offset net global carbon emissions.

be about 42 million ha in nontropical developing countries. The corresponding estimate for developed countries is about 115 million ha. However, to some extent this latter figure probably includes plantations after clear cuts. These figures can be compared with the 80 to 90 million ha estimated for global plantations by Postel and Heise (1988), Mather (1990), and Sedjo and Lyon (1990).

1.2. LARGE-SCALE PLANTATIONS: A LAND USE PROBLEM

Land that is suitable for afforestation may not actually be available. Grainger (1991) stresses that, "even if environmental quality and economic productivity are both low, those who use the land may be unwilling to convert it to forest." He identifies a number of factors preventing massive afforestation, including social, organizational, economic, and market-imposed constraints. Trexler (1991a) claims that, "for at least a decade social, political and infrastructural barriers will keep plausible reforestation rates very modest." Similarly, according to the FAO (1991b), obstacles to the establishment of plantations in the Tropics include degraded soils, limited knowledge of suitable species and planting systems, and the lack of institutional capacity in many developing countries.

Large-scale plantations may also interfere with other priorities for the use of land: "No matter how much money is made available for plantations, local land tenure, land use customs and laws, and cultural characteristics will strongly affect the possibilities to carry out plantations in the tropics" (Andrasko *et al.*, 1991). Trexler (1991a) also identified factors that determine the availability of land, the rate at which plantations can be established, and the long-term sustainability of the project. These factors include the following: population growth and the need for agricultural land; prevailing government policies that encourage or discourage

TABLE IV
Estimates on worldwide afforestation, reforestation, and industrial plantations

Estimate	Period	Reforestation/plantations (in million ha)	Plantations located in the Tropics (in million ha)
Dixon *et al.* (1991b)	by 1990	130	25–30
WRI (1990)	annually during 1980s	15 (including natural regeneration)	—
Postel and Heise (1988), Mather (1990)	1975–1985	80–90 (industrial plantations)	—
Mather (1990)	annually during 1980s	10	—
Grainger (1988)	up to 1980	7 (industrial plantations)	11.5
Centeno (1992)	up to 1985	35.8 (developing world only)	—
Pöyry (1992)	by 1985	39 (industrial plantations)	—

forestry; agricultural policies that affect forest resources; land tenure systems as they affect land management incentives; government receptivity to policy changes in these sectors; institutional capacity to implement and sustain forestry initiatives; the country's economic and political status and stability; the effectiveness of non-governmental institutions in promoting forestry; and public perception of the local costs and benefits of forestry efforts and local experiences with forestry initiatives in the past.

Once these factors are taken into account, the area of land that will actually be available for plantations is reduced. Trexler (1991a) also points out that tree-planting programs "will work best if they yield an economic return." In other words, planting trees just to take up carbon is a difficult concept to apply in practice.

Spears (1983) also identified a number of factors that have accounted for the success of industrial plantations. A clear definition of the program's objectives is crucial at the outset, as is early commitment to use the project results. However, the latter will be difficult to achieve with plantations that are established purely for carbon fixation. Spears also notes that the political commitment of national governments is essential to ensure that the reforestation programs reach maturity.

In India, for example, government programs for the establishment of 1.4 million ha of fast-growing industrial hardwoods (mainly *Eucalyptus*) and 0.3 million ha of nonindustrial plantations caused considerable controversy because of the shortage of land and the program's insensitivity to the needs and opinions of the local people (Centeno, 1992). The plantations have affected the sustainability and self-sufficiency of food production and have weakened traditional systems of community-based resource management.

In the U.S.A., a number of large-scale forestry projects for energy production have also failed. From these cases, Frankena (1987) concludes that decisions made by governments and industry that conflict with the values of citizens are always difficult to carry through. Decision makers are unlikely to receive public support for policies that affect natural and renewable resources. Large-scale projects often threaten environmental values, and conflicts are also likely to arise with the establishment of large-scale plantations for CO_2 fixation. As Centeno (1992) points out, "the rush to capture excess carbon has prompted proposals to choose the fastest growing species. But the overall effect of such plantations must also take into account other factors such as the stress caused to the soil, the hydrological cycle and the stability of the resource."

The problems created by large-scale plantations in Australia concern matters such as "timber resource needs, the state of the economy and employment, land tenure, property rights, and the need to protect remnant native forests, but also ... the areas of the relationships amongst landscape change, community values and welfare, shifting perceptions, and the land as a focus of spiritual tenets and aspirations" (Russell, 1990). Many policy makers are skeptical of large-scale plantation programs whose objective is simply carbon fixation: "The ongoing negotiations on a climate convention have in an unfortunate way been focused on the concept of large-scale plantations for the fixation of carbon" (Nilsson, 1992). Many developing countries perceive the desire of industrialized countries to establish large-scale plantations for carbon fixation as merely a justification for their continued high levels of energy consumption and carbon emissions. Nilsson therefore concludes that it is crucial that such plantations first satisfy all the requirements of the national forest sector objectives, and that they do not just serve a carbon fixation function. The growing public interest in the environment has resulted in the politicization of large-scale plantation programs. Without public cooperation, therefore, such programs stand little chance of success (Zobel *et al.*, 1987).

It should be stressed that in the land-availability calculations presented in this paper, possible negative impacts on land availability or suitability for plantations by the foreseen climate change were not taken into account. The reasons for this are the absence of the detailed data required for such calculations. The socioeconomic influences on the forests for the next 50 years will probably overwhelm any changes by future environmental conditions for the low latitudes (Brown *et al.*, 1993; and Zuidema *et al.*, 1993). For the temperate and boreal forests, increased forested lands and increased productivity are expected during the next 50 years (Zuidema *et al.*, 1993), due to economic factors.

2. Land for Plantations and Corresponding Management Programs

Aggregated regional data on land that is both suitable and available for plantations in the major world regions and corresponding management programs are presented in Table V. It should be pointed out that for some world regions relevant data on land availability were either nonexistent or unobtainable; therefore, some of the data were probably underestimated. The total land area available is 344.8 million ha (275.1 million ha for plantations and 69.7 million ha for agroforestry), which is far less than the area that is regarded as suitable for plantations.

2.1. FOREST MANAGEMENT PROGRAMS

The rotation period, or lifetime, of a plantation depends on its objectives and on the silvicultural management programs employed. Large-scale forest plantations must be managed to avoid natural mortality, decay, disease, and insect infestation. We have only limited knowledge of management programs that would be appropriate for plantations whose only purpose is carbon fixation; therefore, we have drawn on past experience with the management of industrial plantations, for which more information is available.

A wide variety of management programs can be employed throughout the world; in Table VI, average and aggregated information on suitable silvicultural programs in the various regions are presented. The table shows the rotation periods and the corresponding mean annual increments (MAIs). The annual increments presented

TABLE V

Aggregated estimates of suitable and available land for plantations and corresponding management programs

Region	Land suitable for plantations (million ha)	Land available for plantations (million ha)	Average mean annual increment (m^3/ha/yr)	Rotation period (years)	Plantation period	Plantation rate (million ha/yr)
TEMPERATE FORESTS						
Canada						
NSR[1] Land, B.C.	—	0.84	8.0	60	1995–2020	0.034
NSR[1] Land, Rest of Canada	—	18.90	2.5	60	1995–2020	0.760
Converted farmland	—	4.41	3.0	60	1995–2020	0.176
Unimproved farmland	—	4.16	2.5	60	1995–2020	0.166
U.S.A.						
Plantations I	—	9.0	15	35	1995–2025	0.300
II	—	9.0	10	15	1995–2025	0.300
Agroforestry I	—	1.5	8	35	1995–2025	0.050
II	—	1.5	6	40	1995–2025	0.050
Europe						
Nordic countries	—	0.350	5.0	60	1995–2020	0.014
EC-9	—	3.760	8.0	40	1995–2020	0.151
Central	—	0.475	6.0	60	1995–2020	0.019
Southern	—	2.175	10.0	20	1995–2020	0.087
Eastern	—	1.325	6.0	60	1995–2020	0.053
Former Soviet Union	132.0	66.5	3.0	80	1995–2035	1.663
China	86.6	62.5	2.3	80	1995–2020	2.500
Temperate Asia	—	12.5	12.0	40	1995–2020	0.500
Temperate South Africa	—	1.9	16	30	1995–2020	0.075
Temperate South America	—	4.6	15	25	1995–2020	0.182
Australia						
Plantations	9.7–54.8	0.785	23.0	30	1995–2030	0.023
Agroforestry	7.0	3.500	6.0	30	1995–2030	0.100
New Zealand	—	5.0	25.0	25	1995–2045	0.100
TROPICAL FORESTS						
Latin America						
Plant-degraded land	240					
Plant-fallow forest	295	24.5	25	20	1995–2050	0.445
Total plantation	535	16.3	8	20	1995–2050	0.296
Agroforestry	274					
Africa						
Plant-degraded land	284					
Plant-fallow land	456	4.6	16	30	1995–2050	0.084
Total plantation	740	27.0	8	30	1995–2050	0.491
Agroforestry	213					
Asia						
Plant-degraded land	55					
Plant-fallow land	107	37.8	16	20	1995–2050	0.687
Total plantation	162	19.9	8	20	1995–2050	0.362
Agroforestry	304					
Total (million ha)						
Plantations	—	275.1	—	—	—	—
Agroforestry	—	69.7				

[1] Not satisfactorily restocked. Sources: Andrasko, 1990; Centeno, 1992; Congressional Research Service, 1989; Dixon *et al.*, 1991a; Dixon *et al.*, 1991b; Dixon *et al.*, 1994; Eckersley, 1989; FAO, 1991b; Grainger, 1988; Grainger, 1991; Hagler, 1992; Hasenkamp, 1992; Houghton *et al.*, 1991; Lanly *et al.*, 1991; Lavender, 1991; Maclaren, 1992; Marland,1988; Moulton and Richards, 1990; Nilsson *et al.*, 1992a, 1992b; OECD, 1991; Pandey, 1994, Prado,1992; Russell,1990; Sampson,1992; Sedjo, 1983; Sedjo,1992; Sedjo and Lyon, 1990; South African Forest Owners Association, 1991, 1992; Trexler, 1991a, 1991b; Troensegaard, 1989; Van Kooten, 1991; Volz *et al.*, 1991; Whyte, 1990; Winjum *et al.*, 1992; and WRI, 1990.

TABLE VI

Rotation periods and corresponding mean annual increments (MAIs)

Region/species	Rotation period (years)	MAI (m^3/ha/yr)
New Zealand/coniferous	25	25
Australia/coniferous	30	25
Australia/deciduous	30	22
South Africa/coniferous	25	16
Tropical Africa/deciduous	30	17
Tropical Africa/coniferous	30	15
Tropical Latin America/coniferous	15	18
Tropical Latin America/deciduous	20	25
Temperate Latin America/coniferous + deciduous	30	22
Tropical Asia/coniferous + deciduous	20	16
U.S. south/coniferous	35	15
U.S. temperate/coniferous	50	10
Europe: Nordic countries	60	5
EC-9	40	8
Central	60	6
Southern	20	10
Eastern	60	6
Former Soviet Union	80	3
Canada	60	4
China	80	2.3
Temperate Asia	40	12.0

References: Andrasko, 1990; Andrasko *et al.*, 1991; Birdsey, 1990; Centeno, 1992; Dixon *et al.*, 1991a and 1991b; Eckersley, 1989; Hagler, 1992; Kohlmaier *et al.*, 1992; Lunnan *et al.*, 1991; Maclaren, 1992; Marland, 1988; Nilsson, 1988; Nilsson *et al.*, 1992a and 1992b; Pandey, 1994; Pöyry, 1992; Prado, 1992; Sampson, 1992; Sedjo, 1983; Sedjo and Lyon, 1990; South African Forest Owners Association, 1991 and 1992; Troensegaard, 1989; Turnbull *et al.*, 1989; Van Kooten, 1991; Volz *et al.*, 1991; and Whyte, 1990.

do not take into account any considerations of changed increment rates due to expected climate change. The rationale for this is that there currently is no consensus on how much the increment for different species in different regions will change in a changed climate. The projected effects of these programs are conservative because with a large-scale program it is highly likely that the maximum effects (in terms of yield) of the plantations cannot be achieved. In the Aracazuz plantations in Brazil, for example, MAIs of 50 to 70 m^3/ha can be achieved with a seven-year rotation period; however, this requires careful site preparation and a level of intensive management that is unlikely to be achievable on large-scale plantations for carbon fixation. The silvicultural programs presented in Table VI are directed toward the production of pulp and fuelwood. Finally, it should be stressed that the programs in Table VI are simplifications of reality.

3. Rates of Carbon Fixation by Forest Ecosystems

Many papers have been published that estimate the carbon fixation rates in forest ecosystems (see Armson, 1977; Volz *et al.*, 1991; Forestry Canada, 1990; Dudek and Le Blanc, 1990; OECD, 1991; Trexler, 1991a, b; Sampson, 1992; Botkin and Simpson, 1990; Harmon *et al.*, 1990; Lunnan *et al.*, 1991; Melillo *et al.*, 1988; Rodin and Bazilevitch, 1967; Maclaren, 1992; Holt and Spain, 1986; Brown *et al.*, 1986, 1989; Farnum *et al.*, 1983; Houghton *et al.*, 1991, Kolchugina and Vinson 1993 a, b, c). Nevertheless, many uncertainties remain. In order to estimate the time scale of carbon uptake in forest plantations, average fixation rates per ha are insufficient, and we must work with fixation rates linked to the growth rate over time, expressed in cubic meters of stemwood. To our knowledge, no direct estimates of carbon uptake per cubic meter of stemwood at the subregional level are available (see section 4); therefore, we have had to work with approximate aggregate estimates for this factor. Based on the studies listed above, we used the following carbon fixation rates of the total above-ground biomass (carbon uptake by forest soil is excluded):

- 0.3 tons C/m^3 stemwood for Canada, the U.S.A., Europe, the former Soviet Union, China, temperate Asia, temperate South Africa and temperate South America.
- 0.4 tons C/m^3 stemwood for New Zealand, Australia, and the Tropics.

The above aggregates require improvement and may be overestimated. The calculations do not take into account any reduction in the carbon uptake to offset the carbon released at the establishment of the plantations and during management of the plantations (such as the release of carbon through consumption of fossil fuel).

3.1. DEVELOPMENT OF FORESTS OVER TIME

Also presented are the approximate aggregate estimates of the average carbon uptake by the above-ground biomass per cubic meter of stemwood over the entire rotation period, which are linked to the estimates of average MAIs (see Table VI). In order to estimate the carbon uptake rates over time, we must take into account the distribution of the MAI and the carbon uptake over time. Nilsson (1982) obtained a generalized function for the development of stands in even-aged and sustainable managed industrial forests. The concept builds on the belief that the development of the total production has the same path in different types of forests. The different types of forests are distinguished by the level of production and the time frame for the production. This concept is, in turn, based on an established model for forest yield and production developed by Jonson and Modin (1932). The Nilsson function is based on yield tables from different countries and the basic data for the yield tables is from experimental field measurements. The original test of the function was carried out for the boreal forests and the Tropics, and encompassed the species

Picea abies, *Pinus sylvestris*, *Pinus contorta*, *Shorea robusta*, *Cedrus deodara*, and the genus *Eucalyptus*. In spite of the large variation in rotation periods and production levels between the species and zones, the fit to the function was very good (Nilsson, 1978). Later, Nilsson (1982, 1994) enlarged the scope of the tests (based on yield tables) to involve a total of 12 species in the boreal, temperate, and tropical zones, with the same result.

The general function expresses stand development in terms of the relative yield over the relative age:

$$Y(R) = a(1 - b^{-R/100})^c, \qquad (1)$$

where Y is the relative yield, expressed as the ratio of the accumulated yield to the total accumulated yield at the age of the culmination of the MAI; R is the relative age, expressed as the ratio of current age to the age of maximum volume production; and a, b and c are coefficients.

This means that the growing period is defined as the time between the establishment of the stand and the culmination of the MAI. At the culmination, the MAI and the current annual increment (CAI) of the stand are equal. The growing period is set to the relative age of 100, which means that the relative age is equal to the real age of the stand expressed as the percentage of the growing period. In practical applications, the model is calibrated for production level and growing periods (rotation periods), as well as for the extent of thinnings and the distribution over time of the thinnings. The function is illustrated graphically in Figure 1 for an application of coniferous forests in Sweden by Nilsson (1978).

Cooper (1983) used a different formula for the development of biomass in a forest stand based on the Richards growth function:

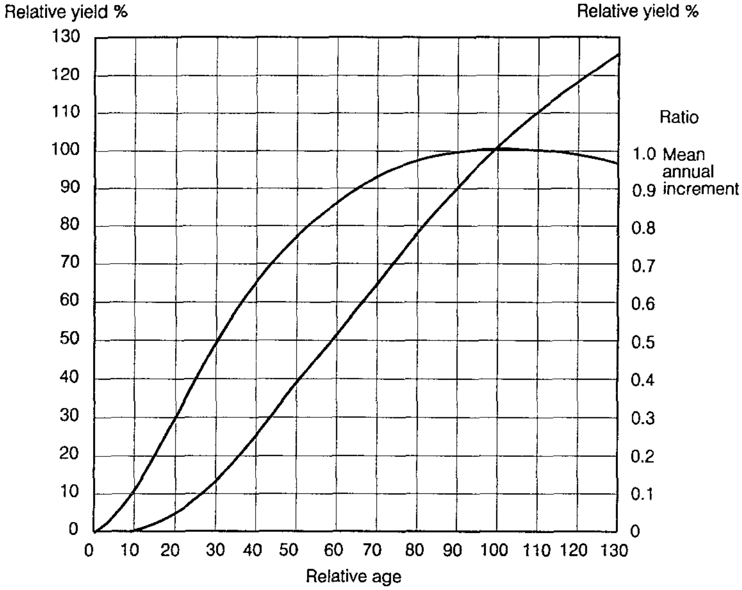
$$B_t = B_m(1 - be^{-rt})^{-1/n}, \qquad (2)$$

where B_t is the biomass volume at time t; B_m is the asymptotic maximum biomass; r is the intrinsic biological growth rate; b is a scaling parameter; and n is the shape parameter at the point of inflection of the growth curve. This approach provides dimensionless biomass growth curves.

Row and Phelps (1990), Row (1990), Thompson and Matthews (1989), and Lunnan *et al.* (1991) also used simplified versions of the above approaches for local calculations. In this study, we used Nilsson's approach to obtain the distributions of the MAI and corresponding carbon uptake rates over time for the world regions based on the information presented in Tables V and VI. We chose this approach because it is based on experimental data and has been tested in the major vegetation zones.

4. Above-Ground Carbon-Sequestration Potential

Specific calculations on carbon sequestration were made for each region listed in Table V; in this paper only aggregated results are presented. The plantation



Relative yield %	1.0	5.5	13.8	25.1	38.0	51.5	54.9	77.7	89.4	100.0	109.4	117.6	124.5
Mean annual increment ratio	0.127	0.315	0.495	0.849	0.771	0.862	0.962	0.967	0.991	1.000	0.998	0.989	0.972

Fig. 1. The relative yield over relative age, an application for coniferous forests in Sweden. After Nilsson (1978).

TABLE VII

Estimates of mean annual increments (MAIs) and above-ground carbon-fixation rates through the proposed global plantation program

Year	MAI (million m^3/yr)	Annual carbon fixation (million t/yr)
2015	1122	407
2025	1784	635
2035	2411	864
2045	2734	991
2055	3112	1140
2070	3000	1092
2085	2879	1058
2095	2918	1084

program is described in Table V and is assumed to start in 1995. The results for the MAIs and carbon fixation rates are presented in Table VII. The above-ground carbon fixation by the proposed plantation program reaches some 400 million tons in 2015, achieves a maximum of 1,140 million tons in 2055, and finishes with a fixation of 1,085 million tons in the year 2095. Thus, it takes a rather long time before substantial above-ground fixation is achieved.

5. Below-Ground Carbon-Sequestration Potential

Forest soils are different from grassland and cultivated soils. Forests produce more organic matter and add more litter to the soil than do other ecosystems although grasslands recycle organic matter faster (Bouwman, 1990). Consequently, the amount of organic matter added to the soil in prairies is two to four times greater than in forests due to its smaller resistance (Schimel *et al.*, 1985). Climatic conditions substantially influence the rate of decomposition, particularly in the temperate zones. Through the decomposition process a pool of dead organic carbon is built up.

At the global level, phytomass stores 560 to 827 Gt C (Ahamer, 1993; Alcamo, 1994, Kohlmaier *et al.*, 1992; Olson *et al.*, 1983; Waring and Schlesinger, 1985), and forest biomass contains 359 to 743 Gt C (Dixon *et al.*, 1994; Olson *et al.*, 1983; Waring and Schlesinger, 1985). By far, the most important pool of organic carbon is the soil, which holds some 1,200 to 2,000 Gt C (Kohlmaier *et al.*, 1992) of which forest soils store 787 to 927 Gt C (Dixon *et al.*, 1994; Post *et al.*, 1982). Sombroek *et al.* (1993) estimate the carbon pool in the upper 1 m of the world's soils to be 1,220 Gt C, which is about 1.5 times higher than that in the above-ground biomass.

The effects of increased atmospheric CO_2 concentrations on vegetation are not well documented; thus, the so-called fertilizer effect has not been considered in this study. Recent research has shown that increased atmospheric CO_2 concentrations may accelerate biomass turnover, resulting in higher litter fall rates, but not in increased plant growth (Körner, 1992; Pitelka, 1992). Mooney and Koch (1994) suggest that increased CO_2 concentrations may result in an increased below-ground biomass production.

5.1. ROOT BIOMASS

Above-ground biomass amounts to 75% to 90% of the total forest biomass; the remaining 10% to 25% is located in the soil (Körner, 1989). According to Olson *et al.* (1983), the ratio of above-ground biomass to below-ground biomass varies from 1.32 to 0.1. The share of roots in the total standing crop biomass is reported to be 17% in coniferous forests and 20% in hardwood forests, of which the share of fine roots accounts for 15% (Cooper, 1983). For tropical and subtropical forests,

TABLE VIII

Calculations of carbon stored by root biomass due to afforestation in various regions. Data compiled from South African Forest Owners' Association (1991, 1992); Prado (1992); Hagler (1992); Cooper (1983); Murphy and Lugo (1986); Olson *et al.* (1983); OECD (1991); Detwiler *et al.* (1985); and Houghton *et al.* (1983)

Region	Carbon stored in root biomass (%)	Carbon stored in roots (t/ha)	Land available for afforestation (million ha)	Total root carbon content (million t)
Boreal	20	11.0	43.1	474.1
Temperate	19	17.1	165.1	2823.2
Tropical	20	14.0	66.9	936.6
Agroforestry	10	3.0	69.7	209.1
Total	—	—	344.8	4443.0

Murphy and Lugo (1986) estimate that roots represent 8% to 50% and < 5% to 33% of plant biomass in dry forests and rainforests, respectively.

It has been estimated that in a North American hardwood forest ecosystem the root biomass accounts for 18% of the total living biomass (Bormann and Likens, 1979). Harmon *et al.* (1990) have shown that the amount of carbon stored in the root biomass remains unchanged at 12% to 13% after an old-growth forest is replaced with secondary forest. Birdsey (1990) estimated the carbon content in roots to be 17% of the total living biomass for an average forest in the U.S.A., representing 5% of the carbon content of the ecosystem. The share of below-ground carbon stored in live tropical forest vegetation is 19% in closed forests and 29% in open forests (Detwiler *et al.*, 1985).

The distribution of roots in the soil profile depends on the soil type, the vegetation, and the parent material. In subtropical dry-forest soils in Puerto Rico, for example, more than 90% of roots are located in the top 40 cm (Murphy and Lugo, 1986). In undisturbed tropical-forest soils in Surinam, root production was measured to be 4.16 t/ha/yr, implying a total root mass of 108 t/ha within the top 150 cm (Van Breemen and Feijtel, 1990). In a simulation by Van Breemen and Feijtel (1990), root production was 4.0 t/ha/yr. In tropical and subtropical dry forests root net primary production is estimated to contribute 22% to 24% to the total net primary production (Murphy and Lugo, 1986). The carbon dioxide evolution by respiration in the roots and soil under forest vegetation has been reported to amount to 5 to 8.5 t C/ha/yr (Bouwman, 1990).

The 'source-sink' theory (Vitousek and Sanford, 1986) suggests that trees growing in infertile soils transfer more energy to the roots for nutrition than do those growing in more fertile soils. This is assumed to encourage additional nutrition

TABLE IX

Litter fall, duration of litter in the litter layer, and litter as a percentage of above-ground biomass in various types of forest. Data from Vitousek and Sanford (1986); Bauer (1989); Bouwman (1990); Murphy and Lugo (1986); Bormann and Likens (1979); OECD (1991); Detwiler *et al.* (1985); and Houghton *et al.* (1983)

Forest type	Litter fall (t/ha)	Litter duration (years)	Litter as a % of above-ground C
Boreal coniferous	0.3	353	0.32
Boreal deciduous	2.6	26	1.61
Temperate coniferous	4.4	17	2.11
Temperate deciduous	5.4	4	3.54
Tropical (primary)	6.0	—	6.08
Tropical (logged)	4.4–8.0	—	5.23

uptake, thus enhancing plant growth. Observations of root–shoot ratios support this theory.

According to the data, the ratio of the below-ground biomass to the above-ground biomass (root–top) is expected to be fairly stable throughout the development of a forest stand. We estimated that the root biomass accounts for about 20% of the total living biomass. Only in dry, swamp, and mangrove forests is this figure significantly exceeded. Applying this estimate to the duration of the proposed afforestation program, more than 4,400 million tons of carbon will be sequestered by root biomass during the study period (Table VIII).

5.2. LITTER

Through the process of decomposition, leaf litter is transformed into humus, which is a stable component of soil (Bouwman, 1990). The speed of decomposition varies according to climate, latitude, vegetation, and substrate. The amount of litter fall varies with the temperature regime, resulting in an increase in detritus from tropical to boreal forests (Cooper, 1983). The amount of litter fall also varies according to soil fertility, from 10.5 to 11.2 t/ha on moderately fertile soils, to 7.4 to 8.8 t/ha on infertile soils in the tropics, to 6.4 t/ha in mountain forests (Vitousek and Sanford, 1986). Van Breemen and Feijtel (1990) estimated the litter fall from leaves, branches, and twigs in undisturbed tropical forests to be 11.2, 4.63, and 4.43 t/ha/yr, respectively. According to Murphy and Lugo (1986), litter production rates in the tropics and subtropics are 3 to 10 and 5 to 14 t/ha/yr in dry forests and rainforests, respectively. The litter fall in a North American hardwood forest is reported to add 5.7 t/ha/yr of biomass to the forest floor (Bormann and Likens,

TABLE X

Calculation of carbon build-up in litter due to afforestation in various regions. Data compiled from South African Forest Owners' Association (1991; 1992); Prado (1992); Hagler (1992); OECD (1991); Detwiler *et al.* (1985); and Houghton *et al.* (1983), and Table V

Region	Carbon in litter (tons/ha)	Land available for afforestation (million ha)	Total carbon in litter (million t C)
Boreal	0.5	43.1	21.6
Temperate	2.8	165.1	462.3
Tropical forests	3.7	66.9	247.5
Tropical agriculture	0.8	69.7	55.8
Total	—	344.8	787.2

1979). Other figures for coniferous and deciduous forests are 4.4 to 5.4 t/ha in temperate forests and 0.3 to 2.6 t/ha in boreal forests (Bauer, 1989; Table IX).

The rates of nutrient cycling and litter decomposition are higher in deciduous forests in temperate and tropical zones than in boreal forests due to their higher moisture and temperature. Only 30% of the total biomass in the tropics is found in the detrital fraction, compared with 75% in boreal forests (Cooper, 1983). Although in boreal forests litter can accumulate in thick layers that take a long time to decompose, the carbon content is less than 1% of above-ground carbon. In an evaluation of the role of litter in an afforestation program, we estimate that 787 million t C will accumulate in litter during stand development (see Table X).

Relatively little carbon is stored in the litter layer of forest ecosystems. According to Körner (1991), although increased atmospheric carbon concentrations speed up photosynthesis and increase root respiration, an accumulation of living biomass is unlikely. Intensified biomass turnover will result in increased litter fall, which may lead to an increase in the accumulated biomass in the litter layer. Because most soil organisms have evolved simultaneously with the ecosystem, they are unlikely to be able to adapt to new circumstances (Körner, 1989). Similar observations that soil organisms are unable to decompose increased litter fall due to forest decline have been reported from Central European forests. However, the effects of rapid climate change or other stresses may revalue the importance of the litter fraction considerably.

5.3. SOIL

Organic matter in soils derives from litter and root decomposition. Nonetheless, the use of biomass evaluations to estimate the soil carbon content remains dubious. Changes in forest soils are not well documented, but from the observed reductions

TABLE XI

Carbon content of above-ground biomass and soils in various types of forest. Data from OECD (1991); Detwiler *et al.* (1985); Houghton *et al.* (1983)

Forest type	Above-ground C (t/ha)	Soil C (t/ha)	Total C (t/h)	Ratio of soil C to total C (%)
Boreal primary	75	206	281	73
Boreal secondary	55	185	240	77
Temperate primary	123	134	257	52
Temperate secondary	90	120	210	57
Tropical primary	97	117	214	55
Tropical logged	70	88	158	56

TABLE XII

Carbon content in soils under various land uses (OECD, 1991; Detwiler, 1986)

Region	Land use	Carbon content in soil (t/ha)
Boreal	Primary forest	120–200
	Secondary forest	175–185
	Agricultural land	96–165
	Pasture	90
Temperate	Primary forest	120–134
	Secondary forest	114–120
	Agricultural land	107
	Pasture	80–151
Tropics	Primary rainforest	100–130
	Primary dry forest	50–75
	Secondary forest	80–100
	Agricultural land	70
	Pasture	50
	Agroforestry	80–100
	Shifting cultivation	80

in the carbon content of forest soils after clearance and cultivation, we can assume that the carbon content increases following reforestation. Increasing the net stock of the forest would lead to increased detritus, and thus to increased soil carbon (Sedjo, 1992).

Up to two-thirds of the total organic (living and dead plant biomass) carbon in forest ecosystems is stored in the soil. There are also wide variations in estimates of the soil organic matter content (24 to 599 t C/ha) of tropical and subtropical forest soils (Marland, 1988). The carbon content of above-ground biomass and of soils of different types of forests is presented in Table XI.

In general, the range in the estimates of soil carbon content is not as wide as that for living biomass. Table XII shows the carbon content in soils under various land uses.

5.4. SOIL CARBON LOSSES DUE TO CHANGES IN LAND USE

Reductions in soil carbon are primarily the result of changes in land-use pattern and are not restricted to forest clearance (Detwiler, 1986). Thus higher soil carbon storage rates can be maintained under selectively logged forests than can be maintained under undisturbed forests (Detwiler, 1986). The degree of disturbance in a forest ecosystem determines the amount of soil carbon that is lost (Johnson, 1992), as does the length of time that the land is left fallow. The disturbance of forest soils, particularly by cultivation, generally results in a loss of organic carbon (Houghton, 1991). It is difficult to obtain accurate estimates of changes in soil carbon due to deforestation, particularly because the changes occur only gradually.

There is a critical recovery phase after clear-cutting during which nutrients are transferred from the dead to the living biomass (Bormann and Likens, 1979). Several studies have shown that the greatest soil carbon losses occur during the first year, affecting the soil to a depth of up to 40 cm (Detwiler, 1986). The highest rates of land-use change, and thus of soil carbon loss, are assumed to occur in tropical and subtropical regions. Various estimates have been made of the net amount of carbon released from soils due to land-use changes: 0.1 to 0.3 Gt C/yr (Detwiler *et al.*, 1985; Detwiler, 1986); 0.2 to 0.9 Gt C/yr (Bouwman, 1990); 0.2 to 0.5 Gt C/yr (Bouwman, 1990); and 0.11 to 0.25 Gt C/yr (Detwiler and Hall, 1988). Several authors have reported data on carbon losses after the clearance of primary forest (Bouwman, 1990; Detwiler *et al.*, 1985; Detwiler, 1986; Alexander, 1985; Trexler, 1991a; Lugo *et al.*, 1986; Johnson, 1992; OECD, 1991; Körner, 1989; Melillo *et al.*, 1988; Houghton, 1991; Harmon *et al.*, 1990). From these results, it can be concluded that soil carbon losses following forest clearance in boreal, temperate, and tropical regions are 15% to 50%, 20% to 60%, and 21% to 56%, respectively. Similar variations can be assumed for forest land converted to pasture: 25% to 35% for temperate and 20% to 46% for tropical zones.

The carbon-sequestration potential of an afforestation program is closely linked to the amount of carbon that is sequestered by the below-ground biomass and the soil. It appears that the carbon content of clear-cut forest soils returns to levels in undisturbed soils if there is an adequate fallow period (Detwiler, 1986). Several authors have reported that the reforestation of abandoned land in some cases leads to a quick recovery of soil carbon content; in other cases recovery occurs only after

TABLE XIII

Aggregated estimates of carbon sequestration by soils as a result of afforestation in various regions. Data compiled from South Africa Forest Owners' Association (1991, 1992); Prado (1992); and Table XI

Land classification according to region	Available land (million ha)	Current soil C content (t/ha)	Increase in soil C (%)
Canada			
West	0.84	100	5
NSR[1] land, B.C.	18.90	80	5
Converted farmland	4.41	70	25
Unimproved farmland	4.16	80	15
U.S.A.			
Plantations	18.00	90	15
Agroforestry			
U.S. South	1.50	80	15
U.S. Temperate	1.50	80	10
Europe			
Nordic	0.35	90	10
EC-9	3.76	75	20
Central	0.48	80	15
Southern	2.18	80	20
Eastern	1.33	80	15
Former Soviet Union	66.50	90	18
China	62.50	80	18
Temperate Asia	12.50	80	18
Temperate South Africa	1.87	80	15
Temperate South America	4.56	80	15
Australia			
Plantations	0.79	70	20
Agroforestry	3.50	90	15
New Zealand	5.00	80	20
Latin America			
Plantations	24.50	80	20
Agroforestry	16.30	80	18
Africa			
Plantations	4.60	70	15
Agroforestry	27.00	75	15
Asia			
Plantations	37.80	80	20
Agroforestry	19.90	80	18
Total	344.73	—	—

[1] Not sufficiently restocked.

TABLE XIV

Estimates of annual carbon-fixation rates by above- and below-ground biomass achieved with the proposed global plantation program

Year	Carbon in above-ground biomass (million t/yr)	Carbon in below-ground biomass (million t/yr)	Total carbon in biomass (million t/yr)
2015	407	122	529
2025	635	191	826
2035	864	259	1123
2045	991	297	1288
2055	1140	342	1482
2070	1092	328	1420
2085	1058	317	1375
2095	1084	325	1409

several hundred years (Bouwman, 1990; WRI, 1990; Johnson, 1992; Postel, 1988; Waldstein, 1992).

An approach to estimating soil carbon buildup due to afforestation of previously unforested land has been used. The land available for afforestation is expected to serve as non-stocked productive forest, agricultural land, and grassland, as well as for shifting cultivation. Furthermore, conservative estimates of the carbon-sequestration rate have been used, so the potential for carbon fixation may be higher under appropriate conditions. Several carbon buildup rates were applied to various land use methods, as well as to respective regional circumstances, and they are the mean values over the suggested rotation periods (Table XIII).

Postel (1988) calculated the amount of soil carbon sequestered under fairly fast-growing tropical hardwood species to be 0.5 t C/ha/yr. By applying this amount to the 67 million ha of tropical land available for afforestation identified in this study, 700 million t C is sequestered in the soil. This differs from our estimate of 1,045 million t C.

6. Total Carbon Uptake by Plantations and Conclusions

We estimate that a total of 345 million ha of land will actually be available for new plantations and agroforestry (275 million ha and 70 million ha, respectively). This is substantially less than existing estimates of land that would be suitable for these uses (1.5 and 1 billion ha, respectively; see Table V).

The plantation growth model developed by Nilsson (1982) has been employed to estimate the carbon-sequestration potential of the proposed global afforestation program presented in Table V. The plantation program is implemented during the period of 1995 to 2050 (implementation time varies for different regions), and the carbon-sequestration effects are calculated for this time period. The calculations consider carbon uptake by above-and below-ground biomass and have been carried through for the individual regions listed in Table V; however, the results are presented only at the global level.

Estimates of the annual carbon fixation rates for above- and below-ground biomass are presented in Table XIV. For estimates of the below-ground (roots, litter, and soil) carbon fixation, a 23% proportion was established. The model simplifies the distribution of below-ground carbon over time, but generates plausible results.

The impact of the proposed plantation program on the carbon balance would be significant only after 40 to 50 years, and the maximum carbon fixation rate of 1.5 Gt of carbon per annum would be reached about 60 years after the initiation of the plantation program. Over the 100-year period studied, the proposed global plantation program would sequester a total of some 104 Gt of carbon. The maximum fixation per year is less than half of the 3.8 Gt of carbon that is currently being added to the atmosphere each year (Winjum *et al.*, 1992), and is one-fourth of the annual CO_2 released by fossil-fuel combustion. Large-scale plantations are therefore unlikely to quickly stabilize the carbon content of the atmosphere. However, approximately 30% of anthropogenic carbon emissions could be sequestered through a global afforestation program. Forest plantations would be only one of several means (such as new energy sources, energy efficiency, etc.) required to solve the emission problem.

References

Ahamer, G.: 1993 'The Influence of an Enhanced Use of Biomass for Energy on the CO_2- Concentration in the Atmosphere', Executive summary of a doctoral thesis, Graz University of Technology, Austria.

Alcamo, J. (ed.): 1994 *IMAGE 2.0: Integrated Modeling of Global Climate Change*, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Alexander, M.: 1985 *Introduction to Soil Microbiology*, J. Wiley & Sons, New York, NY, U.S.A.

Allan, T. and Lanly, J. P.: 1990 'Overview of Status and Trends of World's Forests', in Howlett, D. and Sargent, C. (eds.), *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–30 April 1991, Bangkok, Thailand, International Institute for Environment and Development, London, U.K.

Andrasko, K.: 1990 *Climate Change and Global Forests: Current Knowledge of Potential Effects, Adaption and Mitigation Options*. Forestry Department FO:MISC/90/7. Food and Agriculture Organization of the United Nations, Rome, Italy.

Andrasko, K., Heaton, K. and Winnett, S.: 1991 'Evaluating the Costs and Efficiency of Options to Manage Global Forests: A Cost Curve Approach', in Howlett, D. and Sargent, C. (eds.), *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–30 April, at Bangkok, Thailand, International Institute for Environment and Development, London, U.K.

Armson, K. A.: 1977 *Forest Soils*. University of Toronto Press, Toronto, Canada.

Bauer, H.: 1989 *Nährstoffvorräte von Fichtenbeständen auf einer Standortseinheit im Kobenauserwald untersucht über die Altersklassen*, Diplomarbeit am Institut für Forstökologie, Universität für Bodenkultur, Wien.

Birdsey, R. A.: 1990 *Inventory of Carbon Storage and Accumulation in US Forest Ecosystems*, Paper presented at XIX IUFRO World Congress, August 1990, at Montreal, Canada.

Bormann, F. H. and Likens G. E.: 1979 *Pattern and Processes in a Forested Ecosystem*, Springer New York, NY, U.S.A.

Botkin, D. B. and Simpson, L. G.: 1990 'Biomass of the North American Boreal Forests', *Biogeochemistry* **9**(2), 161–174.

Bouwman A. F. (ed.: 1990 *Soils and the Greenhouse Effect*, J. Wiley & Sons, New York, NY, U.S.A.

Brown, S., Lugo, A. E. and Chapmen, J.: 1986 'Biomass of Tropical Tree Plantations and Its Implications for the Global Carbon Budget', *Canad. J. Forest Res.* **16**(2), 390–394.

Brown, S., Gillespie, A. J. R. and Lugo, A. E.: 1989 'Biomass Estimation Methods for Tropical Forests with Applications to Forest Inventory Data', *Forest Sci.* **35**(4), 881–902.

Brown S., Hall, C. A. S., Knabe, W., Raich, J., Treckler, M. C. and Woomer, P.: 1993, 'Tropical Forests: Their Past, Present, and Potential Future Role in the Terrestrial Carbon Budget', *Water, Air Soil Poll.* **70**(1–4), 71–94.

Centeno, J. C.: 1992 *The Need to Reforest the Tropics*, Merida, Venezuela.

Congressional Research Service, Library of Congress: 1989 *Agriculture, Forestry and Global Climate Change: A Reader*, U.S.A Government Printing Office, Washington, DC, U.S.A.

Cooper, C. F.: 1983 'Carbon Storage in Managed Forests', *Canad. J. Forest Res.* **13**(1), 155–166.

Detwiler, R. P.: 1986 'Land Use Change and the Global Carbon Cycle: The Role of tropical soils', *Biochemistry* **2**(1), 67–93.

Detwiler, R. P. and Hall, A. S.: 1988 'Tropical Forests and the Global Carbon Cycle', *Science* **239**(4835), 42–47.

Detwiler, R. P., Hall, C. A. S. and Bogdonoff, P.: 1985 'Land Use Change and Carbon Exchange in the Tropics II: Estimates for the Entire Region', *Environm. Managem.* **9**(4), 335–344.

Dixon, R. K., Schroeder P. E. and Winjum J. K. (eds.): 1991a *Assessment of Promising Forest Management Practices and Technologies for Enhancing the Conservation and Sequestration of Atmospheric Carbon and their Costs at the Site Level,* US Environmental Protection Agency, Washington, DC, U.S.A.

Dixon, R. K., Winjum, J. K. and Krankina, O. N.: 1991b 'Afforestation and Forest Management Options and their Costs at the Site Level' in Howlett, D. and Sargent, C. (eds.), *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–30 April, at Bangkok, Thailand, International Institute for Environment and Development, London, U.K.

Dixon, R. K., Brown S., Houghton, R. A., Solomon, A. M., Trexler, M. C. and Wisniewski, J.: 1994 'Carbon Pools and Flux of Global Forest Ecosystems', *Science* **263**(5144), 185–190.

Dudek, D. J. and Le Blanc, A.: 1990 'Offsetting New CO_2 Emissions: A Rational First Greenhouse Policy Step', *Contemp. Policy Iss.* **8**(3), 29–42.

Eckersley, R.: 1989 *Regreening Australia: The Environmental, Economic and Social Benefits of Reforestation*, Occasional Paper 3, CSIRO, Melbourne, Australia.

FAO: 1991a *FAO Yearbook 1989: Forest Products*, U.N. Food and Agriculture Organization, Rome, Italy.

FAO: 1991b 'Climate Change and Global Forests: Current Knowledge of Potential Effects, Adaptation and Mitigation', in Howlett, D. and Sargent, C. (eds.), *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–30 April, at Bangkok, Thailand, International Institute for Environment and Development, London, U.K.

Farnum, P., Timmis, R., and Kulp, J.: 1983 'Biotechnology of Forest Yield', *Science* **219**(4585), 694–702.

Forestry Canada: 1990 *Selected Forestry Statistics 1990*, Information Report E-X-44. Economics and Statistics Directorate, Forestry Canada, Ottawa, Canada.

Frankena, F.: 1987 'Rethinking the Scale of Biomass Energy Conversion Facilities: The Case of Wood-Electric Power', *Biomass* **14**(3), 149–71.

Grainger, A.: 1988 'Estimating Areas of Degraded Tropical Lands Requiring Replenishment of Forest Cover', *Internat. Tree Crops J.* **5**(1/2), 31–61.

Grainger, A.: 1991 'Constraints on Increasing Tropical Forest Area to Combat Global Climate Change', in Howlett, D. and Sargent, C. (eds.), *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–30 April, at Bangkok, Thailand, International Institute for Environment and Development, London, U.K.

Hagler, R. W.: 1992 Personal Communication on the Industrial Forest Area of Argentina and Chile, 16 September.

Hall, D. O., Mynick, H. E., and Williams, R. H.: 1990 *Carbon Sequestration versus Fossil Fuel Subscription: Alternative Roles for Biomass in Coping with Greenhouse Warming*, PUICEES Report No. 255, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ, U.S.A.

Hall, D. O., Myknick, H. E. and Williams, R. H.: 1991 'Cooling the Greenhouse with Bioenergy', *Nature* **353**(6339), 11–12.

Harmon, M. E., Ferrell, W. K. and Franklin, J. F.: 1990 'Effects on Carbon Storage of Conversion of Old-Growth Forests to Young Forests', *Science* **247**(4943), 699–702.

Hasenkamp, K. P.: 1992 'Global Reforestation to Solve the Problem of CO_2: Or Mankind Will Be Burning the Wrong Tree until It Finds the Right One', *Yearbook of Renewable Energies*, vol. I. Ponte Press, Bochum, Germany.

Holt, J. A. and Spain, A. V.: 1986 'Some Biological and Chemical Changes in a North Queensland Soil Following Replacement of Rainforest with *Araucaria Cunninghammii*', *J. Appl. Ecol.* **23**(1), 227–237.

Houghton, R. A.: 1991 'Tropical Deforestation and Atmospheric Carbon Dioxide', *Clim. Change* **19**(1/2), 99–118.

Houghton, R. A., Hobbie, J. E., Melillo, J. M., Moore, B., Peterson, B. J., Shaver, G. R. and Woodwell, G. M.: 1983 'Changes in the Carbon Content of Terrestrial Biota and Soils Between 1860 and 1980: A Net Release of CO_2 to the Atmosphere', *Ecol. Monogr.* **53**(3), 235–62.

Houghton, R. A., Unruh, J. and Lefebvre, P. A.: 1991 'Current Land Use in the Tropics and Its Potential for Sequestering Carbon', in Howlett, D. and Sargent, C. (eds.), *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management*, 24–30 April, at Bangkok, Thailand, International Institute for Environment and Development, London, U.K.

Johnson, D. W.: 1992 *Effects of Forest Management on Soil Carbon Storage*, National Council of the Paper Industry for Air and Stream Improvement, Technical Bulletin No. 628, New York, NY, U.S.A.

Jonson, T. and Modin A.: 1932 'In Riksskogstaxeringsnämnden'. Uppskattning av Sveriges Skogstillgångar verkställd åren 1923–1929, Statens Offentliga Utredningar. Stockholm, Sweden.

Kohlmaier, G. H., Würth, G., Häger, C. and, Kindermann, J.: '1992 Management of the World's Forests as a Global Carbon Dioxide Sink', Report on a presentation, Institut für Physikalische und Theoretische Chemie, Johann Wolfgang Goethe-Universität, Frankfurt am Main, Germany.

Kolchugina, T. P. and Vinson T. S.: 1993a 'Equilibrium Analysis of Carbon Pools and Fluxes of Forest Biomes in the Former Soviet Union', *Canad. J. Forest Res.*, **23**(1), 81–88.

Kolchugina, T. P. and Vinson T. S.: 1993b 'Carbon Sources and Sinks in Forest Biomes of the Former Soviet Union', *Global Biochemical Cycles* **7**(2), 291–309.

Kolchugina, T. P. and Vinson T. S.: 1993c 'Comparison of Two Methods to Assess the Carbon Budget of Forest Biomes in the Former Soviet Union', *Water, Air Soil Poll.* **70**(1–4), 207–221.

Körner, C.: 1989 *Bedeutung der Wälder im Naturhaushalt einer vom Menschen veränderten Welt*, Sonderdruck aus Veröffentlichungen der Kommission für Humanökologie, Österreichische Akademie der Wissenschaften, Wien.

Körner, C.: 1991 *Wirkung von Kohlendioxid auf die Vegetation, Bericht über das Jahr 1989/90*, Universität Basel, Switzerland.

Körner, C.: 1992 'Responses to Elevated Carbon Dioxide in Artificial Tropical Ecosystems', *Science* **257**(5077), 1672–1675.

Lanly, J.P., Singh K. and Janz K.: 1991 'FAO's 1990 Reassessment of Tropical Forest Cover', *Nature Resourc.* **27**(2), 21–26.

Lavender, D.P.: 1991 'Reforestation in British Columbia', In Winjum, J.K. and Schroeder, P.E. (eds.) *Proceedings of the International Workshop on Large-Scale Reforestation*, Washington Institute, Inc., Washington, DC, U.S.A.

Lugo, A. E., Sanchez, M. J. and Brown, S.: 1986 'Land Use and Organic Carbon of Some Subtropical Soils', *Plant Soil* **96**(2), 185–196.

Lunnan, A., Navrud, S., Rörstad, P. K., Simensen, K. and Solberg, B.: 1991 *Forestry and Forest Production in Norway for CO_2 Sequestration*, Norwegian Institute for Forestry Research, Skogforsk Report 6/1991, Norway (in Norwegian).

Maclaren, P.: 1992 *Methodology for the Calculation of Carbon Sequestration by New Zealand's Plantation Forests*, Forest Research Institute, Rotorua, New Zealand.

Marland, G.: 1988 *The Prospects for Solving the CO_2 Problem through Global Reforestation*, U.S. Department of Energy, Washington, DC, U.S.A.

Mather, A. S.: 1990 *Global Forest Resources*, Belhaven, London, U.K.

Melillo, J. M., Fruci, J. R. and Houghton, R. A.: 1988 'Land-use Change in the Soviet Union Between 1850 and 1980: Causes of a Net Release of CO_2 to the Atmosphere', *Tellus* **40**(B), 116–28.

Mooney, H. A. and Koch, G. W.: 1994 'The Impact of Rising CO_2 Concentrations on the Terrestrial Biosphere', *AMBIO* **23**(1), 74–76.

Moulton, R. J. and Richards, K. R.: 1990 *Costs of Sequestering Carbon through Tree Planting and Forest Management in the United States*, U.S. Department of Agriculture, Forest Service, Washington, DC, U.S.A.

Murphy, P. G. and Lugo, A. E.: 1986 'Ecology of Tropical Dry Forests', *Annual Rev. Ecol. Systemat.*, **17**, 67–88.

Nilsson, N.-E.: 1978 In 'Statens Offentliga Utredningar: SOU 78:7. Produktionsmall. Skog för Framtid. Appendix 4', Statens Officiella Utredningar: SOU 78:7, Stockholm, Sweden.

Nilsson, N.-E.: 1982 'An Alley Model for Forest Resources Planning', in Ranneby, B. (ed.), *Statistics in Theory and Practice: Essays in Honour of Bertil Matérn,*Swedish University of Agricultural Sciences, Section of Forest Biometry, Umeå, Sweden.

Nilsson, N.-E.: 1992 *The International Forestry Cooperation: Overview, Retrospects and Prospects*, Royal Swedish Academy of Agriculture and Forestry. February 1992 (in Swedish).

Nilsson, N.-E.: 1994 Personal communication, April 12, 1994.

Nilsson, S.: 1988 'Factors Affecting Future Investments in Pulp Capacity', Working Paper WP-88–75, International Institute for Applied Systems Analysis, Laxenburg, Austria.

Nilsson, S., Sallnäs, O., and Duinker, P.: 1992a *Future Forest Resources of Western and Eastern Europe*, Parthenon, Carnforth, U.K.

Nilsson, S., Sallnäs, O., Hugosson, M., and Shvidenko, A.: 1992b *The Future Development of the Forest Resources of the Former USSR,* Parthenon, Carnforth, U.K.

The Noordwijk Declaration on Climate Change: Atmospheric Pollution and Climate Change: 1989, Ministerial Conference, 6–7 November, Noordwijk, The Netherlands.

OECD: 1991 *Estimation of Greenhouse Gas Emissions and Sinks*, Final Report of the Expert Meeting, February, at Paris, Organization for Economic Co-operation and Development.

Olson, J. S., Watts, J. A. and Allison, L. S.: 1983 *Carbon in Live Vegetation of Major World Ecosystems,* Oak Ridge National Laboratory, Oak Ridge, TN, U.S.A.

Pandey, D.: 1994 *Assessment of Tropical Plantations Resources*, U.N. Food and Agriculture Organization, Rome, Italy (in press).

Pitelka, L.: 1992 'Forest Response to Carbon Dioxide', *EPRI J.* **17**(1), 38–41.

Post, W. M., Emanuel, W. R., Zinke, P. J. and Stangenberger, A. G.: 1982 'Soil Pools and World Life Zones', *Nature* **298**(5870), 156–159.

Postel, S.: 1988 'A Green Fix to the Global Warm-Up', *World Watch Institute Newsletter*, September/October, Washington, DC, U.S.A.

Postel, S. and Heise, L.: 1988 *Reforesting the Earth*, World Watch Paper 83, World Watch Institute, Washington, DC, U.S.A.

Pöyry, J.: 1992 *J. P. Data Bank 1992*, Jaakkoo Pöyry, Vantaa, Finland.

Prado, J. A.: 1992 Personal communication on Chilean forests, August 1992.

Rodin, L. E. and Bazilevitch, N. I.: 1967 *Production and Mineral Cycling in Terrestrial Vegetation,* Oliver and Boyd, London, U.K.

Row, C.: 1990 *Tracing the Flow of Carbon through the US Forest Product Sector,* Paper presented at the International Union of Forest Research Organizations: IUFRO 19th World Congress, August, at Montreal, Canada.

Row, C. and Phelps, R. B.: 1990 *Determining the Flows and Deposition of Carbon in Timber Harvests and in Wood-in-Use,* American Forestry Association, Washington, DC, U.S.A.

Russell, J.: 1990 'Plantation Forestry and the Australian Landscape', in Dargavel, J. and Semple, N. (eds.) *Prospects for Australian Forest Plantations,*Centre for Resource and Environmental Studies, Australian National University, Canberra, Australia.

Sampson R.N.: 1992 'Forestry Opportunities in the United States to Mitigate the Effects of Global Warming', *Water, Air Poll.* **64**(1/2), 157–180.

Schimel, D. S., Coleman, D. C., and Horton, K. A.: 1985 'Soil Organic Matter Dynamics in Paired Rangeland and Cropland Toposequences in North Dakota', *Geoderma* **36**(3/4), 201–214.

Sedjo, R. A.: 1983 *The Comparative Economics of Plantation Forestry: A Global Assessment.* Resources for the Future/Johns Hopkins University Press, Baltimore, MD, U.S.A.

Sedjo, R. A.: 1992 'Temperate Forest Ecosystems in the Global Carbon Cycle', *Ambio* **21**(4), 274–277.

Sedjo, R. A. and Lyon, K. S.: 1990 *The Long-Term Adequacy of World Timber Supply,* Resources for the Future, Washington, DC, U.S.A.

Sombroek, W. G., Nachtergaele F. O. and Hebel A.: 1993 'Amounts, Dynamics and Sequestering of Carbon in Tropical and Subtropical Soils', *AMBIO* **22**(7), 417–426.

South African Forest Owners' Association: 1991 *Forestry and Forest Products Industry Facts 1979/80 to 1989/90,* Rivonia, South Africa.

South African Forest Owners' Association: 1992 *Mean Annual Increment Survey: Results and Analysis,* Rivonia, South Africa.

Spears, J.: 1983 'Replenishing the World's Forests: Tropical Reforestation: An Achievable Goal?' *Commonwealth Forestry Review* **62**(3), 201–217.

Thompson, D. A. and Matthews, R. W.: 1989 *The Storage of Carbon in Trees and Timber,* Research Report 160. Forest Research Station, Alice Holt, Surrey, U.K.

Trexler, M. C.: 1991a 'Estimating Tropical Biomass Futures: A Tentative Scenario', in Howlett, D. and Sargent, C. (eds.), *Proceedings of the Technical Workshop to Explore Options for Global Forestry Management,* 24–30 April, at Bangkok, Thailand, International Institute for Environment and Development, London, U.K.

Trexler, M. C.: 1991b *Minding the Carbon Store: Weighing US Forestry Strategies to Slow Global Warming,* World Resources Institute, Washington, DC, U.S.A.

Troensegaard, J.: 1989 *Summary of Cost Estimates of Afforestation,* Food and Agriculture Organization of the United Nations, Rome, Italy.

Turnbull, C. R. A., Traill, J. R. and Beadle, C. L.: 1989 *Productivity and Costs of Establishment of Eucalypt Plantations on Native Forest Sites in Southern Tasmania,* IUFRO Symposium, September, Rotorua, New Zealand.

Van Breemen, N. and Feijtel T. C. J.: 1990 'Soil Processes and Properties Involved in the Production of Greenhouse Gases, with Special Relevance to Soil Taxonomic Systems', in Bouwman, A.F. (ed.), *Soils and the Greenhouse Effect,* J. Wiley & Sons, New York, NY, U.S.A.

Van Kooten, G. C.: 1991 *Economic Issues Relating to Climate Change. Effects on Canada's Forests,* Working Paper 151, Forestry and Economic Policy Analysis: FEPA Research Unit, University of British Columbia, Vancouver, BC, Canada.

Vitousek P. M. and Sanford R. L., Jr.: 1986 'Nutrient Cycling in Moist Tropical Forest', in *Annual Rev. Ecol. Systemat.* **17**, 137–167.

Volz, H.-A., Kriebitzch, W. U. and Schneider, T. W.: 1991 'Assessment of Potential, Feasibility and Costs of Forestry Options in the Temperate and Boreal Zones', in Howlett, D. and Sargent, C. (eds.), *Proceedings of the Technical Workshop to Explore Forestry Options for Global Forestry Management,* 24–30 April, at Bangkok, Thailand, International Institute for Environment and Development, London, U.K.

Waldstein, C.: 1992 'Sanierung der CO_2-Bilanz durch Humusproduktion, *Umweltschutz* **4**, 14.

Waring, R. H. and Schlesinger, W. H.: 1985 *Forest Ecosystems. Concepts and Management,* Academic Press, Orlando, FL, U.S.A.

Whyte, I. N.: 1990 'APPM'S Tree-Farming Program: Past, Present and Future', in Dargavel, J. and Semple, N. (eds.) *Prospects for Australian Forest Plantations*, Centre for Resource and Environmental Studies. Australian National University, Canberra, Australia.

Winjum, J. K., Dixon, R. K. and Schroeder, P. E.: 1992 'Estimating the Global Potential of Forest and Agroforest Management Practices to Sequester Carbon', *Water, Air Soil Poll.* **64**(1/2), 213–227.

WRI: 1990 *World Resources 1990–91: A Guide to the Global Environment,* World Resources Institute, Oxford University Press, New York, NY, U.S.A.

Zobel, B. J., Van Wyk, G., and Stahl, P.: 1987 *Growing Exotic Forests*, J. Wiley & Sons, New York, NY, U.S.A.

Zuidema, G., von den Born, G. J., Alcamo, J., and Kreileman, G. J. J.: 1993 'Simulating Changes in Global Cover as Affected by Economic and Climatic Factors' *Water, Air Soil Poll.* **76**(1/2), 163–198.