

Land Use, Land-Use Change, and Forestry

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A Special Report of the IPCC

Published for the Intergovernmental Panel on Climate Change



CAMBRIDGE
UNIVERSITY PRESS

Global Perspective

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EXECUTIVE SUMMARY

The Global Carbon Cycle

- During the period 1850–1998, approximately 405 ± 60 Gt C has been emitted as carbon dioxide (CO_2) into the atmosphere as a result of fossil fuel burning and cement production (67 percent), and land use and land-use change (33 percent), predominantly from forested areas. As a result, the atmospheric CO_2 concentration has risen from 285 ± 5 ppmv to 366 ppmv (i.e., about a 28 percent increase). This increase in CO_2 concentration accounts for about 40 percent of these anthropogenic emissions, the remainder having been absorbed by the oceans and terrestrial ecosystems.
- CO_2 that is dissolved into the ocean will be transferred progressively to the deep ocean, and the carbon content of this reservoir is increased. The fate of CO_2 that is fixed on land depends on which ecosystem and which carbon pool is the repository (e.g., living biomass or soils). Carbon fixed into a pool with a turnover time of one year or less (leaves, fine roots) is returned to the atmosphere or transferred into pools with a longer turnover time of decades to centuries (stems, trunks, soil organic matter).
- The net global carbon flux between terrestrial ecosystems and the atmosphere is the result of a small imbalance between uptake by photosynthesis and release by various return processes. Plants, soil microbes, biochemical processes, animals, and disturbances contribute to the latter. Variations of climate and human activities have a major impact through land use and land-use changes, as well as indirectly through carbon dioxide fertilization, nutrient deposition, and air pollution.
- This global net carbon exchange has resulted in an uptake of CO_2 by the terrestrial biosphere amounting to 0.2 ± 1.0 Gt C yr^{-1} (90-percent confidence interval) over the 1980s (1980–89), and 0.7 ± 1.0 Gt C yr^{-1} during the most recent decade (1989–98) (see Table 1-2). It is unclear if the increase in the 1990s is a result of natural variability or, to some extent, also a trend induced by human activities.
- The direct effects of land use and land-use change are estimated to have led to a net emission of 1.7 ± 0.8 Gt C yr^{-1} during the 1980s, and 1.6 Gt C yr^{-1} during the 1990s. The difference between the net global terrestrial uptake and human-induced emissions as a result of land use and land-use change leaves a residual terrestrial uptake of 1.9 ± 1.3 Gt C yr^{-1} for the 1980s and 2.3 ± 1.3 Gt C yr^{-1} for the 1990s.
- The global net carbon flux varies from one year to another. These variations are on the order ± 1 Gt C yr^{-1} and are correlated with variations in climate (e.g., El Niño/La Niña events) and major volcanic eruptions.

Present Knowledge about Global Terrestrial Ecosystems

- Gross Primary Productivity (GPP) is the uptake of carbon from the atmosphere by plants (global total approximately 120 Gt C yr^{-1}). Carbon losses as a result of plant respiration reduce this uptake to the Net Primary Productivity (NPP; global total approximately 60 Gt C yr^{-1}). Further losses occur because of decomposition of dead organic matter, resulting in Net Ecosystem Productivity (NEP; global total approximately 10 Gt C yr^{-1}). Additional losses are caused by disturbances, such as fire, wind-throw, drought, pests, and human activities. The resulting net imbalance of the terrestrial ecosystem can be interpreted as the Net Biome Productivity (NBP; presently approximately 0.7 ± 1.0 Gt C yr^{-1} , as a decadal average; see Figure 1-2).
- Forests contain a large part of the carbon stored on land, in the form of biomass (trunks, branches, foliage, roots etc.) and in the form of soil organic carbon (Table 1-1). On a time scale of years, most forests accumulate carbon through the growth of trees and an increase in soil carbon, until the next disturbance occurs. The net carbon uptake (NEP) may locally reach 7 t C $\text{ha}^{-1} \text{yr}^{-1}$, but losses may also be observed when soil carbon is decreasing or trees are overmature and mortality is occurring.
- In cropland ecosystems, carbon stocks are primarily in the form of below-ground plant organic matter and soil. Most of these ecosystems have large annual carbon uptake rates, but much of the gain is exported in the form of agricultural products and their associated waste materials; this gain is rapidly released to the atmosphere. Although carbon is recaptured during the succeeding cropping season, many agricultural soils are currently net sources of carbon. Shifting to low or no till cultivation is, however, increasingly being used to mitigate such trends.
- By far most of the carbon stocks in grassland and savannas, including rangelands and pasture, are found in the soils. These stocks are stable over long time spans, but losses can occur if grazing pressure exceeds carrying capacity or if the frequency of fires increases.
- Wetland stocks of carbon are found almost entirely in the soil as dead organic matter, which can be released by human activity, such as drainage. Afforestation may effectively compensate for such development. Soil carbon in subarctic wetlands may also be released as a result of reduction of permafrost resulting from climate warming.
- Globally, carbon stocks in the soil exceed carbon stocks in vegetation by a factor of about five (Table 1-1). This ratio ranges from about 1:1 in tropical forests to 5:1 in boreal

forests and much larger factors in grasslands and wetlands. Changes in soil carbon stocks are at least as important for carbon budgets as changes in vegetation carbon stocks.

Assessing Carbon Stocks and Their Change Over Time

- A sustainably managed forest comprising all stages in the stand life cycle operates as a functional system that maintains an overall carbon balance, retaining a part in the growing trees, transferring another part into the soils, and exporting carbon as forest products. Recently disturbed and regenerating areas lose carbon; young stands gain carbon rapidly, mature stands less so; and overmature stands may lose carbon. The Kyoto Protocol (Articles 3.3 and 3.4) focuses on only part of the stand life cycle for a few decades. During the early years of the life cycle, when trees are small, the area is likely to be a source of carbon; it becomes a sink when carbon assimilation exceeds soil respiration.
- Change in the carbon stocks of stands of forest trees over a 5-year period (NPP) can be assessed with good precision through standard inventory methods. Carbon stocks in soils have been determined by standard sampling techniques, but large numbers of samples are required to achieve adequate precision (see Figure 1-4).
- Changes in total carbon stocks—vegetation and soils—in forest stands have been assessed by direct determination of net sources and sinks (NEP) over periods of 1 or more years. This approach has been applied worldwide, predominantly to mature forest stands of a range of species and history. The annual NEP varies between approximately -1 and $2.5 \text{ t C ha}^{-1} \text{ yr}^{-1}$ for boreal forests, 2.5 to $7 \text{ t C ha}^{-1} \text{ yr}^{-1}$ for temperate forests, and 1 to $6 \text{ t C ha}^{-1} \text{ yr}^{-1}$ for humid tropical forests.
- At present, direct measurements of NEP alone are inadequate to provide estimates of NBP because of lack of data covering all stages in the life cycle from regeneration to harvest, as well as lack of data on the impacts of disturbances such as fire, wind-throw, drought, pollution, pests, and diseases. Thus, forest inventories and ecosystem process models, combined with assessments of harvest and disturbance-related carbon flows, must be used. These methodologies require further development and comparison with measurements of NEP.
- Measurements of NEP on young stands of trees and forest inventory yield tables indicate that in new forests planted since 1990 in relation to Article 3.3 of the Kyoto Protocol, sequestration of carbon is likely to continue for 20 to 200 years or more after establishment, depending on species and site conditions.
- Sequestration of carbon is stimulated by fertilization with atmospheric CO_2 and deposition of nutrients, particularly nitrogen and phosphorus. The quantitative contribution of these resources to carbon sequestration is difficult to determine and varies from region to region depending on the magnitude of nutrient inputs and inputs of associated, negatively acting, pollutants (e.g., acid precipitation or ozone).

- Ecosystem models indicate that the additional terrestrial sink arising from global climate change is likely to be maintained in the short term (over several decades) if management is appropriate and sustainable, but may gradually diminish in the medium term. One reason for this result is that the capacity of some ecosystems to sequester carbon may be approached; another is that photosynthesis will no longer increase as CO_2 concentration continues to rise, whereas respiration is expected to continue to increase with the rise in temperature. A third reason is that trees may begin to die as a result of climate change. The balance between forest photosynthesis and respiration is crucially dependent on the nutrient dynamics of the forest ecosystem, as well as other environmental variables. Because of current limitations on our understanding with respect to acclimation of the physiological processes, climatic constraints, and feedbacks amongst these processes, particularly those acting at biome scale, projections beyond a few decades are highly uncertain.

Impact of Human Activities

- Human activities modify carbon flows between the atmosphere, the land, and the oceans. Land use and land-use change are the main factors that affect terrestrial sources and sinks of carbon. Clearing of forests has resulted in a reduction of the global area of forests by almost 20 percent during the past 140 years. Management practices can restore, maintain, and enlarge vegetation and soil carbon stocks, however.
- Expansion of agriculture through conversion of forests and grassland during the past 140 years has led to a net release of about 121 Gt C, of which about 60 percent has been emitted in the tropics (primarily during the past half-century) and about 40 percent in middle and high latitudes (primarily before the middle of the 20th century). During the 1980s, more than 90 percent of the net release of carbon to the atmosphere was the result of land-use changes in the tropics.
- Reducing the rate of forest clearing can reduce carbon losses from terrestrial ecosystems. Establishing forests on previously cleared land provides an opportunity to sequester carbon in tree biomass and forest soils, but it will take decades to centuries to restore carbon stocks that have been lost as a result of land-use change in the past.
- Ecosystem conservation and management practices can restore, maintain, and enlarge soil carbon stocks. Forests and wetlands managed as nature reserves or recreation areas can sequester significant amounts of carbon.
- On cropland, soil carbon is lost through disturbances of soil by tillage. Management practices (e.g., irrigation and application of fertilizers) can enhance soil carbon stocks. Application of nitrogen fertilizer in croplands, however, probably is the largest human-induced source of the greenhouse gas nitrous oxide (N_2O) at present (see Section 1.2.3).

- Global emissions of the greenhouse gases methane (CH_4) and N_2O from land use-related activities [expressed as CO_2 -equivalents (C-eq)] exceed net CO_2 emissions from land-use change. Anthropogenic emissions include 0.9 Gt C-eq yr^{-1} of N_2O from cultivated soils, 0.6 Gt C-eq yr^{-1} of CH_4 and 0.1 Gt C-eq yr^{-1} of N_2O from livestock, 0.3 Gt C-eq yr^{-1} of CH_4 from rice paddies, and 0.2 Gt C-eq yr^{-1} of CH_4 and 0.1 Gt C-eq yr^{-1} of N_2O from biomass burning. In addition, emissions from forest soils or wetlands, for example, which may be considered natural, are affected by land use-related activities that affect these ecosystems (see Table 1-3).
- Multiple uses of land, while enhancing carbon stocks and producing energy, may present opportunities to reduce

greenhouse gas emissions with a minimum use of resources. Products made from biomass comprise carbon stocks and present an opportunity to substitute for materials that might otherwise lead to larger greenhouse gas emissions (see Section 1.4.3 and Chapter 4). Biomass energy can be produced continuously by planting and harvesting, thereby reducing the consumption of fossil fuels. The development of new technologies for efficient production of biomass energy is essential to keep costs low and to secure land in competition for its use for alternative services (see Section 1.4.4 and Chapter 4).

1.1. Introduction

The emergence of life on earth has led to the conversion of carbon dioxide in the atmosphere and carbon dissolved in the oceans into innumerable inorganic and organic compounds on land and in the sea. The development of different ecosystems over millions of years has established patterns of carbon flows through the global environmental system. Natural exchanges of carbon between the atmosphere, the oceans, and terrestrial ecosystems are now being modified by human activities, primarily as a result of fossil fuel burning and changing land use. This activity has led to a steady addition of carbon dioxide to the atmosphere and enhancement of the atmospheric concentration by more than 28 percent over the past 150 years.

We need to understand the global environmental system and in particular the circulation of carbon in nature, as well as how human activities have modified it, to assess how we may do so increasingly in the future. In addition to reducing emissions from fossil fuel use, we may also have an opportunity to reduce the rate of build-up of carbon dioxide in the atmosphere by taking advantage of the fact that carbon can accumulate in vegetation and soils in terrestrial systems—an opportunity that was brought into focus at the Third Conference of the Parties (COP) to the Framework Convention on Climate Change (FCCC) in Kyoto. This introductory chapter provides an overview of our present understanding of the fundamental natural processes at work, which is essential for an analysis of the opportunities, limitations, and implications of actions related to land use and land-use change.

Natural flows of carbon between the atmosphere, the oceans, and the terrestrial and freshwater systems vary from one part of the globe to another and in time (i.e., between seasons, from one year to the next, and over decades and centuries). It is often difficult to separate changes resulting from human interventions from these natural variations.

Some of the measures specified in the Kyoto Protocol are ambiguous because the terminology being used is not always adequately defined. Clarifications in this regard are required, and we need to analyze the implications of alternative interpretations as a basis for political agreements on how to proceed. The measures specified in the Protocol might also induce secondary changes that need to be evaluated. Knowledge about the functioning of global biogeochemical cycles, particularly the global carbon cycle, is essential in this context.

Information about human-induced disturbances of sources and sinks of other greenhouse gases is also provided. Methane emissions may be changed unintentionally when actions are taken to enhance carbon dioxide sinks, and sources and sinks of nitrous oxide will be modified if the cycle of nitrogen is disturbed. Changes in the nitrogen cycle will in turn influence terrestrial ecosystems and thereby the exchange of carbon dioxide between the terrestrial system and the atmosphere.

To judge the long-term consequences of the ways in which human activities disturb the circulation of carbon in nature and change its distribution between natural reservoirs, we need to analyze the carbon cycle in detail, particularly with respect to the terrestrial ecosystems. This analysis will also shed light on the implications of the measures specified in the Kyoto Protocol.

1.2. Biogeochemical Cycles of Greenhouse Gases

Terrestrial ecosystems are important components in the biogeochemical cycles that create many of the sources and sinks of carbon dioxide, methane, and nitrous oxide and thereby influence global responses to human-induced emissions of greenhouse gases (GHGs). The dynamics of terrestrial ecosystems depend on interactions between a variety of biogeochemical cycles, particularly the carbon cycle, the nutrient cycles, and the circulation of water—all of which may be modified indirectly by climate changes and by direct human actions (e.g., land-use/cover change).

1.2.1. The Global Carbon Cycle

1.2.1.1. Natural and Human-Induced Changes in the Past Carbon Cycle

Analyses of air bubbles in ice cores from Greenland and the Antarctic have given us a reasonably clear idea about variations in atmospheric CO₂ concentration since the end of the last glacial maximum. It was then about 200 ppmv; it rose gradually to about 250 ppmv 8,000 years ago and subsequently by 25 ppmv during the following 7,000 years. During the past millennium until the beginning of the industrial revolution, CO₂ varied between 275 and 285 ppmv. There seems to have been an increase of about 10 ppmv around 1300 AD, followed by a 10 ppmv decrease around 1600 AD (i.e., during the Little Ice Age) (Barnola *et al.*, 1995; Etheridge *et al.*, 1996; Indermühle *et al.*, 1999). All of these changes took place gradually, and the rate of change in the atmospheric reservoir probably seldom exceeded a few Gt C per decade (Ciais, 1999).

The CO₂ concentration has risen from the range noted above to a concentration of 366 ppmv in 1998 (Keeling and Whorf, 1999). The decadal rate of change over the past century has been persistent and more rapid than during any other period in the last millennium. This rate of change can be explained by the cumulative effects of emissions from fossil fuel combustion and land clearing and the response of the oceans and biosphere to this anthropogenic perturbation.

From 1850 to 1998, 270 ± 30 Gt C were emitted from fossil fuel burning and cement production (Marland *et al.*, 1999); 176 ± 10 Gt C accumulated in the atmosphere (Etheridge *et al.*, 1996; Keeling and Whorf, 1999). The cumulative ocean uptake during this time has been estimated (with the aid of ocean carbon cycle models) to be 120 ± 50 Gt C (Kheshti *et al.*, 1999; Joos

et al., 1999). This estimate of ocean uptake is more uncertain than estimates of total emissions from fossil fuel burning and the accumulation in the atmosphere (Siegenthaler and Joos, 1992; Enting *et al.*, 1994). Nevertheless, balancing the carbon budget for this period yields a global net terrestrial source of about 26 ± 60 Gt C. In other words, it is likely that the terrestrial system has been a source during this period.

It is relevant to compare the magnitude of this global net terrestrial source with direct estimates of emissions during this time resulting from the expansion of cropland, deforestation, and other land-use changes (see Section 1.4.1). The area covered by cropland in temperate regions (particularly in North America and the former Soviet Union) reached a maximum by the middle of the 20th century (Ramankutty and Foley, 1998). The rate of increase of croplands in tropical regions (mainly Latin America), however, surpassed that of temperate regions around 1960 (Houghton, 1994, 1999).

During the period 1850–1998, net cumulative global CO₂ emissions from land-use change are estimated to have been 136 ± 55 Gt C (assuming that the relative uncertainty of land-use change emissions is the same as the estimate for the 1980s). Of these emissions, about 87 percent were from forest

areas and about 13 percent from cultivation of mid-latitude grasslands (Houghton, 1999; Houghton *et al.*, 1999, 2000). A residual global terrestrial sink of 110 ± 80 Gt C is therefore required to reconcile the difference between the net terrestrial source estimated by balancing the carbon budget (26 ± 60 Gt C) and the larger terrestrial source estimated by accounting for the effects land-use change on carbon stocks (136 ± 55 Gt C). Thus, this residual terrestrial carbon sink—popularly referred to as the “missing carbon sink”—was comparable in size to the net ocean uptake over this period.

1.2.1.2. A More Detailed Analysis of the Carbon Budget and its Change during the Past 20 Years

Carbon in the form of inorganic and organic compounds, notably CO₂, is cycled between the atmosphere, oceans, and terrestrial biosphere (Figure 1-1). The largest natural exchanges occur between the atmosphere and terrestrial biota (GPP about 120 Gt C yr⁻¹, NPP about 60 Gt C yr⁻¹) and between the atmosphere and ocean surface waters (about 90 Gt C yr⁻¹). The atmosphere contains about 775 Gt C; the residence time for a CO₂ molecule in the atmosphere is therefore only about 2.5 years. The characteristic adjustment times between reservoirs in response

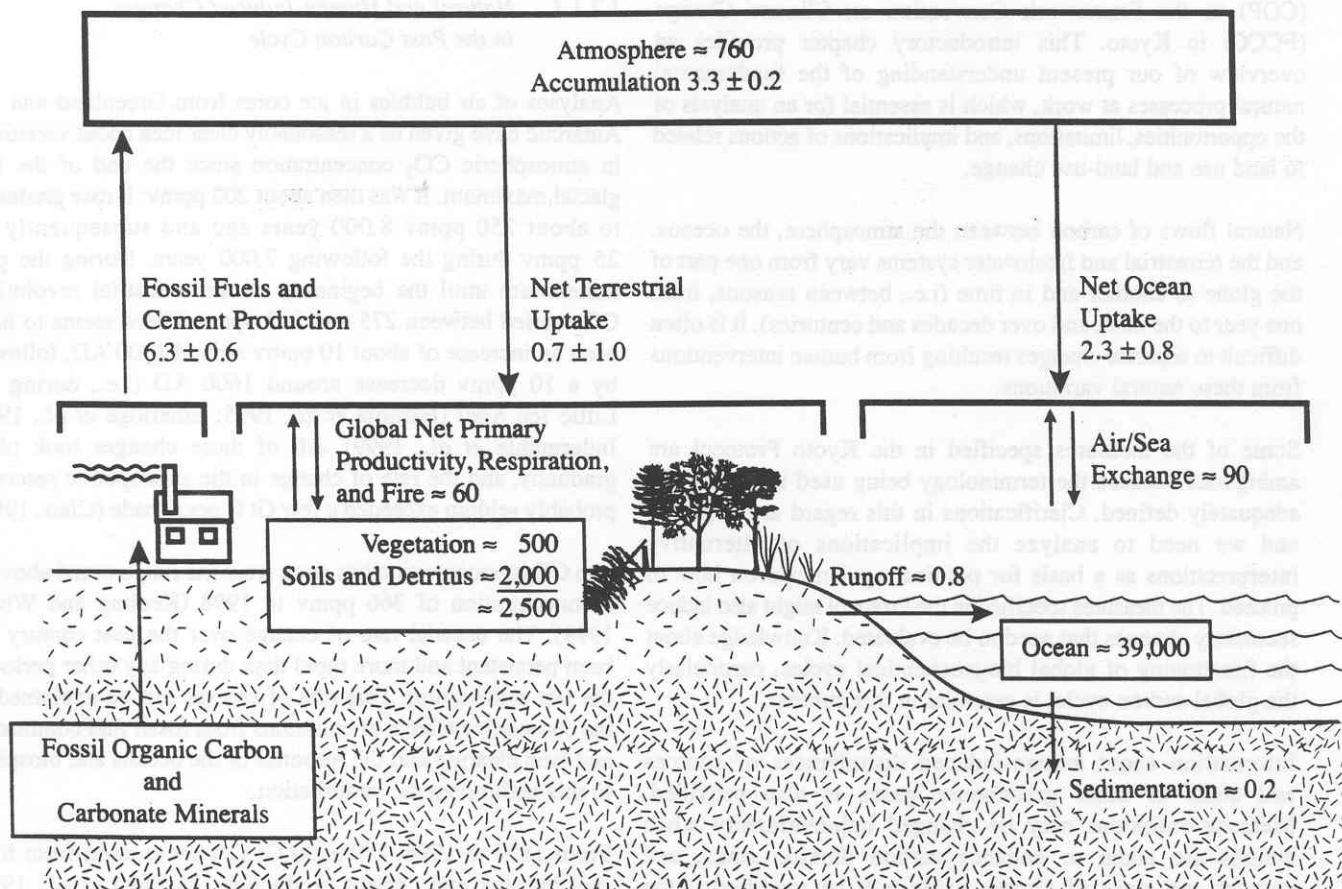


Figure 1-1: The global carbon cycle, showing the carbon stocks in reservoirs (in Gt C = 10^{15} g C) and carbon flows (in Gt C yr⁻¹) relevant to the anthropogenic perturbation as annual averages over the decade from 1989 to 1998 (Schimel *et al.*, 1996, Tables 2.1 and 2.2). Net ocean uptake of the anthropogenic perturbation equals the net air-sea input plus runoff minus sedimentation (discussed by Sarmiento and Sundquist, 1992).

Table 1-1: Global carbon stocks in vegetation and top 1 m of soils (based on WBGU, 1998).

Biome	Area (10 ⁶ km ²)	Carbon Stocks (Gt C)		
		Vegetation	Soils	Total
Tropical forests	17.6	212	216	428
Temperate forests	10.4	59	100	159
Boreal forests	13.7	88	471	559
Tropical savannas	22.5	66	264	330
Temperate grasslands	12.5	9	295	304
Deserts and semideserts	45.5	8	191	199
Tundra	9.5	6	121	127
Wetlands	3.5	15	225	240
Croplands	16.0	3	128	131
Total	151.2	466	2011	2477

to perturbations to the system, however, are on the order of decades to centuries (Schimel *et al.*, 1996).

The oceans, vegetation, and soils are significant reservoirs of carbon; they actively exchange CO₂ with the atmosphere. Oceans contain about 50 times as much carbon as the atmosphere, predominantly in the form of dissolved inorganic carbon. Ocean uptake of carbon is limited, however, by the solubility of CO₂ in seawater (including the effects of carbonate chemistry) and the slow rate of mixing between surface and deep-ocean waters. Terrestrial vegetation and soils contain about three and a half times as much carbon as the atmosphere; the exchange is controlled by photosynthesis and respiration.

The amount of carbon stored globally in soils is much larger than that in vegetation (Table 1-1). Soil is a major carbon pool in all biomes, whereas carbon stocks in vegetation are predominantly in the forest biomes. Boreal forests have a larger proportion of carbon stored in soils than in trees, compared with temperate or tropical forests. There are wide local variations, however, in the amounts and proportions of carbon per unit ground area in vegetation and soil within each biome (see Section 1.3).

The average global carbon budget for the 1980s (1980 to 1989) (Schimel *et al.*, 1996) has been reassessed for the most recent decade from 1989 to 1998. There are some significant differences between the two decades (Table 1-2). Emissions from fossil fuel combustion and cement production have increased by about 0.8 Gt C yr⁻¹ (based on estimates through 1996 by Marland *et al.*, 1999, and energy statistics for 1997 and 1998 by British Petroleum Company, 1999). There has been a slight decrease, however, in these emissions from Annex I countries in aggregate, with a marked decrease from Annex I countries with "economies in transition." The increase in these emissions from non-Annex I countries in aggregate has been about 0.9 Gt C yr⁻¹. The rate of increase in the atmospheric stock of carbon, on the other hand, has remained about the same (Keeling and Whorf, 1999). Although the net ocean uptake appears to have increased somewhat (Jain *et al.*, 1995; Harvey *et al.*, 1997), the difference between emissions resulting from the burning of fossil fuels and

cement production, on the one hand, and atmospheric and oceanic uptake, on the other, has increased—with the result that the net terrestrial uptake of carbon for the period 1989–1998 was probably 0.7 ± 1.0 Gt C yr⁻¹.

Precise molecular oxygen (O₂) measurements in the atmosphere make it possible to quantify the net global terrestrial carbon flux and the oceanic uptake of carbon in an independent manner. Reconstruction of the mean atmospheric O₂ trend from air enclosed in bubbles in glacier ice (Battle *et al.*, 1996) and air archived in tanks yields a net terrestrial uptake of 0.6 ± 0.9 Gt C yr⁻¹ (± 1 standard deviation) for the 1980s. High-precision atmospheric observations (Keeling *et al.*, 1996b) yield a value of 0.9 ± 0.7 Gt C yr⁻¹ for the period 1990–1997. Thus, there is satisfactory consistency between the estimates from the two approaches.

Factors that influence the net terrestrial uptake of carbon include the direct effects of land use and land-use change (e.g., deforestation and agricultural abandonment and regrowth) (see Section 1.4) and the response of terrestrial ecosystems to CO₂ fertilization, nutrient deposition, climatic variation, and disturbance (e.g., fires, wind-throws, and major droughts) (see Section 1.3). These natural phenomena may partially be indirect effects of other human activities: Many ecosystems are in some state of recovery from past disturbances. For the 1980s, the combination of estimates of the strength of these factors (Schimel *et al.*, 1995) yields a value for net terrestrial uptake that is consistent with, but more uncertain than, the residual calculated in line 4 of Table 1-2. For the 1980s, Houghton (1999) estimates the net CO₂ source from land-use change to be 2.0 ± 0.8 Gt C yr⁻¹, which was later revised to 1.7 ± 0.8 Gt C yr⁻¹ considering newer regional data (Houghton *et al.*, 1999, 2000). Estimates for the most recent decade are 1.6 ± 0.8 Gt C yr⁻¹ based on regional data up to 1995 (Houghton *et al.*, 1999, 2000). Yet from the revised carbon budget (Table 1-2) we can infer that the net global effect of all other factors has offset the source from land-use change, yielding a significant net terrestrial sink over the past 20 years. The residual terrestrial uptake for both decadal periods in Table 1-2 is comparable in size to the oceanic uptake.

Table 1-2: Average annual budget of CO₂ perturbations for 1980 to 1989 (consistent with values given in Schimel *et al.*, 1996) and 1989 to 1998 (note the 1-year overlap in the two decadal periods). Flows and reservoir changes of carbon are expressed in Gt C yr⁻¹; error limits correspond to an estimated 90-percent confidence interval.

	1980 to 1989	1989 to 1998
1) Emissions from fossil fuel combustion and cement production	5.5 ± 0.5	6.3 ± 0.6 ^a
a) from Annex I countries ^d	3.9 ± 0.4 ^a	3.8 ± 0.4 ^a
i) from countries excluding those with economies in transition	2.6 ± 0.3	2.8 ± 0.3
ii) from countries with economies in transition ^d	1.3 ± 0.3 ^a	1.0 ± 0.3 ^a
b) from rest of world ^d	1.6 ± 0.3 ^a	2.5 ± 0.4 ^a
2) Storage in the atmosphere	3.3 ± 0.2	3.3 ± 0.2 ^b
3) Ocean uptake	2.0 ± 0.8	2.3 ± 0.8 ^c
4) Net terrestrial uptake = (1) - [(2)+(3)]	0.2 ± 1.0	0.7 ± 1.0
5) Emissions from land-use change	1.7 ± 0.8 ^e	1.6 ± 0.8 ^f
6) Residual terrestrial uptake = (4)+(5)	1.9 ± 1.3	2.3 ± 1.3

^aBased on emission estimates through 1996 by Marland *et al.* (1999) and estimates derived from energy statistics for 1997 and 1998 (British Petroleum Company, 1999).

^bBased on atmospheric CO₂ concentrations measured at Mauna Loa, Barrow, and South Pole (Keeling and Whorf, 1999).

^cBased on ocean carbon cycle model (Jain *et al.*, 1995) used in the IPCC Second Assessment Report (IPCC, 1996; Harvey *et al.*, 1997) consistent with an uptake of 2.0 Gt C yr⁻¹ in the 1980s.

^dAnnex 1 countries and countries with economies in transition (a subset of Annex 1 countries) defined in the FCCC. Emissions include emission estimates from geographic regions preceding this designation and include emissions from bunker fuels from each region.

^eBased on land-use change emissions estimated by Houghton (1999) and modified by Houghton *et al.* (1999, 2000), which include the net emissions from wood harvesting and agricultural soils.

^fBased on estimated annual average emissions for 1989–1995 (Houghton *et al.*, 1999, 2000).

1.2.1.3. Inter-Annual and Decadal Variability of Atmospheric CO₂ Concentrations

The uncertainty ranges in Table 1-2 result partly from our limited ability to determine accurately the gradual changes in the carbon balance resulting from human-induced emissions. In addition, however, variations in the atmospheric CO₂ growth rate that have been recorded since 1960 imply that global terrestrial and oceanic carbon sources and sinks may vary significantly in time (Conway *et al.*, 1994; Francey *et al.*, 1995; Keeling *et al.*, 1996a). Fossil fuel emissions, on the other hand, do not fluctuate much from one year to the next, whereas the exchange of atmospheric CO₂ with the oceans and the terrestrial biosphere responds to inter-annual climate variations. High atmospheric CO₂ growth rates have been recorded during three recent El Niño events—in 1983, 1987, and 1998—indicating a lower than normal uptake of atmospheric CO₂ by the terrestrial biosphere and the oceans (Gaudry *et al.*, 1987; Keeling *et al.*, 1989; Keeling and Whorf, 1999). Conversely, low atmospheric CO₂ growth rates were observed between 1991 and 1993, indicating enhanced uptake—particularly over the northern hemisphere (Ciais *et al.*, 1995a,b; Keeling *et al.*, 1996b).

Ocean carbon models and available data suggest that the oceans contribute less to observed year-to-year changes in atmospheric CO₂ concentration than does the terrestrial biosphere (Winguth *et al.*, 1994; Le Quééré *et al.*, 1998; Lee *et al.*, 1998; Feely *et al.*,

1999; Rayner *et al.*, 2000). The terrestrial biosphere therefore appears to drive most of the inter-annual variation in CO₂ flows. The way ecosystems respond to climate variability is not well understood, although the correlation and lag-correlation of inter-annual variability between CO₂ growth rates, climate, and the remotely sensed “greenness” normalized difference vegetation index (NDVI), which is related to photosynthesis, is illustrative (Braswell *et al.*, 1997; Myneni *et al.*, 1997).

When terrestrial biogeochemical models are forced with realistic year-to-year changes in temperature and precipitation, they can simulate changes in the global and regional biosphere and associated changes in CO₂ exchange with the atmosphere (Kindermann *et al.*, 1996; Tian *et al.*, 1998). These models can reproduce the magnitude and to some extent the phase of observed inter-annual variability of atmospheric CO₂ concentrations, though different processes have been implicated in attempts to explain the observed fluctuations (e.g., Heimann *et al.*, 1997). There are still differences in detail that have not been resolved.

Shifts in magnitude and phase of atmospheric CO₂ fluctuations on a decadal time scale suggest that seasonality of terrestrial biotic fluxes has been changing slowly at mid to high northern latitudes (Keeling *et al.*, 1996b; Randerson *et al.*, 1997). Remotely sensed data (Myneni *et al.*, 1997), as well as phenological observations (Menzel and Fabian, 1999), independently indicate

a longer growing season in the boreal zone and in temperate Europe during recent decades.

1.2.1.4. Non-Land Use Influences on Sources and Sinks of CO₂

In addition to land use and land-use change, several other factors—many of which are anthropogenic in origin—affect large-scale sources and sinks of atmospheric CO₂. These factors contribute to the observed variability and upward trend in CO₂ concentration, thus complicate the determination of how much of the observed changes in carbon stocks in vegetation and soils during a commitment period should be attributed to the direct activities initiated in accordance with Articles 3.3 or 3.4 of the Kyoto Protocol. For example, changes in climate and climate variability influence sources and sinks of CO₂ from vegetation and soils and *vice versa*, and these may have natural or anthropogenic causes. Projections of future atmospheric CO₂ concentrations will, therefore, be quite uncertain, at least beyond the next few decades (Tans and Wallace, 1999).

Other factors that may have contributed to the rate of carbon sequestration into vegetation and soils include the increase in atmospheric CO₂ concentration during 1850–1998 from about 285 to 366 ppmv (see Section 1.3.2.3) and increasing atmospheric concentrations of NO_x (NO and NO₂) and NH₃ that enhance the atmospheric deposition of nitrogen—a limiting plant nutrient in many ecosystems (Schimel *et al.*, 1995) (see Section 1.3.2.4). On the other hand, emissions of NO_x and SO₂ also lead to atmospheric deposition of nitrogen and sulfur compounds that cause acidification of soils and waters, which may negatively affect plant growth and reduce carbon uptake. In addition, elevated concentrations of surface ozone that also reduce plant growth (Semenov *et al.*, 1998, 1999) result from NO_x emissions in the

presence of volatile organic compounds (Houghton *et al.*, 1996). All of these factors affect the net removal of CO₂ from the atmosphere by terrestrial ecosystems, as given in Table 1-2, in addition to the direct effects of land use and land-use change.

1.2.2. Sources and Sinks of Methane

Methane (CH₄) is the most important greenhouse gas in the atmosphere after water vapor and CO₂. CH₄ concentrations have increased from about 700 ppbv in pre-industrial times to about 1700 ppbv today (Etheridge *et al.*, 1992; Prather *et al.*, 1995). About 550 Mt CH₄ yr⁻¹ is emitted into the atmosphere from a variety of sources; chemical reaction with OH radicals and (to a smaller extent) uptake by soils remove approximately the same amount (Prather *et al.*, 1995). The small imbalance between global production and destruction of CH₄ resulted in an increase in the atmospheric concentration at a rate of 13 ppbv yr⁻¹ during the early 1980s. This rate diminished, however, to 8 ppbv yr⁻¹ in 1990 and dropped further to 4 ppbv yr⁻¹ in 1996 (Steele *et al.*, 1992; Dlugokencky *et al.*, 1998). The lifetime of CH₄ with respect to the OH sink is about 9 years (Prinn, 1994), so the characteristic adjustment time of the atmospheric concentration to a perturbation in emissions is much shorter than for CO₂.

During pre-industrial times, wetlands (bogs at high northern latitudes and swamps in the tropics), termites, and wild animals (Chappelaz *et al.*, 1993) controlled atmospheric CH₄. Anthropogenic CH₄ sources are associated with rice cultivation, cattle breeding, biomass burning, waste treatment (landfills, sewage, and animal waste), and the use of fossil fuels, including natural gas and coal extraction as well as petroleum industry activities in general (Prather *et al.*, 1995) (Table 1-3). At present, anthropogenic sources represent about 70 percent of total CH₄

Table 1-3: Global estimates (Prather *et al.*, 1995) of recent sources of CH₄ and N₂O that are influenced by land-use activities.

CH ₄ Sources	Mt CH ₄ yr ⁻¹	Gt C-eq yr ⁻¹ a,b
Livestock (enteric fermentation and animal waste)	110 (85–130)	0.6 (0.5–0.7)
Rice paddies	60 (20–100)	0.3 (0.1–0.6)
Biomass burning	40 (20–80)	0.2 (0.1–0.5)
Natural wetlands	115 (55–150)	0.7 (0.3–0.9)
N ₂ O Sources	Mt N yr ⁻¹	Gt C-eq yr ⁻¹ a,c
Cultivated soils	3.5 (1.8–5.3)	0.9 (0.5–1.4)
Biomass burning	0.5 (0.2–1)	0.1 (0.05–0.3)
Livestock (cattle and feed lots)	0.4 (0.2–0.5)	0.1 (0.05–0.13)
Natural tropical soils—wet forests	3 (2.2–3.7)	0.8 (0.6–1)
Natural tropical soils—dry savannas	1 (0.5–2)	0.3 (0.1–0.5)
Natural temperate soils—forests	1 (0.1–2)	0.3 (0.03–0.5)
Natural temperate soils—grasslands	1 (0.5–2)	0.3 (0.1–0.5)

^a 12 Gt C-equivalent = 44 Gt CO₂-equivalent.

^b Carbon-equivalent emissions based on CH₄ GWP of 21.

^c Carbon-equivalent emissions based on N₂O GWP of 310.

emissions. Although the global CH₄ source is relatively well known, the magnitude of individual sources is still uncertain (Fung *et al.*, 1991; Prather *et al.*, 1995). Table 1-3 lists estimated land use-related emissions of CH₄ on both a CH₄- and a CO₂-equivalent basis.¹ The likely changes in these CH₄ sources and sinks associated with changes in land use and other modifications of terrestrial ecosystems are uncertain. There may also be indirect changes resulting from human activities in accordance with Articles 3.3 and 3.4 of the Kyoto Protocol.

1.2.3. Sources and Sinks of Nitrous Oxide

Nitrous oxide (N₂O), another major greenhouse gas, has no significant sinks on land and is destroyed by chemical reactions in the upper atmosphere. Land surfaces are the main source of atmospheric N₂O; thus, changes in land-use practices modify soil emissions and influence N₂O concentration in the atmosphere (Kroeze *et al.*, 1999). Uncertainty with respect to current magnitudes of sources and sinks of N₂O (Prasad, 1997) and its atmospheric lifetime limit an accurate budget: Existing data on fluxes of N₂O from soils and oceans are insufficient to quantify them in detail. Nevertheless, present-day global N₂O emissions have been estimated to be about 14 Mt N yr⁻¹ (Prasad, 1997). Roughly half of the global N₂O emissions are anthropogenic (Davidson, 1991; Khalil and Rasmussen, 1992; Hutchinson, 1995; Prather *et al.*, 1995; Prasad, 1997).

Microbiological processes in soils are the primary sources of N₂O (Davidson, 1991, 1992; Shiller and Hastie, 1996). Table 1-3 lists estimated land use-related emissions of N₂O on both a nitrogen content and a CO₂-equivalent basis.² Emissions from soils are enhanced under warm and wet conditions (e.g., those present in the soils of moist tropical forests) and when nitrogen fertilizers are applied in agriculture (Conrad *et al.*, 1983; Winchester *et al.*, 1988; Khalil and Rasmussen, 1992). Thus, changes in agricultural soil management and tropical forestry may alter N₂O emissions from soils and influence its concentration in the atmosphere.

1.3. The Carbon Budget of Terrestrial Ecosystems

The carbon sequestration potential of terrestrial ecosystems depends on the type and condition of the ecosystem—that is, its species composition, structure, and (in the case of forests) age distribution. Also important are site conditions, including climate and soils, natural disturbances, and management. For the analysis of a carbon budget, the fundamental differences between GPP, NPP, NEP, and NBP must be recognized (see Figure 1-2). The justification of the quantitative global flux

¹Emissions given as CO₂-equivalent are calculated, as specified in the Kyoto Protocol, using the Global Warming Potentials (GWPs) given in the IPCC Second Assessment Report (SAR) (Houghton *et al.*, 1996); the GWP for CH₄ was 21 (100-year time horizon).

²Emissions given as CO₂-equivalent are calculated, as specified in the Kyoto Protocol, using the GWP given in the IPCC SAR (Houghton *et al.*, 1996), which was 310 for N₂O (100-year time horizon).

estimates as defined below is given in the succeeding sections of this chapter (see also Steffen *et al.*, 1998).

Gross Primary Production denotes the total amount of carbon fixed in the process of photosynthesis by plants in an ecosystem, such as a stand of trees. GPP is measured on photosynthetic tissues, principally leaves. Global total GPP is estimated to be about 120 Gt C yr⁻¹.

Net Primary Production denotes the net production of organic matter by plants in an ecosystem—that is, GPP reduced by losses resulting from the respiration of the plants (autotrophic respiration). Global NPP is estimated to be about half of the GPP—that is, about 60 Gt C yr⁻¹.

Net Ecosystem Production denotes the net accumulation of organic matter or carbon by an ecosystem; NEP is the difference between the rate of production of living organic matter (NPP) and the decomposition rate of dead organic matter (heterotrophic respiration, RH). Heterotrophic respiration includes losses by herbivory and the decomposition of organic debris by soil biota. Global NEP is estimated to about 10 Gt C yr⁻¹. NEP can be measured in two ways: One is to measure changes in carbon stocks in vegetation and soil; the other is to integrate the fluxes of CO₂ into and out of the vegetation (the net ecosystem exchange, NEE) with instrumentation placed above (Aubinet *et al.*, 2000). The precision of both of these methods is improving.

Net Biome Production denotes the net production of organic matter in a region containing a range of ecosystems (a biome) and includes, in addition to heterotrophic respiration, other processes leading to loss of living and dead organic matter (harvest, forest clearance, and fire, etc.) (Schulze and Heimann, 1998). NBP is appropriate for the net carbon balance of large areas (100–1000 km²) and longer periods of time (several years and longer). In the past, NBP has been considered to be close to zero (Figure 1-2). Compared to the total fluxes between atmosphere and biosphere, global NBP is comparatively small; NBP for the decade 1989–1998 has been estimated to be 0.7 ± 1.0 Gt C yr⁻¹ (Table 1-2)—about 1 percent of NPP and about 10 percent of NEP.

1.3.1. Carbon Stocks and Flows in Major Biomes

For the estimation of present and future carbon sequestration potential, it is necessary to consider broad vegetation types differentiated by climatic zones and water availability (i.e., tropical, temperate, and boreal regions). Table 1-1 lists the areas, current estimates of aboveground and below-ground carbon stocks, and NPP of the world's major regions or biomes. Within each biome, large additional variation exists resulting from local conditions and topography. In the tropics, for example, moist and dry forests have widely differing carbon stocks and NPP.

- Pristine forests (e.g., in the wet tropics or boreal region) were long believed to be mostly in a state of

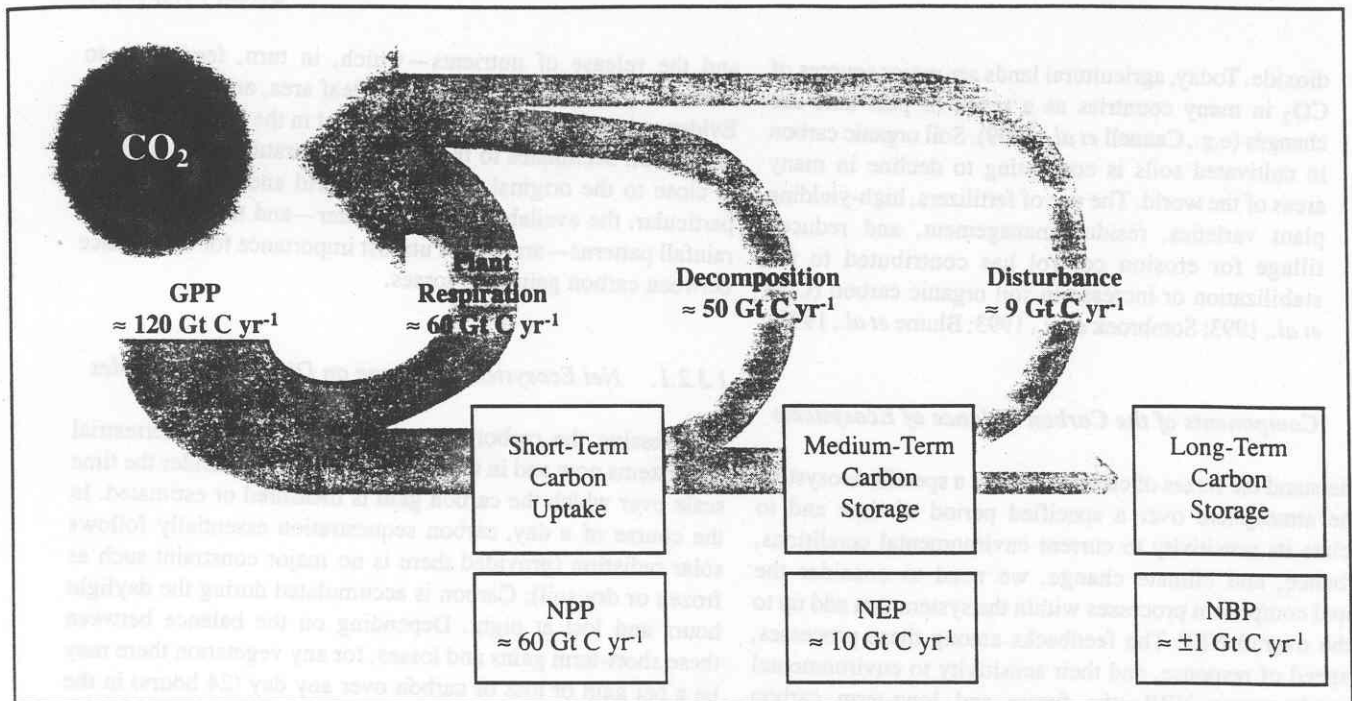


Figure 1-2: Global terrestrial carbon uptake. Plant (autotrophic) respiration releases CO_2 to the atmosphere, reducing GPP to NPP and resulting in short-term carbon uptake. Decomposition (heterotrophic respiration) of litter and soils in excess of that resulting from disturbance further releases CO_2 to the atmosphere, reducing NPP to NEP and resulting in medium-term carbon uptake. Disturbance from both natural and anthropogenic sources (e.g., harvest) leads to further release of CO_2 to the atmosphere by additional heterotrophic respiration and combustion—which, in turn, leads to long-term carbon storage (adapted from Steffen *et al.*, 1998).

equilibrium, such that over a period of several years their carbon balance would be neutral. This view has been challenged in more recent years by increasing evidence from sample plot studies that undisturbed areas of forests also sequester carbon (e.g., Lugo and Brown, 1993; Phillips *et al.*, 1998, for the tropics; Schulze *et al.*, 1999, for the Siberian boreal forest). These carbon quantities will eventually be returned to the atmosphere when patches of trees die for biological or climatic reasons, localized natural disturbance occurs, or compartments of the forest are cleared. Because of its importance to the Kyoto Protocol, carbon sequestration by managed and unmanaged forests is considered in some detail below (Section 1.3.2).

- Grassland ecosystems store most of their carbon in soils, where turnover is relatively slow (Table 1-1). In most grassland types, below-ground NPP is at least equal to or higher than aboveground production. Carbon accumulation by combined aboveground and below-ground NPP may be as much as $3.4 \text{ t C ha}^{-1} \text{ yr}^{-1}$ in tropical humid savannas and as little as $0.7 \text{ t C ha}^{-1} \text{ yr}^{-1}$ in tropical dry savannas and $0.5 \text{ t C ha}^{-1} \text{ yr}^{-1}$ in temperate steppe (Parton *et al.*, 1995).
- Wetlands are important reservoirs of carbon. Undrained peatlands in high latitudes have accumulated appreciable amounts of carbon from the atmosphere since the retreat of the ice and continue to be significant CO_2

sinks ($0.2\text{--}0.5 \text{ t C ha}^{-1} \text{ yr}^{-1}$), but they are also sources of methane ($0.03\text{--}0.3 \text{ t CH}_4 \text{ ha}^{-1} \text{ yr}^{-1}$). By contrast, peatlands that are drained for agriculture or for afforestation release carbon as CO_2 because of accelerated decomposition of the aerobic peat (Cannell *et al.*, 1993), although they no longer release methane in significant amounts. The quantitative balance between these two processes is poorly understood (Cannell *et al.*, 1999), although it is important because the GWP of methane is 21 times that of CO_2 (see Section 1.2). Peatlands drained for agriculture continue to be a sustained carbon source as long as any peat remains in the soil. Peatlands drained for afforestation may continue to be a source of carbon in spite of forest biomass growth (Zoltai and Martikainen, 1985), but under certain climatic conditions they can also revert to carbon sinks (Minkinen and Laine, 1998).

- In agricultural land, by far most of the carbon is stored below ground (see Table 1-1). Losses of carbon from terrestrial systems during the past 200 years, particularly until the middle of the 20th century, were mostly the result of the establishment of agriculture on grassland and land that was previously covered by forests. Regular plowing, planting, and harvesting led to enhanced oxidation of organic matter in the soils, which has been emitted into the atmosphere as carbon

dioxide. Today, agricultural lands are major sources of CO₂ in many countries as a result of past land-use changes (e.g., Cannell *et al.*, 1999). Soil organic carbon in cultivated soils is continuing to decline in many areas of the world. The use of fertilizers, high-yielding plant varieties, residue management, and reduced tillage for erosion control has contributed to the stabilization or increase in soil organic carbon (Cole *et al.*, 1993; Sombroek *et al.*, 1993; Blume *et al.*, 1998).

and the release of nutrients—which, in turn, feed back to stimulate photosynthesis, increased leaf area, and tree growth. Evidence is accumulating, however, that in the longer term soil respiration acclimates to the rise in temperature and stabilizes at close to the original rate. In semi-arid and arid regions in particular, the availability of soil water—and thus changes in rainfall patterns—are also of utmost importance for the balance between carbon gains and losses.

1.3.2. Components of the Carbon Balance of Ecosystems

To understand the fluxes of carbon between a specific ecosystem and the atmosphere over a specified period of time and to appreciate its sensitivity to current environmental conditions, disturbance, and climate change, we need to consider the principal component processes within the system that add up to give the overall NEP. The feedbacks among these processes, their speed of response, and their sensitivity to environmental change determine NBP—the future and long-term carbon sequestration potential of the ecosystem.

Figure 1-3 shows measured annual carbon fluxes in a typical boreal, temperate, and tropical forest. NEP is the difference between the gross input of carbon in photosynthesis, GPP, and the sum of the losses of carbon in autotrophic respiration (RA) and RH. The component fluxes accumulated over a year should add up to the annual NEP, which is measured independently as described below (see Section 1.3.2.3). A mass balance of the component fluxes above ground (photosynthesis; foliage, branch, and stem respiration; leaf, branch, and stem litter production; and aboveground NPP) enables an estimate to be made of the amount of carbon internally translocated below ground. A mass balance of the component fluxes below ground (the inputs of litter and translocate from above, root and heterotrophic respiration, fine root turnover, mycorrhizal and root system NPP) enables an approximate estimate to be made of net changes in the pool of soil carbon. There are appreciable errors, however, in measuring all component fluxes (below-ground fluxes in particular), so close agreement between the two estimates of NEP is not to be expected.

The processes of photosynthesis and respiration are functions of several environmental and plant variables, including solar radiation, air and soil temperature and humidity, availability of water and nutrients, atmospheric ozone and other pollutants, leaf area, and foliar nutrition. Climate change therefore affects these processes in several ways. Photosynthesis is likely to be reduced by an increase in cloud cover but increased by enhanced global atmospheric CO₂ concentration and, on some sites, by atmospheric nutrient deposition. All respiratory processes are sensitive to temperature, as is the rate of population growth of respiring organs—particularly the fine roots and heterotrophic organisms in the soil. Thus, “soil respiration” is a function of soil temperature (e.g., Boone *et al.*, 1998; Rayment and Jarvis, 2000), which, if increased, leads in the short term to enhanced mineralization of soil organic matter

1.3.2.1. Net Ecosystem Exchange on Different Time Scales

In assessing the carbon sequestration potential of terrestrial ecosystems now and in the future, we need to consider the time scale over which the carbon gain is measured or estimated. In the course of a day, carbon sequestration essentially follows solar radiation (provided there is no major constraint such as frozen or dry soil): Carbon is accumulated during the daylight hours and lost at night. Depending on the balance between these short-term gains and losses, for any vegetation there may be a net gain or loss of carbon over any day (24 hours) in the year. In boreal forest, for example, carbon may be gained in daytime by a stand of trees on about 75 percent of the days through a growing season but lost on 25 percent of the days, the latter being days of particularly low solar radiation input (e.g., days with clouds and rain, or smoke in the atmosphere), high temperatures, or drought (see, e.g., Jarvis *et al.*, 1997; Lindroth *et al.*, 1998).

Over a year, the length of the growing season has a major influence on carbon gain. In boreal coniferous forest, for example, one-third to one-half of the carbon gained in the summer months is lost during autumn and the long winter period when the ground is partly frozen. The length of the growing season in broad-leaved temperate forest is defined by bud burst in the spring and leaf senescence in the autumn, whereas the season of net photosynthetic gain in temperate coniferous forest is conditioned largely by the day length and daily total radiation input in the winter months, thus may be 10 months long in maritime climates. Vegetation in Mediterranean climates is generally sparse and strongly seasonal, with small NEP that is strongly constrained by water availability for a large part of the time. Only in moist tropical forests is the carbon gain nearly continuous throughout the year, reduced only by occasional short periods of low solar radiation (cloudiness), low temperature, or water deficit (Malhi *et al.*, 1998).

Annual dynamics are particularly important in forest systems because their carbon turnover times can be many decades, characterized by major changes in structure through a series of stages in the life cycle. The carbon sequestration potential of a young forest stand that is regenerating or regrowing after a disturbance such as fire or harvesting is critically dependent on the point of time within the life cycle. Initially the disturbed area is likely to be losing carbon to the atmosphere (the length of this period depends on species, site conditions, and degree of disturbance), but the trees that subsequently occupy the site fully will eventually replace the lost carbon (Krankina *et al.*,

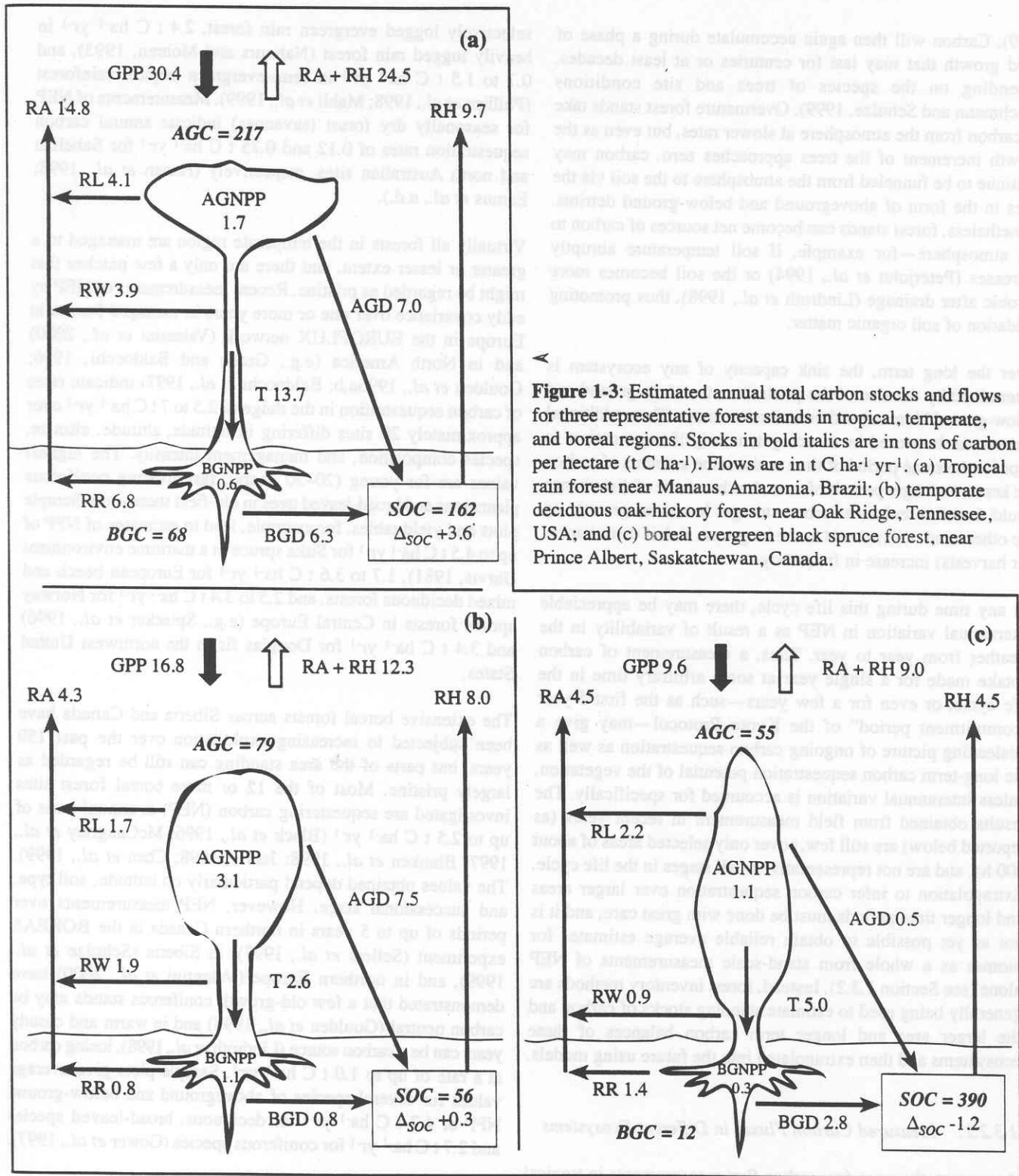


Figure 1-3: Estimated annual total carbon stocks and flows for three representative forest stands in tropical, temperate, and boreal regions. Stocks in bold italics are in tons of carbon per hectare (t C ha⁻¹). Flows are in t C ha⁻¹ yr⁻¹. (a) Tropical rain forest near Manaus, Amazonia, Brazil; (b) temperate deciduous oak-hickory forest, near Oak Ridge, Tennessee, USA; and (c) boreal evergreen black spruce forest, near Prince Albert, Saskatchewan, Canada.

Notes: AGC = aboveground carbon stock; BGC = below-ground carbon stock; SOC = soil organic carbon stock; GPP = gross primary production; RA = autotrophic respiration; RH = heterotrophic respiration; RL = foliage respiration; RW = aboveground wood respiration; RR = root respiration; AGD = aboveground detritus (litter fall and mortality); BGD = below-ground detritus (fine root turnover, exudation, root mortality); T = translocation from above to below ground; AGNPP = aboveground net biomass carbon increment; BGNPP = below-ground net biomass carbon increment; and ΔSOC = net increment in soil organic carbon.

1999). Carbon will then again accumulate during a phase of rapid growth that may last for centuries or at least decades, depending on the species of trees and site conditions (Buchmann and Schulze, 1999). Overmature forest stands take up carbon from the atmosphere at slower rates, but even as the growth increment of the trees approaches zero, carbon may continue to be funneled from the atmosphere to the soil via the trees in the form of aboveground and below-ground detritus. Nonetheless, forest stands can become net sources of carbon to the atmosphere—for example, if soil temperature abruptly increases (Peterjohn *et al.*, 1994) or the soil becomes more aerobic after drainage (Lindroth *et al.*, 1998), thus promoting oxidation of soil organic matter.

Over the long term, the sink capacity of any ecosystem is determined by the size of the pools (i.e., the aboveground and below-ground biomass) and their turnover times. Thus, additional carbon can be stored in an ecosystem only if more carbon is kept for the same period of time or the same amounts of carbon are kept over longer periods of time. A reduced rate of disturbance could therefore enhance carbon storage. Increased growth, on the other hand, will not add to the long-term sink if disturbances (or harvests) increase in frequency.

At any time during this life cycle, there may be appreciable interannual variation in NEP as a result of variability in the weather from year to year. Thus, a measurement of carbon uptake made for a single year at some arbitrary time in the life cycle, or even for a few years—such as the first 5-year “commitment period” of the Kyoto Protocol—may give a misleading picture of ongoing carbon sequestration as well as the long-term carbon sequestration potential of the vegetation, unless interannual variation is accounted for specifically. The results obtained from field measurement in recent years (as reported below) are still few, cover only selected areas of about 200 ha, and are not representative of all stages in the life cycle. Extrapolation to infer carbon sequestration over larger areas and longer time periods must be done with great care, and it is not as yet possible to obtain reliable average estimates for biomes as a whole from stand-scale measurements of NEP alone (see Section 1.3.2). Instead, forest inventory methods are generally being used to estimate standing stocks of carbon and the larger area and longer term carbon balances of these ecosystems and then extrapolated into the future using models.

1.3.2.2. Measured Carbon Fluxes in Different Ecosystems

At present, there are few carbon flux measurements in tropical forests over periods long enough to provide an annual estimate of NEP, although the number of such measurements are expected to increase appreciably over the next 5 to 10 years. Measurements in pristine, seasonal tropical rain forests in Amazonia indicate NEP of approximately 1.0 t C ha⁻¹ yr⁻¹ (Grace *et al.*, 1995a,b) and approximately 2.0 and 5.9 t C ha⁻¹ yr⁻¹ for dense, moist rain forest (Fan *et al.*, 1990; Malhi *et al.*, 1998, 1999). Sample plot studies also indicate net carbon sequestration rates within this range: 2.9 t C ha⁻¹ yr⁻¹ in

selectively logged evergreen rain forest, 2.4 t C ha⁻¹ yr⁻¹ in heavily logged rain forest (Nabuurs and Mohren, 1993), and 0.7 to 1.5 t C ha⁻¹ yr⁻¹ in semi-evergreen tropical rainforest (Phillips *et al.*, 1998; Mahli *et al.*, 1999). Measurements of NEP for seasonally dry forest (savannas) indicate annual carbon sequestration rates of 0.12 and 0.75 t C ha⁻¹ yr⁻¹ for Sahelian and north Australian sites, respectively (Hanan *et al.*, 1998; Eamus *et al.*, n.d.).

Virtually all forests in the temperate region are managed to a greater or lesser extent, and there are only a few patches that might be regarded as pristine. Recent measurements of NEP by eddy covariance over one or more years in managed forests in Europe in the EUROFLUX network (Valentini *et al.*, 2000) and in North America (e.g., Greco and Baldocchi, 1996; Goulden *et al.*, 1996a,b; Baldocchi *et al.*, 1997) indicate rates of carbon sequestration in the range of 2.5 to 7 t C ha⁻¹ yr⁻¹ over approximately 20 sites differing in latitude, altitude, climate, species composition, and management intensity. The highest values are for young (20–50 years), fast-growing coniferous plantations and broad-leaved trees in old-field succession. Sample plots and yield tables, for example, lead to estimates of NPP of up to 4.5 t C ha⁻¹ yr⁻¹ for Sitka spruce in a maritime environment (Jarvis, 1981), 1.7 to 3.6 t C ha⁻¹ yr⁻¹ for European beech and mixed deciduous forests, and 2.5 to 3.4 t C ha⁻¹ yr⁻¹ for Norway spruce forests in Central Europe (e.g., Spiecker *et al.*, 1996) and 3.4 t C ha⁻¹ yr⁻¹ for Douglas fir in the northwest United States.

The extensive boreal forests across Siberia and Canada have been subjected to increasing exploitation over the past 150 years, but parts of the area standing can still be regarded as largely pristine. Most of the 12 or more boreal forest sites investigated are sequestering carbon (NEP) at annual rates of up to 2.5 t C ha⁻¹ yr⁻¹ (Black *et al.*, 1996; McCaughey *et al.*, 1997; Blanken *et al.*, 1998; Jarvis, 1998; Chen *et al.*, 1999). The values obtained depend particularly on latitude, soil type, and successional stage. However, NEP measurements over periods of up to 5 years in northern Canada in the BOREAS experiment (Sellers *et al.*, 1997), in Siberia (Schulze *et al.*, 1999), and in northern Europe (Valentini *et al.*, 2000) have demonstrated that a few old-growth coniferous stands may be carbon neutral (Goulden *et al.*, 1998) and in warm and cloudy years can be a carbon source (Lindroth *et al.*, 1998), losing carbon at a rate of up to 1.0 t C ha⁻¹ yr⁻¹. Sample plots give average values for several species of aboveground and below-ground NPP of 4.7 t C ha⁻¹ yr⁻¹ for deciduous, broad-leaved species and 2.7 t C ha⁻¹ yr⁻¹ for coniferous species (Gower *et al.*, 1997).

Interannual variability in NEP may be considerable. The sequestration potential of tropical forests may vary by 10 percent from year to year depending on the length of the dry period and variation in solar radiation inputs and temperature, such as those caused by the eruption of Pinatubo (Grace *et al.*, 1995a,b) or those that occur during strong El Niño years (Tian *et al.*, 1998). The NEP of evergreen temperate forests (largely conifers) is similarly affected by variations in radiation input and temperature over the year and by the length of the

photosynthetic season, particularly in oceanic climates (Valentini *et al.*, 2000). The NEP of deciduous temperate forest (mostly broad-leaved trees) is also particularly sensitive to the length of the growing season as defined by the times of bud burst and leaf senescence, which may vary by 2 to 3 weeks from year to year (Goulden *et al.*, 1996a,b). The NEP of boreal forests is even more sensitive to the onset of the spring thaw, which can vary from year to year by 2 to 3 weeks and may result in variation in annual carbon sequestration of $1.0 \text{ t C ha}^{-1} \text{ yr}^{-1}$ (Havranek and Tranquillini, 1995; Bergh *et al.*, 1998; Goulden *et al.*, 1998; Lindroth *et al.*, 1998; Bergh and Linder, 1999; Chen *et al.*, 1999).

1.3.2.3. Carbon Dioxide Fertilization

The impact of the slow progressive rise in the atmospheric concentration of CO_2 on the carbon sequestration capacity of stands of trees and other vegetation is difficult to measure. Some indications can be obtained, however, from the large number of recent experimental programs in which young trees have been exposed to double the current atmospheric CO_2 concentration over periods of up to 6 years. When rooted in the ground with unconfined root systems in open-top chambers, open-side chambers, closed chambers, and Free Air Carbon Dioxide Enrichment (FACE) rings, there is similar enhancement (up to 60 percent) of aboveground and below-ground growth rate (NPP) and carbon accumulation (Saxe *et al.*, 1998; Norby *et al.*, 1999). Trees grown in double the atmospheric CO_2 concentration translocate appreciably more carbon below ground than do trees grown in ambient CO_2 concentration. For example, 4-year-old birch trees grown in elevated CO_2 concentration translocated three times as much carbon below ground as trees grown in ambient CO_2 (Wang *et al.*, 1998). Much of this carbon ends up as fine roots, microbes, and mycorrhizae that contribute detritus to the pool of soil organic matter (Rey and Jarvis, 1997).

Meta-analysis of the results from several experiments in Europe on deciduous and coniferous species gave an average increase of 54 percent (Medlyn *et al.*, 2000), with no significant differences between the functional types or between stressed and unstressed groups of experiments. Similar results were found through meta-analysis of similar experiments in the United States (Curtis and Wang, 1998; Peterson *et al.*, 1999). Moderate lack of nutrients and water reduces growth but has little effect on the relative impact of the increase in CO_2 concentration. Generally, the increase in CO_2 concentration speeds up development, so trees get bigger more quickly but otherwise remain very similar in most respects to trees of the same size growing in current ambient conditions. The rate of photosynthetic uptake of CO_2 is almost always higher in air with elevated CO_2 concentration than in ambient air. Meta-analysis of data from experiments largely on temperate trees has shown that the key enzymatic parameters that define the capacity for photosynthetic CO_2 as a result of growth in elevated CO_2 uptake are down-regulated on average by no more than 12 percent, in approximate proportion to the reduction in foliar

nitrogen concentration; stomatal conductance is down-regulated by approximately 15 percent, with consequent increased efficiency of use of both nitrogen and water (Curtis, 1996; Curtis and Wang, 1998; Peterson *et al.*, 1999; Medlyn *et al.*, 2000).

Most experimental studies to date have been limited to exposure of young trees to elevated CO_2 concentrations for a few years of treatment. A key question that is yet to be resolved is the extent to which the responses of key parameters to increased CO_2 concentration will change when a stand of young trees reaches canopy closure. It is uncertain whether the primary result of the increased rate of growth is that maturity is approached more quickly or whether more carbon will also be finally stored in the trees and soil as a forest stand matures. Some experimental and observational studies suggest that the initial positive effects of elevated CO_2 on growth rate cited above are greatly reduced or disappear as a stand matures but that more carbon does remain sequestered (e.g., Hättenschwiler *et al.*, 1997). These questions may be partially resolved through the long-term FACE experiments currently in progress on young stands (e.g., Ellsworth, 1999), but at present the long-term effect of CO_2 fertilization on carbon sequestration by forest stands remains an open question.

The phenological development and growth rate of agricultural crops and grassland are accelerated in elevated atmospheric CO_2 concentration. This leads to increases in crop productivity and increases in harvestable yield in some cases (e.g., Tubiello *et al.*, 1999), though not in others (Wechsung *et al.*, 1999). Tropical grasslands have very high NPP, especially below ground (House and Hall, 2000), but whether the amount of carbon stored in the soil is increasing is uncertain.

1.3.2.4. Nutrient Deposition and Mineralization

Production in the forests of the world, with the exception of lowland tropical forests (Vitousek and Sanford, 1986), is generally restricted by lack of nitrogen, particularly in northern temperate and boreal regions (Vitousek and Howarth, 1991), or lack of phosphorus, in the tropics (Lloyd *et al.*, n.d.). Nitrogen fertilization is an efficient means for enhancing agricultural production and is very effective in enhancing the productivity of forest plantations in Mediterranean, temperate, and boreal climatic regions (e.g., McMurtrie and Landsberg, 1992; Linder *et al.*, 1996). Addition of nitrogen and phosphorus promotes the activity of photosynthesis per leaf, and nitrogen in particular stimulates increases in the number and growth of leaves, increasing the area of leaves in vegetation canopies. Many experiments worldwide have demonstrated that the growth of temperate forests is very responsive to the application of fertilizers, particularly of nitrogen (Linder and Rook, 1984; Tamm, 1991). For example, recent long-term experiments have shown a four-fold increase in the growth of Norway spruce in response to annual, complete fertilizer applications ($75 \text{ kg N ha}^{-1} \text{ yr}^{-1}$) at 64°N over the past 12 years and a doubling of growth at 57°N over the past 10 years (Linder, 1995; Bergh *et al.*, 1999). Maritime commercial spruce forest is also responsive

to applications of nitrogen (Taylor and Tabbush, 1990; Wang *et al.*, 1991). Comparable information from tropical forests is not readily available. The additional growth of vegetation may also lead to an increase in the amount of organic matter in the soil—or at least minimize the decrease brought about by tillage, harvesting, and other agricultural and forestry management practices.

Inventory data from sample plots indicate that the growth of trees has been increasing across Europe (Spiecker *et al.*, 1996), and these trends have been observed elsewhere. Wet and dry deposition of nutrients from the atmosphere may be contributing to this enhancement of forest growth. In general, annual total (wet and dry) deposition of nitrogen (oxidized and reduced) to forests in rural areas is in the range of 5 to 40 kg ha⁻¹ yr⁻¹; the smaller amounts are in more remote forests, particularly at high latitudes and in the tropics (e.g., Forti and Moreira-Nordemann, 1991; Eklund *et al.*, 1997; Freydier *et al.*, 1998). Larger amounts are deposited on forests close to cities and industrial centers from which there are substantial nitrogen emissions, as well as in the near vicinity of intensive agricultural pig and poultry enterprises; this deposition may lead to problems such as acidification and loss of biodiversity. It is likely that such nitrogen inputs are supporting additional growth of young forests of particular relevance to the Kyoto forests and hence carbon sequestration (see Section 1.4; Cannell *et al.*, 1999; Valentini *et al.*, 2000), although recently this effect has been disputed (Nadelhoffer *et al.*, 1999). A key uncertainty is to what extent and for how long the current annual rate of nitrogen deposition can sustain the growth rate and NEP of forests on Kyoto lands.

1.3.2.5. Spatial and Temporal Integration

Measurements of NEP are demanding of resources, therefore still are not numerous. They also are not always representative for the whole growing season, and they are never representative for the whole life cycle of longer lived plants. Few observational series extend over more than 5 years. Within decades, a forest site that was chosen for measuring NEP will likely enter a different phase or be subjected to natural disturbances such as fire, pests, and wind-throw or management operations such as thinning and felling. Although measurements made from satellites may suggest that NPP has been increasing over the past decades in some regions and measurements of NEP may seem to indicate that many forests are significant carbon sinks, when the effects of disturbances are included the sequestration of carbon into these forests may be significantly less or even, in some areas, close to zero. Importantly, the disturbances themselves may be influenced by climate, and a change in the disturbance regime may turn a positive NBP into a negative one—or vice versa. For example, measurements of NEP in Canadian boreal forests suggest that many of these forests are carbon sinks (see Section 1.3.2.3), but estimates of NBP from measurement of changes in disturbance regimes and consideration of forest stand dynamics indicate that NBP may have declined significantly over the past 3 decades and that these forests, over large areas, are close to being carbon neutral

(Walker *et al.*, 1999). With the limited empirical data available, however, it is difficult to derive accurate local estimates of NBP for regions, biomes, countries, or continents from spatial and temporal integration of the constituent processes and disturbances (Schulze *et al.*, 1999; Houghton *et al.*, 2000). Our restricted ability to build estimates of NBP from its components at the present time defines a gap in our knowledge and the need to use other methodologies.

If the values in the preceding sections are considered representative for the major forest biomes—tropical, temperate, and boreal forests, respectively—and for the total area that they cover (approximately 40 × 10⁶ km²), total NEP for these systems would be about 10 Gt C yr⁻¹. However, global NBP, derived as the difference between the output resulting from fossil fuel burning, on the one hand, and the increase of atmospheric concentrations and net ocean uptake, on the other, is currently a little less than about 1 Gt C yr⁻¹ (see Table 1-2). If the effects of land-use change are excluded from this estimate of NBP, the estimate of global NBP increases to about 2–3 Gt C yr⁻¹—about five times less than the total NEP (see Section 1.2.1.4). Thus, NEP values as reported so far are clearly not representative of the large-scale, long-term storage of carbon. This fact emphasizes the importance of viewing the activities defined in Articles 3.3 and 3.4 of the Kyoto Protocol in a large-scale and long-term perspective.

Recent attempts to determine the large-scale distribution of terrestrial sources and sinks (i.e., NBP) indirectly, on the basis of the observed spatial variation of atmospheric carbon dioxide concentrations, have interpreted low values as indications of net uptake and high values as the presence of net sources (Fan *et al.*, 1998; Bousquet *et al.*, 1999; Rayner *et al.*, 2000). In light of the relatively small magnitude of the regional NBP, this determination requires accurate knowledge about both the spatial distribution of carbon dioxide concentrations and its horizontal and vertical transport as a result of air motions. The inverse modeling analyses of Rayner *et al.* (2000) and Bousquet *et al.* (1999) agree reasonably closely in indicating a net terrestrial carbon sink in Siberia and comparable, smaller net sinks in North America and Europe, with small net sources in South America and Africa.

1.3.3. The Future of the Terrestrial Carbon Sink

Table 1-2 illustrates the considerable uncertainty about the relative importance of the present global oceanic and terrestrial sinks in acting as negative feedbacks on the rate of CO₂ increase. These sinks may also change in the future as atmospheric CO₂ continues to rise. The question therefore arises whether these feedbacks may reach some limit, so that no additional carbon can be stored on land. This possibility would imply that the airborne fraction of emissions would increase more rapidly in the future than at present.

How long the current carbon sink capacity of the terrestrial biosphere is likely to be maintained into the future is a matter

of conjecture; several hypotheses proposed as the basis for quantitative explanation are discussed here. Consideration of the nature of the uncertainties for such projections is essential, however. The time scale of our immediate concerns with respect to the biospheric sink as a possible means of reducing the impact of GHG emissions is considered to be several decades, but longer time scales may become relevant if emissions of GHGs continue to rise. Projections of future sources and sinks of carbon in terrestrial ecosystems depend on multiple aspects of the future environment: climate (temperature, precipitation, humidity, and radiation), atmospheric CO₂ concentration, nutrient deposition, land use, and ecosystem management (Thompson *et al.*, 1996). Projections of most of these variables into the medium term are highly uncertain, particularly with respect to their future spatial patterns. The regional distribution of ecosystems is an important factor influencing the overall sink capacity. Therefore, improved regional scenarios for human land use are as important for better sink strength projections as they are for better regional climate scenarios.

We may assume that the total capacity for carbon storage in terrestrial ecosystems has an upper limit as a result of mechanical and physiological constraints on the amount of aboveground biomass and physiochemical constraints on the amount of carbon that can be held in soils. These fundamental limits are presently not known in quantitative terms, but it does not seem very likely that they will become of importance within a few decades. Over the past 10,000 years—since the last glaciation—carbon has accumulated in the boreal and north temperate forest ecosystems very largely as transfer from the atmosphere, via vegetation, to the soil organic carbon (SOC) pool. Experimental addition of nutrients has demonstrated the large capacity of these ecosystems for additional tree growth, production of detritus, and SOC. We may therefore conclude that this accumulation of carbon has been constrained since the retreat of the ice by the slow concurrent accumulation of nutrients, particularly nitrogen, in the ecosystem. The present small size of trees in the boreal region and their low nitrogen content suggest that the capacity of the system to store carbon will not by itself limit the transfer of carbon from the atmosphere to the tree and soil pools in the immediate future. Because an accelerated rate of climate change, as well as continuing atmospheric inputs, may increase the availability of nitrogen, it is possible that boreal ecosystems could increase their aboveground and below-ground carbon storage considerably.

By contrast, moist tropical forests in general have large standing stocks of carbon in the trees (Table 1-2). Therefore, there may be limited scope for additional storage of carbon in the trees, although that is less likely to be the case in sparse or secondary tropical forest (Phillips *et al.*, 1998). At present, moist tropical forests currently have high NPP and NEP (Section 1.3.2.2), so it is questionable whether this ongoing flow of carbon from the atmosphere into tropical forests can be maintained. Significant amounts of carbon leave tropical forests in floodwaters as particulate and dissolved organic carbon, some of which is subsequently stored in coastal sediments (Schlesinger, 1997). This and other removals of carbon from tropical forests may

provide the opportunity for some increased uptake from the atmosphere and transfer to storage.

Research has demonstrated that in the short term, increased photosynthesis resulting from the rise in atmospheric CO₂ concentration diminishes at higher CO₂ concentrations, whereas RA and RH increase exponentially with increasing temperature (e.g., Boone *et al.*, 1998; Rayment and Jarvis, 2000). Thus, Scholes *et al.* (1998) have hypothesized that as atmospheric CO₂ concentration and temperature rise, the overall capacity to take up additional carbon from the atmosphere will progressively diminish so that at some point respiration will exceed photosynthesis and the carbon sink will become a source. Based on these two short-term physiological response functions, Scholes (1999) evaluated the global terrestrial carbon sink under various assumptions and concluded that the global sink would be likely to decline from its current level of approximately 2 Gt C yr⁻¹ and become a source within a few decades. This approach assumes that acclimation to higher CO₂ concentrations and temperatures does not occur, that respiration is independent of photosynthesis, and that there are no feedbacks involving nutrition between the processes. A similar, parallel, hypothesis is that the present sink might be a temporary consequence of CO₂ fertilization that eventually will be overtaken by respiratory losses of carbon as temperature rises and respiration “catches up.” It is supposed that while photosynthesis increases in response to the increased availability of CO₂, respiration will initially lag behind but will eventually catch up as the supply of substrate increases or the temperature lag resulting from the thermal inertia of the oceans declines.

To better understand the range of future terrestrial uptake of carbon, calculations with a suite of several more detailed terrestrial biosphere models have been based on the IPCC IS92a scenario of CO₂ increase and the associated climate change simulated by the HadCM2 General Circulation Model (GCM) (Cramer *et al.*, 2000). These models include integrated physiological effects of climate, CO₂, and nutrition on plant growth and plant population dynamics but include no consideration of land-use or management effects. Stimulation of carbon uptake as a result of enhanced uptake of soil nitrogen is included in several of the models. For the IPCC IS92a scenario, all of the models confirm that there is a terrestrial CO₂ sink of the same order of magnitude as above that explains the present-day overall balance; that this sink might increase in strength with further increases in CO₂ concentration; and that when the CO₂ concentration increases beyond about 500 ppmv CO₂ (i.e., around 2030–2050), the rate of increase of the sink approaches zero as the sink reaches a steady asymptote.

A similar result has been obtained using a well-validated local-scale ecosystem model (G'Day) that treats interactions and feedbacks between the effects of CO₂ and temperature on the pools and fluxes of carbon and nitrogen within vegetation and soil compartments of terrestrial ecosystems (Dewar *et al.*, 1999; McMurtrie *et al.*, n.d.). This model was parameterized for a boreal coniferous forest in northern Sweden; temperature and CO₂ concentration were increased according to the IPCC

IS92a scenario as above. The G'Day model indicates that, after initiation, NPP consistently exceeds RH and the carbon sink rises to an asymptotic maximum after about 60 years and remains there for another 50 years without significant decline (McMurtrie *et al.*, n.d.). The capacity at which the sink stabilizes depends on the availability of nitrogen and the fraction of nitrogen released in decomposition that is subsequently re-immobilized. Thus, with appropriate feedbacks and N:C relationships considered, this model also predicts that the carbon sink will be maintained well into the medium term.

On the other hand, sinks may disappear if climate change or deforestation would lead to widespread tree mortality (Friend *et al.*, 1997; Cao and Woodward, 1998; Walker *et al.*, 1999). Of the suite of models discussed above, one model (HYBRID) (Friend *et al.*, 1997) predicts a drastic decline in NPP that is primarily the result of drought-induced die-back of tropical forest in the Amazon basin. This finding highlights two points: First, changes in vegetation structure can have significant effects on terrestrial carbon sinks and indeed can be as important or more important than the physiological effects discussed above (see also Mooney *et al.*, 1999); second, projections of climate change impacts should be based on a range of predictions of future regional climates. The HadCM2 GCM produces somewhat drier climate change predictions for the Amazon than do some other GCMs, which might well lead to different results.

These model experiments and other analyses (e.g., Walker *et al.*, 1999) suggest that the current global terrestrial sink will be maintained over the short term of the next few decades unless serious mortality occurs but may diminish toward the end of the 21st century. With the present state of knowledge, projections beyond a few decades must be regarded as uncertain; this situation is improving rapidly, however.

This conclusion is based on consideration of the effects of future CO₂ and climate change on the present terrestrial sink only; it does not take into account future deforestation or possible actions taken to enhance the terrestrial sink through land use, land-use change, and afforestation or reforestation. Higher CO₂ concentration and warmer climate may be expected to modify the effectiveness of such activities to enhance the medium-term terrestrial sink. Improved understanding of these effects would enable these activities to be better adapted to future CO₂ and climate conditions.

1.4. The Influence of Land Use on Greenhouse Gas Sources and Sinks

Land use and land-use change directly affect the exchange of greenhouse gases between terrestrial ecosystems and the atmosphere. Changes such as the clearing of forests for use in agriculture or as settlements are associated with clear changes in land cover and carbon stocks. Much of the world's land area continues to be managed for food and wood production, human habitation, recreation, and ecosystem preservation without a change in land use. Management of these land uses affects

sources and sinks of CO₂, CH₄, and N₂O. Furthermore, the resulting agricultural and wood products contain carbon. The carbon stocks held in these products are eventually released back to the atmosphere, after the products have served their use. Biomass carbon stocks are also used to produce energy that serves as a substitute for, and as complement to, fossil fuels.

1.4.1. Land-Use Change

Different factors and mechanisms drive land use and land cover transformation. In many cases, climate, technology, and economics appear to be determinants of land-use change at different spatial and temporal scales. At the same time, land conversion seem to be an adaptive feedback mechanism that farmers use to smooth the impact of climate variability, especially in extremely dry and humid periods (e.g., Viglizzo *et al.*, 1995). Land-use change is often associated with a change in land cover and an associated change in carbon stocks. For example, as Figure 1-4 shows, if a forest is cleared, the carbon stocks in aboveground biomass are either removed as products, released by combustion, or decay back to the atmosphere through microbial decomposition. Stocks of carbon in soil will also be affected, although this effect will depend on the subsequent treatment of the land. Following clearing, carbon stocks in aboveground biomass may again increase, depending on the type of land cover associated with the new land use. During the time required for the growth of the new land cover—which can be decades for trees—the aboveground carbon stocks will be smaller than their original value.

Houghton (1991) assessed seven types of land-use change for carbon stock changes: (1) conversion of natural ecosystems to permanent croplands, (2) conversion of natural ecosystems for shifting of cultivation, (3) conversion of natural ecosystems to pasture, (4) abandonment of croplands, (5) abandonment of pastures, (6) harvest of timber, and (7) establishment of tree plantations. We recognize that, depending on the temporal scope of the assessment, classes 6 and 7 may also be considered a land-use practice rather than land-use change.

When forests are cleared for conversion to agriculture or pasture (1,3), a very large proportion of the aboveground biomass may be burned, releasing most of its carbon rapidly into the atmosphere. Some of the wood may be used as wood products; these carbon stocks could thereby be preserved for a longer time. Forest clearing also accelerates the decay of dead wood and litter, as well as below-ground organic carbon (see Figure 1-4). Local climate and soil conditions will determine the rates of decay; in tropical moist regions, most of the remaining biomass decomposes in less than 10 years. Some carbon or charcoal accretes to the soil carbon pool. When wetlands are drained for conversion to agriculture or pasture, soils become exposed to oxygen. Carbon stocks, which are resistant to decay under the anaerobic conditions prevalent in wetland soils, can then be lost by aerobic respiration (Minkinen and Laine, 1998).

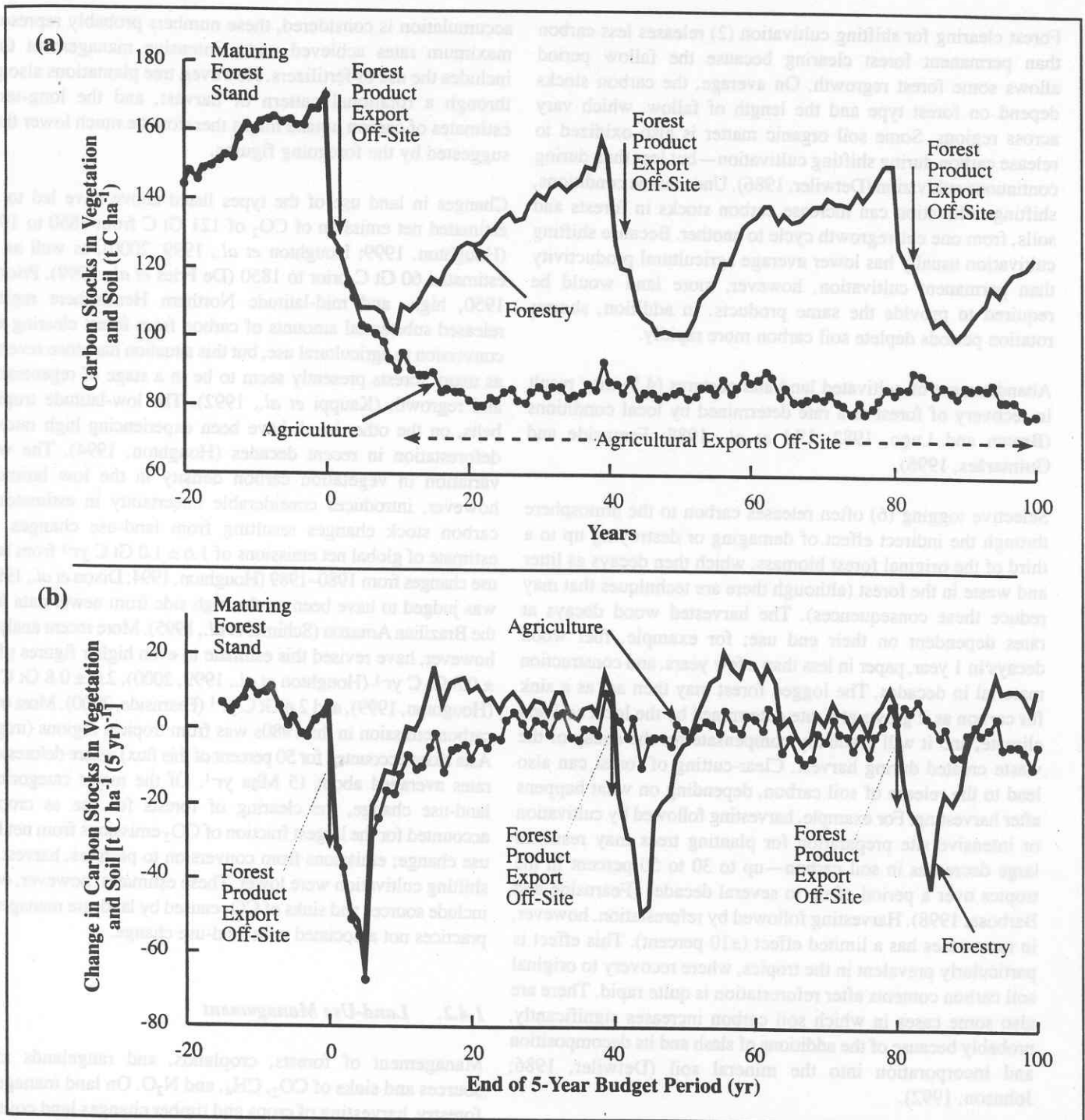


Figure 1-4: The hypothetical time-evolution of annual-average on-site carbon stocks is given (a) for two illustrative cases of land use, land-use change, and forestry. Both cases begin with a common maturing forest stand that is undisturbed for the first 20 years; natural variability, as well as an overall increase, in stocks occurs over this period. After 20 years, the forest stand is cleared and a fraction of the forest stocks is exported off-site as forest products. Following clearing, the land is used for forestry in one case and agriculture in the other. In both cases, carbon stocks continue to fall immediately following clearing due to loss of carbon from detritus and soils. In the cases subsequent to clearing, sustainable forestry is carried out with a 40-year stand cycle, and cultivation is carried out to yield crops with some further loss of soil carbon. For these cases, the change in carbon stocks over a running 5-year period (b) fluctuates due to both variability and human activities. Carbon stocks contained in forest and agricultural product exports off-site are not included in this illustration. Carbon stocks in products generally have a finite lifetime (see Section 1.4.3) and can be considered in a total carbon stock inventory (see Chapter 3).

Forest clearing for shifting cultivation (2) releases less carbon than permanent forest clearing because the fallow period allows some forest regrowth. On average, the carbon stocks depend on forest type and the length of fallow, which vary across regions. Some soil organic matter is also oxidized to release carbon during shifting cultivation—but less than during continuous cultivation (Detwiler, 1986). Under some conditions, shifting cultivation can increase carbon stocks in forests and soils, from one cut-regrowth cycle to another. Because shifting cultivation usually has lower average agricultural productivity than permanent cultivation, however, more land would be required to provide the same products. In addition, shorter rotation periods deplete soil carbon more rapidly.

Abandonment of cultivated land and pastures (4,5) may result in recovery of forest at a rate determined by local conditions (Brown and Lugo, 1982; Uhl *et al.*, 1988; Fearnside and Guimarães, 1996).

Selective logging (6) often releases carbon to the atmosphere through the indirect effect of damaging or destroying up to a third of the original forest biomass, which then decays as litter and waste in the forest (although there are techniques that may reduce these consequences). The harvested wood decays at rates dependent on their end use; for example, fuel wood decays in 1 year, paper in less than a few years, and construction material in decades. The logged forest may then act as a sink for carbon as it grows at a rate determined by the local soil and climate, and it will gradually compensate for the decay of the waste created during harvest. Clear-cutting of forest can also lead to the release of soil carbon, depending on what happens after harvesting. For example, harvesting followed by cultivation or intensive site preparation for planting trees may result in large decreases in soil carbon—up to 30 to 50 percent in the tropics over a period of up to several decades (Fearnside and Barbosa, 1998). Harvesting followed by reforestation, however, in most cases has a limited effect (± 10 percent). This effect is particularly prevalent in the tropics, where recovery to original soil carbon contents after reforestation is quite rapid. There are also some cases in which soil carbon increases significantly, probably because of the additions of slash and its decomposition and incorporation into the mineral soil (Detwiler, 1986; Johnson, 1992).

If tree plantations are raised on land that has been specifically cleared (7), initially there would be net carbon emissions from the natural biomass and the soil. The plantations would then begin to fix carbon at rates dependent on site conditions and species grown. To estimate the time scale of carbon uptake in forest plantations, previous work has linked fixation rates to the growth rate over time (Nilsson and Schopfhauser, 1995). Nilsson and Schopfhauser summarize data suggesting the following rates of aboveground carbon accumulation in plantations: 10 t ha⁻¹ yr⁻¹ for coniferous plantations in Australia and New Zealand, 1.5 to 4.5 t ha⁻¹ yr⁻¹ in coniferous temperate plantations of Europe and the United States, 0.9 to 1.2 t ha⁻¹ yr⁻¹ in Canada and the former Soviet Union, and 6.4 to 10.0 t ha⁻¹ yr⁻¹ in tropical Asia, Africa, and Latin America. Even if soil carbon

accumulation is considered, these numbers probably represent maximum rates achieved under intensive management that includes the use of fertilizers. However, tree plantations also go through a rotational pattern of harvest, and the long-term estimates of carbon uptake might therefore be much lower than suggested by the foregoing figures.

Changes in land use of the types listed above have led to an estimated net emission of CO₂ of 121 Gt C from 1850 to 1990 (Houghton, 1999; Houghton *et al.*, 1999, 2000), as well as an estimated 60 Gt C prior to 1850 (De Fries *et al.*, 1999). Prior to 1950, high- and mid-latitude Northern Hemisphere regions released substantial amounts of carbon from forest clearing and conversion to agricultural use, but this situation has since reversed as many forests presently seem to be in a stage of regeneration and regrowth (Kauppi *et al.*, 1992). The low-latitude tropical belts, on the other hand, have been experiencing high rates of deforestation in recent decades (Houghton, 1994). The wide variation in vegetation carbon density in the low latitudes, however, introduces considerable uncertainty in estimates of carbon stock changes resulting from land-use changes. An estimate of global net emissions of 1.6 ± 1.0 Gt C yr⁻¹ from land-use changes from 1980–1989 (Houghton, 1994; Dixon *et al.*, 1994a) was judged to have been on the high side from newer data from the Brazilian Amazon (Schimel *et al.*, 1995). More recent analyses, however, have revised this estimate to even higher figures of 1.7 ± 0.8 Gt C yr⁻¹ (Houghton *et al.*, 1999, 2000), 2.0 ± 0.8 Gt C yr⁻¹ (Houghton, 1999), and 2.4 Gt C yr⁻¹ (Fearnside, 2000). Most of the carbon emission in the 1980s was from tropical regions (tropical Asia alone accounted for 50 percent of this flux) where deforestation rates averaged about 15 Mha yr⁻¹. Of the major categories of land-use change, the clearing of forests for use as cropland accounted for the largest fraction of CO₂ emissions from net land-use change; emissions from conversion to pastures, harvest, and shifting cultivation were lower. These estimates, however, do not include sources and sinks of CO₂ caused by land-use management practices not associated with land-use change.

1.4.2. Land-Use Management

Management of forests, croplands, and rangelands affects sources and sinks of CO₂, CH₄, and N₂O. On land managed for forestry, harvesting of crops and timber changes land cover and carbon stocks in the short term while maintaining continued land use. Moreover, most agricultural management practices affect soil condition. A forest that is managed in a wholly sustainable manner will encompass stands, patches, or compartments comprising all stages from regeneration through harvest, including areas disturbed by natural events and management operations. Overall, a forest comprising all stages in the stand life cycle operates as a functional system that removes carbon from the atmosphere, utilizing carbon in the stand cycle and exporting carbon as forest products. Forests of such characteristics, if well managed, assure rural development through working opportunities at the beginning and establishment of forest industries in later stages of the development process. In addition, such forests provide other benefits, such as biodiversity,

nature conservation, recreation, and amenities for local communities. For historical and economic reasons, however, many forests today depart from this ideal and are fragmented or have strongly skewed stand age distribution that influences their carbon sequestration capability.

Forest soils present opportunities to conserve or sequester carbon (Johnson, 1992; Lugo and Brown, 1993; Dixon *et al.*, 1994a). Several long-term experiments demonstrate that carbon can accrete in the soil at rates of 0.5 to 2.0 t ha⁻¹ yr⁻¹ (Dixon *et al.*, 1994b). Management practices to maintain, restore, and enlarge forest soil carbon pools include fertilizer use; concentration of agriculture and reduction of slash-and-burn practices; preservation of wetlands, peatlands, and old-growth forest; forestation of degraded and nondegraded sites, marginal agricultural lands, and lands subject to severe erosion; minimization of site disturbance during harvest operations to retain organic matter; retention of forest litter and debris after silvicultural activities; and any practice that reduces soil aeration, heating, and drying (Johnson, 1992).

Cropland soils can lose carbon as a consequence of soil disturbance (e.g., tillage). Tillage increases aeration and soil temperatures (Tisdall and Oades, 1982; Elliott, 1986), making soil aggregates more susceptible to breakdown and physically protected organic material more available for decomposition (Elliott, 1986; Beare *et al.*, 1994). In addition, erosion can significantly affect soil carbon stocks through the removal or deposition of soil particles and associated organic matter. Erosion and redistribution of soil may not result in a net loss of carbon at the landscape level because carbon may be redeposited on the landscape instead of being released to the atmosphere (van Noordwijk *et al.*, 1997; Lal *et al.*, 1998; Stallard, 1998). Although some the displaced organic matter may be redeposited and buried on the landscape, in general the productivity of the soil that is eroded—and its inherent ability to support carbon fixation and storage—is reduced. Losses through leaching of soluble organic carbon occur in many soils; although this leaching is seldom a dominant carbon flux in soils, it is a contributor to the transport of carbon from the terrestrial environment to the marine environment via runoff (Meybeck, 1982; Sarmiento and Sundquist, 1992; *cf.* runoff in Figure 1-1). Soil carbon content can be protected and even increased through alteration of tillage practices, crop rotations, residue management, reduction of soil erosion, improvement of irrigation and nutrient management, and other changes in forestland and cropland management (Kern and Johnson, 1993; Lee *et al.*, 1993; Cole *et al.*, 1996).

Livestock grazing on grasslands, converted cropland, savannas, and permanent pastures is the largest areal extent of land use (FAO, 1993). Grazing alters ground cover and can lead to soil compaction and erosion, as well as alteration of nutrient cycles and runoff. Soil carbon, in turn, is affected by these changes. Avoiding overgrazing can reduce these effects.

Croplands and pastures are the dominant anthropogenic source of CH₄ (Section 1.2.2) and N₂O (Section 1.2.3), although estimates of the CH₄ and N₂O budgets remain uncertain (Melillo *et al.*,

1996). Rice cultivation and livestock (enteric fermentation) have been estimated to be the two primary sources of CH₄. The primary sources of N₂O are denitrification and nitrification processes in soils. Emissions of N₂O are estimated to have increased significantly as a result of changes in fertilizer use and animal waste (Kroeze *et al.*, 1999). Alteration of rice cultivation practices, livestock feed, and fertilizer use are potential management practices that could reduce CH₄ and N₂O sources.

Ecosystem conservation may also influence carbon sinks. Many forests, savannas, and wetlands, if managed as nature reserves or/and recreation areas, can preserve significant stocks of carbon, although these stocks might be affected negatively by climate change. Some wetlands and old-growth forests exhibit particularly high carbon densities; other semi-natural ecosystems (e.g., savannas) may conserve carbon simply because of their large areal extent.

1.4.3. The Fate of Stored Carbon in Biomass Products

Carbon is sequestered in products made from biomass. These products can be traded among nations, lowering the carbon stock of the exporting country and adding to the carbon stock of the importing country. When carbon is sequestered into biomass for specific climate mitigation options—such as wood for fuel or industrial purposes—a life cycle analysis is needed to describe the fate of the stored carbon. Improvement of life cycle assessment methods and comprehensive application of these assessment methods to case studies are important ways to judge the industrial side of the forest carbon cycle. Such analysis would include the conversion efficiency from tree growth into wood products.

Several waste products of wood processing (sawdust, wood chips, bark or lignin from cellulose production, etc.) decay and emit carbon, although such products can be further processed to produce boards or pulp—thereby increasing the efficiency of conversion (Hall *et al.*, 1991)—or be used as energy sources. Wood products such as newsprint, fuel wood, paper, plywood, and sawn timber decay at rates that depend on the nature of their storage and use. Four life-span categories have been described for modeling carbon in forest products (Pussinen *et al.*, 1997). Half of the short life-span products (fuel wood, newsprint, some packing paper, paperboard, and printing and writing paper) manufactured in 1 year were assumed to have not yet decayed after 4 years. The respective half-life-spans were 13 years for medium-short life-span products (the rest of packing paper, paperboard, and printing and writing paper), 30 years for medium-long life-span products (part of sawn timber and plywood), and 65 years for long life-span products (rest of sawn timber and plywood) products. Waste by-products can, however, be used as biomass to produce energy (see Section 1.4.4).

1.4.4. Biomass Energy

Biomass energy can be used to avoid greenhouse gas emissions from fossil fuels by providing equivalent energy services:

electricity, transportation fuels, and heat. The avoided fossil fuel CO₂ emissions of a biomass energy system are equal to the fossil fuels substituted by biomass energy services minus the fossil fuels used in the biomass energy system. These quantities can be estimated with a full fuel-cycle analysis of the system. The net effect on fossil fuel CO₂ emissions is evident as a reduction in fossil fuel consumption.

For biomass energy to lead to an overall reduction in greenhouse gas emissions, land use and land-use change emissions of the biomass energy system must also be included (Marland and Schlamadinger, 1995). For example, if biomass is harvested and subsequently regrows without an overall loss of carbon stocks, there would be no net CO₂ emissions over a full harvest/growth cycle. In this way, land can be used continuously for the production of biomass energy to avoid fossil fuel CO₂ emissions. By contrast, using land to grow carbon stocks to be conserved thereafter can only be a temporary measure to limit fossil fuel use.

Biomass can originate as a co-product of forestry or from crops grown expressly for biomass energy. For example, logging and paper mill residues are being widely used for heat production in Sweden (Gustavsson *et al.*, 1995; Johansson and Lundqvist, 1999). In Brazil, sugar cane crops are used to provide ethanol for blending into motor vehicle fuels, and sugar cane residue (bagasse) is being used for electricity generation. The use of sugar cane biomass in Brazil led to the avoidance of fossil fuel CO₂ emissions of 9.2 Mt C yr⁻¹ through the blending of ethanol with fossil fuels in 1997 and 1998 (Macedo, 1998)—approximately 11 percent of Brazil's fossil fuel CO₂ emissions (British Petroleum Company, 1999). During the next 10 years, the generation of an additional 3 GW of electrical power from sugar cane products is expected.

The use of land to hold stocks of carbon and to provide energy as a substitute for fossil fuels adds to the existing primary uses of land for agriculture, forestry, settlements, recreation, and conservation. The competition for land among these uses will partly determine the extent to which land can be used to reduce greenhouse gas concentrations. Analyses of scenarios of future development show that expanded use of biomass energy could lead to a significant reduction in atmospheric CO₂ concentrations (Edmonds *et al.*, 1996; Ishitani *et al.*, 1996; Leemans *et al.*, 1996). The development of technology for efficient production of biomass energy, as well as for competing land uses, will affect the amount of land available for alternative uses. Consideration of multiple uses of land to provide food and fiber while enhancing carbon stocks and producing energy may present further opportunities to reduce greenhouse gas concentrations with minimum use of resources.

References

- Aubinet, M., A. Grelle, A. Ibrom, Ü. Rannik, J. Moncrieff, T. Foken, A.S. Kowalski, P.H. Martin, P. Berbigier, C. Bernhofer, R. Clement, J. Elbers, A. Granier, T. Grünwald, K. Morgenstern, K. Pilegaard, C. Rebmann, W. Snijders, R. Valentini, and T. Vesala, 2000: Estimates of the annual net carbon and water exchange of forests: The EUROFLUX Methodology. *Advances in Ecological Research*, **30**, 113–175.
- Baldocchi, D.D., C.A. Vogel, and B. Hall, 1997: Seasonal variation of carbon dioxide exchange rates above and below a boreal jack pine forest. *Agricultural and Forest Meteorology*, **83**, 147–170.
- Barnola, J.M., M. Anclin, J. Porcheron, D. Raynaud, J. Schwander, and B. Stauffer, 1995: CO₂ evolution during the last millennium as recorded by Antarctic and Greenland ice. *Tellus*, **47B**, 264–272.
- Battle, M., M. Bender, T. Sowers, P.P. Tans, J.H. Butler, J.W. Elkins, J.T. Ellis, T. Conway, N. Zhang, P. Lang, and A.D. Clarke, 1996: Atmospheric gas concentrations over the past century measured in air from firn at the South Pole. *Nature*, **383**, 231–235.
- Beare, M.H., P.F. Hendrix, and D.C. Coleman, 1994: Water-stable aggregates and organic matter fractions in conventional- and no-tillage soils. *Soil Science Society of America Journal*, **58**, 777–786.
- Bergh, J. and S. Linder, 1999: Effects of soil warming during spring on photosynthetic recovery in boreal Norway spruce stands. *Global Change Biology*, **5**, 245–253.
- Bergh, J., R.E. McMurtrie, and S. Linder, 1998: Climatic factors controlling the productivity of Norway spruce: a model-based analysis. *Forest Ecology and Management*, **110**, 125–139.
- Bergh, J., S. Linder, T. Lundmark, and B. Elfving, 1999: The effect of water and nutrient availability on the productivity of Norway spruce in northern and southern Sweden. *Forest Ecology and Management*, **119**, 51–62.
- Black, T.A., G. den Hartog, H. Neumann, P. Blanken, P. Yang, Z. Nescic, S. Chen, C. Russel, P. Voroney, and R. Stabeller, 1996: Annual cycles of CO₂ and water vapour fluxes above and within a boreal aspen stand. *Global Change Biology*, **2**, 219–230.
- Blanken, P.D., T.A. Black, H.H. Neumann, G. den Hartog, P.C. Yang, Z. Nescic, R. Stabeller, W. Chen, and M.D. Novak, 1998: Turbulent flux measurements above and below the overstory of a boreal aspen forest. *Boundary Layer Meteorology*, **89**, 109–140.
- Blume, H.P., H. Eger, E. Fleischhauer, A. Hebel, C. Reij, and K.G. Steiner (eds.), 1998: Towards sustainable land use. *Advances in Geocology*, **31**, 1625 pp.
- Boone, R.D., K.J. Nadelhoffer, J.D. Canary, and J.P. Kaye, 1998: Roots exert a strong influence on the temperature sensitivity of soil respiration. *Nature*, **396**, 570–572.
- Bousquet, P., P. Ciais, P. Peylin, M. Ramonet, and P. Monfray, 1999: Inverse modelling of annual atmospheric CO₂ sources and sinks 1. Method and control inversion. *Journal of Geophysical Research*, **104**, 26161–26178.
- Braswell, B.H., D.S. Schimel, E. Linder, and B. Moore III, 1997: The response of global terrestrial ecosystems to interannual temperature variability. *Science*, **278**, 870–872.
- British Petroleum Company, 1999: *BP Statistical Review of World Energy 1999*. British Petroleum Company, London, United Kingdom.
- Brown, S. and A.E. Lugo, 1982: The storage and production of organic matter in tropical forests and their role in the global carbon cycle. *Biotropica*, **14**, 161–187.
- Buchmann, N. and E.-D. Schulze, 1999: Net CO₂ and H₂O fluxes of terrestrial ecosystems. *Global Biogeochemical Cycles*, **13**, 751–760.
- Cannell, M.G.R., R.C. Dewar, and D.G. Pyatt, 1993: Conifer plantations on drained peat in Britain: A net gain or loss of carbon? *Forestry*, **66**, 353–369.
- Cannell, M.G.R., R. Milne, K.J. Hargreaves, T.A.W. Brown, M.M. Cruickshank, R.I. Bradley, T. Spencer, D. Hope, M.F. Billett, W.N. Adger, and S. Subak, 1999: National inventories of terrestrial carbon sources and sinks, the UK experience. *Climatic Change*, **42**, 505–530.
- Cao, M. and F.I. Woodward, 1998: Dynamic responses of terrestrial ecosystem carbon cycling to global climate change. *Nature*, **393**, 249–252.
- Chappelaz, J., I.Y. Fung, and A.M. Thomson, 1993: The atmospheric CH₄ increase since the last glacial maximum: (1) sources estimates. *Tellus*, **45B**, 228–241.
- Chen, W.J., T.A. Black, P.C. Yang, A.G. Barr, H.H. Neumann, Z. Nescic, P.D. Blanken, M.D. Novak, J. Eley, R.J. Ketler, and R. Cuenca, 1999: Effects of climatic variability on the annual carbon sequestration by a boreal aspen forest. *Global Change Biology*, **5**, 41–53.
- Ciais, P., 1999: Restless carbon pools. *Nature*, **398**, 111–112.
- Ciais, P., P.P. Tans, J.W. White, M. Trolrier, R. Francey, J. Berry, D. Randall, P. Sellers, J. Collatz, and D.S. Schimel, 1995a: Partitioning of the ocean and land uptake of CO₂ from delta ¹³C measurements from the NOAA/CMDL global air sampling network. *Journal of Geophysical Research*, **100(D3)**, 5051–5057.

- Ciais, P., P.P. Tans, M. Trolier, J.W.C. White, and R.J. Francey, 1995b: A large northern hemisphere terrestrial CO₂ sink indicated by the ¹³C/¹²C ratio of atmospheric CO₂. *Science*, **269**, 1017–1188.
- Cole, C.V. K. Paustian, E.T. Elliott, A.K. Metherell, D.S. Ojima, W.J. Parton, 1993: Analysis of agroecosystems carbon pools. *Water, Air and Soil Pollution*, **70**, 357–371.
- Cole, C.V., C. Cerri, K. Minami, A. Mosier, N. Rosenberg, D. Sauerbeck, J. Dumanski, J. Duxbury, J. Freney, R. Gupta, O. Heinemeyer, T. Kolchugina, J. Lee, K. Paustian, D. Powelson, N. Sampson, H. Tiessen, M. Van Noordwijk, Q. Zhao, I.P. Abrol, T. Barnwell, C.A. Campbell, R.L. Desjardin, C. Feller, P. Garin, M.J. Glendinning, E.G. Gregorich, D. Johnson, J. Kimble, R. Lal, C. Monreal, D.S. Ojima, M. Padgett, W. Post, W. Sombroek, C. Tarnocai, T. Vinson, S. Vogel, and G. Ward, 1996: Agricultural options for mitigation of greenhouse gas emissions. In: *Climate Change 1995—Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analyses* [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 745–771.
- Conrad, R., W. Seiler, and G. Bunse, 1983: Factor influencing the loss of fertilizers nitrogen, emission of nitrogen into the atmosphere as N₂O. *Journal of Geophysical Research*, **88**, 6709–6718.
- Conway, T.J., P.P. Tans, L.S. Waterman, K.W. Thoning, D.R. Kitzis, K.A. Masarie, and N. Zhang, 1994: Evidence for interannual variability of the carbon cycle from the National Oceanic and Atmospheric Administration Climate Monitoring and Diagnostic Laboratory Global Air Sampling Network. *Journal of Geophysical Research*, **99(D11)**, 22831–22855.
- Cramer, W., A. Bondeau, F.I. Woodward, F.I., I.C. Prentice, R.A. Betts, V. Brovkin, P.M. Cox, V. Fisher, J.A. Foley, A.D. Friend, C. Kucharik, M.R. Lomas, N. Ramankutty, S. Sitch, B. Smith, A. White, and C. Young-Molling, 2000: Global response of terrestrial ecosystem structure and function to CO₂ and climate change: results from six dynamic global vegetation models. *Global Change Biology*, (in press).
- Curtis, P.S. 1996: A meta-analysis of leaf gas exchange and nitrogen in trees grown under elevated carbon dioxide. *Plant, Cell and Environment*, **19**, 127–137.
- Curtis, P.S. and Wang, X., 1998: A meta-analysis of elevated CO₂ effects on woody plant mass, form, and physiology. *Oecologia*, **113**, 299–313.
- Davidson, E.A., 1991: Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. In: *Microbial Production and Consumption of Greenhouse Gases: Methane, Nitrous Oxide and Halomethanes* [Rogers, J.E. and W.B. Witman (eds.)]. American Society of Microbiology, Washington, DC, USA, pp. 219–235.
- Davidson, E.A., 1992: Sources of nitrous oxide following wetting of dry soils. *Soil Science Society of America Journal*, **56**, 95–102.
- De Fries, R.S., C.B. Field, I. Fung, G.J. Collatz, and L. Bounoua, 1999: Combining satellite data and biogeochemical models to estimate global effects of human-induced land cover change on carbon emissions and primary productivity. *Global Biogeochemical Cycles*, **13**, 803–815.
- Detwiler, R.P., 1986: Land use change and the global carbon cycle: The role of tropical soils. *Biogeochemistry*, **2**, 67–93.
- Dewar, R.C., B.E. Medlyn, and R.E. McMurtrie, 1999: Acclimation of the respiration/photosynthesis ratio to temperature: insights from a model. *Global Change Biology*, **5**, 615–622.
- Dixon, R.K., S. Brown, R.A. Houghton, A.M. Solomon, M.C. Trexler, and J. Wisniewski, 1994a: Carbon pools and flux of global forest ecosystems. *Science*, **263**, 185–190.
- Dixon, R., J. Winjum, K. Andrasko, J. Lee, and P. Schroeder, 1994b: Integrated systems: assessment of promising agroforest and alternative land-use practices to enhance carbon conservation and sequestration. *Climatic Change*, **30**, 1–23.
- Dlugokencky, E.J., K.A. Masarie, P.M. Lang, and P.P. Tans, 1998: Continuing decline in the growth rate of the atmospheric methane burden. *Nature*, **393**, 447–450.
- Eamus, D., L.B. Hutley, and A.P. O'Grady, n.d.: *Daily and Seasonal Patterns of Carbon and Water Fluxes Above a North Australian Savanna*, unpublished manuscript.
- Edmonds, J.A., M.A. Wise, R.D. Sands, R.A. Brown, and H.S. Kheshgi, 1996: *Agriculture, Land Use, and Commercial Biomass Energy: A Preliminary Integrated Analysis of the Potential Role of Biomass Energy for Reducing Future Greenhouse Related Emissions*. Research Report PNNL-111555, Pacific Northwest National Laboratory, Washington, DC, USA.
- Eklund, T.J., W.H. McDowell, and C.M. Pringle, 1997: Seasonal variation of tropical precipitation chemistry: La Selva, Costa Rica. *Atmospheric Environment*, **23**, 3903–3910.
- Elliott, E.T., 1986: Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. *Soil Science Society of America Journal*, **50**, 627–633.
- Ellsworth, D.S., 1999: CO₂ enrichment in a maturing pine forest: are CO₂ exchange and water status in the canopy affected? *Plant, Cell and Environment*, **22**, 461–472.
- Enting, I.G., T.M.L. Wigley, and M. Heimann (eds.), 1994: *Future emissions and concentrations of carbon dioxide: Key ocean/atmosphere/land analyses*. Commonwealth Scientific and Industrial Research Organization (CSIRO) Division of Atmospheric Research, Technical Paper No. 31, Melbourne, Australia, 120 pp.
- Etheridge, D.M., G.I. Pearman, and P.J. Fraser, 1992: Changes in tropospheric methane between 1841 and 1978 from a high accumulation rate Antarctic ice core. *Tellus*, **44**, 282–294.
- Etheridge, D.M., L.P. Steele, R.L. Langenfelds, R.J. Francey, J.-M. Barnola, and V.I. Morgan, 1996: Natural and anthropogenic changes in atmospheric CO₂ over the last 1000 years from air in Antarctic ice and firn. *Journal of Geophysical Research*, **101**, 4115–4128.
- Fan, S.-M., S.C. Wofsy, P.S. Bakwin, and D.J. Jacob, 1990: Atmosphere-biosphere exchange of CO₂ and O₃ in the central Amazon forest. *Journal of Geophysical Research*, **95**, 16851–16864.
- Fan, S., M. Gloor, J. Mahlman, S. Pacala, J. Sarmiento, T. Takahashi, and P. Tans, 1998: A large terrestrial carbon sink in North America implied by atmospheric and oceanic carbon dioxide data and models. *Science*, **282**, 442–446.
- FAO, 1993: *1992 Production Yearbook*. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Fearnside, P.M., 2000: Global warming and tropical land-use change: greenhouse gas emissions from biomass burning, decomposition and soils in forest conversion, shifting cultivation and secondary vegetation. *Climatic Change*, (in press).
- Fearnside, P.M. and R.I. Barbosa, 1998: Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. *Forest Ecology and Management*, **108**, 147–166.
- Fearnside, P.M. and W.M. Guimarães, 1996: Carbon uptake by secondary forests in Brazilian Amazonia. *Forest Ecology and Management*, **80**, 35–46.
- Feely, R.A., R. Wanninkhof, T. Takahashi, and P.P. Tans, 1999: Influence of El Niño on the equatorial Pacific contribution to atmospheric CO₂ accumulation. *Nature*, **398**, 597–601.
- Forti, M.C. and L.M. Moeira-Nordemann, 1991: Rainwater and throughfall chemistry and in a "Terra Firme" rain forest: Central Amazonia. *Journal of Geophysical Research*, **96**, 7415–7421.
- Francey, R.J., P.P. Tans, C.E. Allison, I.G. Enting, J.W.C. White, and M. Trolier, 1995: Changes in oceanic and carbon uptake since 1982. *Nature*, **373**, 326–330.
- Freydier, F., R. Dupret, and J.P. Lacaux, 1998: Precipitation chemistry in intertropical Africa. *Atmospheric Environment*, **32**, 749–765.
- Friend, A.D., A.K. Stevens, R.G. Knox, and M.G.R. Cannell, 1997: A process-based, terrestrial biosphere model of ecosystem dynamics (Hybrid v3.0). *Ecological Modelling*, **95**, 249–287.
- Fung, I., J. John, J. Lerner, E. Matthews, M. Prather, L.P. Steele, and P.J. Fraser, 1991: Three dimensional model synthesis of the global methane cycle. *Journal of Geophysical Research*, **96**, 13033–13065.
- Gaudry, A., P. Monfray, G. Polian, and G. Lambert, 1987: The 1982–83 El Niño: a 6 billion ton CO₂ release. *Tellus*, **39B**, 209–213.
- Goulden, M.L., J.W. Munger, S.M. Fan, B. Daube, and S.C. Wofsy, 1996a: Exchange of carbon dioxide by a deciduous forest: response to interannual climate variability. *Science*, **271**, 1576–1578.
- Goulden, M.L., J.W. Munger, S.M. Fan, B.C. Daube, and S.C. Wofsy, 1996b: Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. *Global Change Biology*, **2**, 169–182.
- Goulden, M.L., S.C. Wofsy, J.W. Harden, S.E. Trumbore, P.M. Crill, S.T. Gower, T. Fries, B.C. Daube, S.M. Fan, D.J. Sutton, A. Bazzaz, and J.W. Munger, 1998: Sensitivity of boreal forest carbon balance to soil thaw. *Science*, **279**, 214–217.

- Gower, S.T., J.G. Vogel, J.M. Norman, C.J. Kucharik, S.J. Steele, and T.K. Stow, 1997: Carbon distribution and aboveground net primary production in aspen, jack pine, and black spruce stands in Saskatchewan and Manitoba, Canada. *Journal of Geophysical Research*, **102**, 29029–29041.
- Grace, J., J. Lloyd, J. McIntyre, A.C. Miranda, P. Meir, H. Miranda, J.B. Moncrieff, J. Massheder, I.R. Wright, and J. Gash, 1995a: Fluxes of carbon dioxide and water vapor over an undisturbed tropical rainforest in south-west Amazonia. *Global Change Biology*, **1**, 1–12.
- Grace, J., J. Lloyd, J. McIntyre, A.C. Miranda, P. Meir, H. Miranda, C. Nobre, J.B. Moncrieff, J. Massheder, Y. Malhi, I.R. Wright, and J. Gash, 1995b: Carbon dioxide uptake by an undisturbed tropical rain forest in South-West Amazonia 1992–1993. *Science*, **270**, 778–780.
- Greco, S., and D.D. Baldocchi, 1996: Seasonal variation of CO₂ and water vapor exchange rates over a temperate deciduous forest. *Global Change Biology*, **2**, 183–198.
- Gustavsson, L., P. Börjesson, B. Johansson, and P. Svenningsson, 1995: Reducing CO₂ emissions by substituting biomass for fossil fuels. *Energy*, **20**, 1097–1113.
- Hättenschwiler, S., F. Miglietta, A. Raschi, and C. Körner, 1997: Thirty years of in situ tree growth under elevated CO₂, a model for future forest responses. *Global Change Biology*, **3**, 463–471.
- Hall, D.O., H. Mynick, and R. Williams, 1991: Cooling the greenhouse with bioenergy. *Nature*, **353**, 11–12.
- Hanan, N.P., P. Kabat, A.J. Dolman, and J.A. Elbers, 1998: Photosynthesis and carbon balance of a Sahelian fallow savanna. *Global Change Biology*, **4**, 523–538.
- Harvey, L.D.D., J. Gregory, M. Hoffert, A. Jain, M. Lal, R. Leemans, S.C.B. Raper, T.M.L. Wigley, and J.R. de Wolde, 1997: *An Introduction to Simple Climate Models Used in the IPCC Second Assessment Report*. IPCC Technical Paper, Intergovernmental Panel on Climate Change, Bracknell, United Kingdom, 250 pp.
- Havranek, W.H. and W. Tranquillini, 1995: Physiological processes during winter dormancy and their ecological significance. In: *Ecophysiology of Coniferous Forests* (Smith, W.K. and T.M. Hinckley (eds.)). Academic Press, London, United Kingdom, pp. 95–124.
- Heimann, M., G. Esser, J. Kaduk, D. Kicklighter, G. Kohlmaier, D. McGuire, B. Moore III, C. Prentice, W. Sauf, A. Schloss, U. Wittenberg, and G. Würth, 1997: Interannual variability of CO₂ exchanges fluxes as simulated by four terrestrial biogeochemical models (AB0179). In: *Fifth International Carbon Dioxide Conference*, edited by Commonwealth Scientific and Industrial Research Organization (CSIRO), Cairns, Australia, pp. 129–130.
- Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.), 1996: *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 572 pp.
- Houghton, R.A., 1991: Tropical deforestation and atmospheric carbon dioxide. *Climate Change*, **19**, 99–118.
- Houghton, R.A., 1994: The worldwide extent of land-use change. *BioScience*, **44**, 305–313.
- Houghton, R.A., 1999: The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus*, **50B**, 298–313.
- Houghton, R.A. J.L. Hackler, and K.T. Lawrence, 1999: The U.S. carbon budget: contributions from land-use change. *Science*, **285**, 574–578.
- Houghton, R.A., D.L. Skole, C.A. Nobre, J.L. Hackler, K.T. Lawrence, and W.H. Chomentowski, 2000: Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. *Nature*, **403**, 301–304.
- House, J.I. and D.O. Hall, 2000: Net primary production of savannas and tropical grasslands. In: *Terrestrial Global Productivity: Past, Present and Future* (Mooney, H., J. Roy, and B. Saugier (eds.)). (in press).
- Hutchinson, G.L., 1995: Biosphere-atmosphere exchange of gases. In: *Soils and Global Change* [Lal, R., J. Kimble, E. Levine, and B. Stewart (eds.)]. Lewis Publishers, Chelsea, United Kingdom, pp. 219–236.
- Indermühle, A., T.F. Stocker, F. Joos, H. Fisher, H.J. Smith, M. Wahlen, B. Deck, D. Mastroianni, J. Tschumi, T. Blunier, R. Meyer, and B. Stauffer, 1999: Holocene carbon cycle dynamics based on CO₂ trapped in ice at Taylor Dome, Antarctica. *Nature*, **398**, 121–126.
- Ishitani, H., T.B. Johansson, and S. Al-Khouli, 1996: Energy supply. In: *Climate Change 1995: Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Watson, R.T., M.C. Zinyowera, and R.H. Moss (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 587–647.
- Jain, A.K., H.S. Khesghi, M.I. Hoffert, and D.J. Wuebbles, 1995: Distribution of radiocarbon as a test of global carbon cycle models. *Global Biogeochemical Cycles*, **9**, 153–166.
- Jarvis, P.G., 1981: Production efficiency of coniferous forest in the UK. In: *Physiological Processes Limiting Plant Productivity* [Johnson, C.B. (ed.)]. Butterworth Scientific Publications, London, United Kingdom, pp. 81–107.
- Jarvis, P.G. (ed.), 1998: *European Forests and Global Change, the Likely Impacts of Rising CO₂ and Temperature*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 380 pp.
- Jarvis, P.G., J.M. Massheder, S.E. Hale, J.B. Moncrieff, M. Rayment, and S. Scott, 1997: Seasonal variation of carbon dioxide, water vapor and energy exchanges of a boreal black spruce forest. *Journal of Geophysical Research*, **102**, 28953–28966.
- Johansson, J. and U. Lundqvist, 1999: Estimating Swedish biomass energy supply. *Biomass and Bioenergy*, **17**, 85–93.
- Johnson, D.W., 1992: Effects of forest management on soil carbon storage. *Water, Air and Soil Pollution*, **64**, 83–120.
- Joos, F., R. Meyer, M. Bruno, and M. Leuenberger, 1999: The variability in the carbon sinks as reconstructed for the last 1000 years. *Geophysical Research Letters*, **26**, 1437–1441.
- Kauppi, P.E., K. Mielkainen, and K. Kuusela, 1992: Biomass and carbon budget of European forests, 1971 to 1990. *Science*, **256**, 70–74.
- Keeling, C.D. and T.P. Whorf, 1999: Atmospheric CO₂ records from sites in the SIO air sampling network. In: *Trends: A Compendium of Data on Global Change*. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA.
- Keeling, C.D., J.F.S. Chin, and T.P. Whorf, 1996a: Increased activity of northern vegetation inferred from atmospheric CO₂ measurements. *Nature*, **382**, 146–149.
- Keeling, R.F., S.C. Piper, and M. Heimann, 1996b: Global and hemispheric CO₂ sinks deduced from changes in atmospheric O₂ concentrations. *Nature*, **381**, 218–221.
- Keeling, C.D., R.B. Bacastow, A.F. Carter, S.C. Piper, T.P. Whorf, M. Heimann, W.G. Mook, and H.A. Roeloffzen, 1989: A three-dimensional model of atmospheric CO₂ transport based on observed winds: 1. analysis of observational data. In: *Geophysical Monographs*, **55**, American Geophysical Union, Washington, DC, USA, pp. 165–236.
- Kern, J. and M. Johnson, 1993: Conservation tillage impacts on national soil and atmospheric carbon levels. *Soil Science Society of America Journal*, **57**, 200–210.
- Khalil, M.A.K. and R.A. Rasmussen, 1992: The global sources and sinks of nitrous oxide. *Journal of Geophysical Research*, **97**, 14651–14658.
- Khesghi, H.S., A.K. Jain, and D.J. Wuebbles, 1999: Model-based estimation of the global carbon budget and its uncertainty from carbon dioxide and carbon isotope records. *Journal of Geophysical Research*, **104**, 31127–31144.
- Kindermann, J., G. Würth, G.H. Kohlmaier, and F.-W. Badeck, 1996: Interannual variation of carbon exchange flux in terrestrial ecosystems. *Global Biogeochemical Cycles*, **10**, 737–755.
- Krankina, O.N., M.E. Harmon, and A.V. Griazkin, 1999: Nutrient stores and dynamics of woody detritus in a boreal forest: modeling potential implications at the stand level. *Canadian Journal of Forest Research*, **29**, 20–32.
- Kroeze, C., A. Mosier, and L. Bouwman, 1999: Closing the global N₂O budget: a retrospective analysis 1500–1994. *Global Biogeochemical Cycles*, **13**, 1–8.
- Lal, R., J.M. Kimble, R.F. Follett, and C.V. Cole, 1998: *The Potential of U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect*. Ann Arbor Press, Chelsea, MI, USA, 128 pp.
- Lee, J., D. Phillips, and R. Liu, 1993: The effect of trends in tillage practices on erosion and carbon content of soils in the US corn belt. *Water, Air, and Soil Pollution*, **70**, 389–401.

- Lee, K., R. Wanninkhof, T. Takahashi, S.C. Doney, and D. Feely, 1998: Low interannual variability in recent oceanic uptake of atmospheric carbon dioxide. *Nature*, **396**, 155–159.
- Leemans, R., A. van Amstel, C. Battjes, E. Kreileman, and S. Toet, 1996: The land cover and carbon cycle consequences of biomass as an energy source. *Global Environmental Change*, **6**, 335–357.
- Le Quéré, C., J.C. Orr, and P. Monfray, 1998: Modeling the inter-annual variability of the air to sea flux of carbon dioxide in the years 1979–1993. *Proceedings of the International CO₂ Conference*, Cairns, Australia.
- Linder, S., 1995: Foliar analysis for detecting and correcting nutrient imbalances in Norway spruce. *Ecological Bulletins (Copenhagen)*, **44**, 178–190.
- Linder, S., R.E. McMurtrie, and J.J. Landsberg, 1996: Global change impacts on managed forests. In: *Global Change and Terrestrial Ecosystems* [Walker, B. and W. Steffen (eds.)]. International Geosphere-Biosphere Programme (IGBP) Book Series No. 2, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 275–290.
- Linder, S. and D.A. Rook, 1984: Effects of mineral nutrition on carbon dioxide exchange and partitioning of carbon in trees. In: *Nutrition of Plantation Forests* [Bowen, G.D. and E.K.S. Nambiar (eds.)]. Academic Press, London, United Kingdom, pp. 212–236.
- Lindroth, A., A. Grelle, and A.S. Morén, 1998: Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity. *Global Change Biology*, **4**, 443–450.
- Lloyd, J., M.I. Bird, E. Veenendaal, and B. Kruijt, n.d.: *Should Phosphorus Availability Be Constraining Moist Tropical Forest Responses to Increasing CO₂ Concentrations?* unpublished manuscript.
- Lugo, A. and S. Brown, 1993: Management of tropical soils as sinks or sources of atmospheric carbon. *Plant and Soil*, **149**, 27–41.
- Macedo, C., 1998: Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil. *Biomass and Energy*, **14**, 77–81.
- Malhi, Y., A.D. Nobre, J. Grace, B. Kruijt, M.G.P. Pereira, A. Culf, and S. Scott, 1998: Carbon dioxide transfer over a Central Amazonian rain forest. *Journal of Geophysical Research*, **D24**, 31593–31612.
- Malhi, Y., D.D. Baldocchi, and P.G. Jarvis, 1999: The carbon balance of tropical, temperate and boreal forests. *Plant, Cell and Environment*, **22**, 715–740.
- Marland, G. and B. Schlamadinger, 1995: Biomass fuels and forest-management strategies: How do we calculate the greenhouse-gas emissions benefits? *Energy—The International Journal*, **20**, 1131–1140.
- Marland, G., R.J. Andres, T.A. Boden, C. Johnston, and A. Brenkert, 1999: *Global, Regional, and National CO₂ Emission Estimates from Fossil Fuel Burning, Cement Production, and Gas Flaring: 1751–1996*. Report NDP-030, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA.
- McCaughey, J.H., P.M. Lafleur, D.W. Joiner, P.A. Bartlett, A.M. Costello, D.E. Jelinski, and M.G. Ryan, 1997: Magnitudes of seasonal patterns of energy, water and carbon exchanges at boreal young jack pine forest in the BOREAS northern study area. *Journal of Geophysical Research*, **102**, 28997–29009.
- McMurtrie, R.E., B.E. Medlyn, and R.C. Dewar, n.d.: *Increased Understanding of Nutrient Immobilisation in Soil Organic Matter Is Critical for Predicting the Carbon Sink Strength of Forest Ecosystems Over the Next 100 Years*, unpublished manuscript.
- McMurtrie, R.E. and J.J. Landsberg, 1992: Using a simulation model to evaluate the effects of water and nutrients on growth and carbon partitioning of *Pinus radiata*. *Forest Ecology and Management*, **52**, 243–260.
- Medlyn, B.E., F.-W. Badeck, D.G.G. de Pury, C.V.M. Barton, M. Broadmeadow, R. Ceulemans, P. de Angelis, M. Forstreuter, M.E. Jach, S. Kellomäki, E. Laitat, M. Marek, S. Philippot, A. Rey, J. Strassmeyer, K. Laitinen, R. Liozon, B. Portier, P. Roberntz, Y.P. Wang, and P.G. Jarvis, 2000: Effects of elevated CO₂ on photosynthesis in European forest species: A meta-analysis of model parameters. *Plant, Cell and Environment*, **22**, 1475–1495.
- Melillo, J.M., I.C. Prentice, G.D. Farquhar, E.-D. Schulze, and O.E. Sala, 1996: Terrestrial biotic responses to environmental change and feedbacks to climate. In: *Climate Change 1995: The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom, and New York, NY, USA, pp. 445–481.
- Menzel, A., and P. Fabian, 1999: Growing season extended in Europe. *Nature*, **397**, 659.
- Meybeck, M., 1982: Carbon, nitrogen and phosphorus transport by world rivers. *American Journal of Science*, **282**, 401–450.
- Minkkinen, K. and J. Laine, 1998: Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. *Canadian Journal of Forest Research*, **28**, 1267–1275.
- Mooney, H.A., J. Canadell, F.S. Chapin III, J.R. Ehleringer, C. Körner, R.E. McMurtrie, W.J. Parton, L.F. Pitelka, and E.-D. Schulze, 1999: Ecosystem physiology responses to global change. In: *Implications of Global Change for Natural and Managed Ecosystems. A Synthesis of GCTE and Related Research* [Walker, B.H., W.L. Steffen, J. Canadell, and J.S.I. Ingram (eds.)]. International Geosphere-Biosphere Programme (IGBP) Book Series No. 4, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 141–189.
- Myneni, R.B., C.D. Keeling, C.J. Tucker, G. Asrar, and R.R. Nemani, 1997: Increased plant growth in the northern high latitudes from 1981–1991. *Nature*, **386**, 698–702.
- Nabuurs, G.J. and G.M.J. Mohren, 1993: *Carbon Fixation Through Forestation Activities*. IBN Research Report 93/4, Institute for Forestry and Nature Resources, Wageningen, The Netherlands, 205 pp.
- Nadelhoffer, K.J., B.A. Emmett, P. Gundersen, O.J. Kjonaas, C.J. Koopmans, P. Schleppi, A. Tietema, and R.F. Wright, 1999: Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. *Nature*, **398**, 145–148.
- Nilsson, S. and W. Schopfhauser, 1995: The carbon-sequestration potential of a global afforestation program. *Climatic Change*, **30**, 267–293.
- Norby, R.J., S.D. Wullschlegel, C.A. Gunderson, D.W. Johnson, and R. Ceulemans, 1999: Tree responses to rising CO₂ in field experiments: implications for the future forest. *Plant, Cell and Environment*, **22**, 683–714.
- Parton, W.J., J.M.O. Scurlock, D.S. Ojima, D.S. Schimel, and D.O. Hall, 1995: Impact of climate change on grassland production and soil carbon worldwide. *Global Change Biology*, **1**, 13–22.
- Peterjohn, W.T., J.M. Melillo, P.A. Steudler, K.M. Newkirk, F.P. Bowles, and J.D. Aber, 1994: Response of trace gas fluxes and N availability to experimentally elevated soil temperatures. *Ecological Applications*, **43**, 617–625.
- Peterson, A.G., J.T. Ball, Y. Luo, C.B. Field, P.B. Reich, P.S. Curtis, K.L. Griffin, C.A. Gunderson, R.J. Norby, D.T. Tissue, M. Forstreuter, A. Rey, C.S. Vogel, and CMEAL Participants, 1999: The photosynthesis-leaf nitrogen relationship at ambient and elevated atmospheric carbon dioxide: a meta-analysis. *Global Change Biology*, **5**, 331–346.
- Phillips, O.L., Y. Malhi, N. Higuchi, W.F. Laurance, R.M. Núñez, D.J.D. Vázquez, L.V. Laurance, S.G., Ferreira, M. Stern, S. Brown, and J. Grace, 1998: Changes in the carbon balance of tropical forests: evidence from long-term plots. *Science*, **282**, 439–442.
- Prasad, S.S., 1997: Potential atmospheric sources and sinks of nitrous oxide 2. Possibilities from exited O₂ “embryonic” O₃, and optically pumped exited O₃. *Journal of Geophysical Research*, **102**, 21527–21537.
- Prather, M., R. Derwent, D. Ehhalt, P. Fraser, E. Sanhueza, and X. Zhou, 1995: Other trace gases and atmospheric chemistry. In: *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios* [Houghton, J.T., L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callander, E. Haites, N. Harris, and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 73–126.
- Prinn, R. (ed.), 1994: *Global Atmospheric-biospheric Chemistry*. Plenum Press, New York, NY, USA.
- Pussinen, A., T. Karjalainen, S. Kellomäki, and R. Mäkipää, 1997: Contribution of the forest sector in carbon sequestration in Finland. *Biomass and Bioenergy*, **13**, 377–387.
- Ramankutty, N. and J.A. Foley, 1998: Characterizing patterns of global land use: an analysis of global croplands data. *Global Biogeochemical Cycles*, **12**, 667–685.
- Randerson, J.T., M.V. Thompson, T.J. Conway, I.Y. Fung, and C.B. Field, 1997: The contribution of terrestrial sources and sinks to trends in the seasonal cycle of atmospheric carbon dioxide. *Global Biogeochemical Cycles*, **11**, 535–560.

- Rayment, M.B. and P.G. Jarvis, 2000: Long-term measurement of photosynthesis, respiration and transpiration of black spruce. *Canadian Journal of Forest Research*, (in press).
- Rayner, P.J., I.G. Enting, R.J. Francey, and R. Langenfelds, 2000: Reconstructing the recent carbon cycle from atmospheric CO₂, δ¹³C and O₂/N₂ observations. *Tellus*, (in press).
- Rey, A. and P.G. Jarvis, 1997: An overview of long term effects of elevated atmospheric CO₂ concentrations on the growth and physiology of birch (*Betula pendula* Roth.). *Botanical Journal of Scotland*, **49**, 325–340.
- Sarmiento, J.L. and E.T. Sundquist, 1992: Revised budget of the oceanic uptake of anthropogenic carbon dioxide. *Nature*, **356**, 589–593.
- Saxe, H., D.S. Ellsworth, and J. Heath, 1998: Tansley Review No. 98. Tree and forest functioning in an enriched CO₂ atmosphere. *New Phytologist*, **139**, 395–436.
- Schmiedl, D., I. Enting, M. Heimann, T. Wigley, D. Raynaud, D. Alves, and U. Siegenthaler, 1995: CO₂ and the carbon cycle. In: *Climate Change 1994: Radiative Forcing of Climate Change and an Evaluation of the IPCC IS92 Emission Scenarios* [Houghton, J.T., L.G. Meira Filho, J. Bruce, H. Lee, B.A. Callander, E. Haites, N. Harris, and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 73–126.
- Schmiedl, D., D. Alves, I. Enting, M. Heimann, F. Joos, D. Raynaud, T. Wigley, M. Prather, R. Derwent, D. Ehhalt, P. Fraser, E. Sanhueza, X. Zhou, P. Jonas, R. Charlson, H. Rodhe, S. Sadasivan, K.P. Shine, Y. Fouquart, V. Ramaswamy, S. Solomon, J. Srinivasan, D. Albritton, I. Isaksen, M. Lal, and D. Wuebbles, 1996: Radiative forcing of climate change. In: *Climate Change 1995. The Science of Climate Change. Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change* [Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg, and K. Maskell (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 65–131.
- Schlesinger, W.H., 1997: *Biogeochemistry and Analysis of Global Change* (2nd ed.). Academic Press, San Diego, CA, USA, 588 pp.
- Scholes, R.J., 1999: Will the terrestrial carbon sink saturate soon? *Global Change Newsletter*, **37**, 2–3.
- Scholes, R.J., E.-D. Schulze, L.F. Pitelka, and D.O. Hall, 1998: Biogeochemistry of terrestrial ecosystems. In: *Implications of Global Change for Natural and Managed Ecosystems: A Synthesis of GCTE and Related Research* [Walker, B.H., W.L. Steffen, J. Canadell, and J.S.I. Ingram (eds.)]. International Geosphere-Biosphere Programme (IGBP) Book Series No. 4, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 271–303.
- Schulze, E.-D. and M. Heimann, 1998: Carbon and water exchange of terrestrial ecosystems. In: *Asian Change in the Context of Global Change* [Galloway, J.N. and J. Melillo (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 145–161.
- Schulze, E.-D., J. Lloyd, F.M. Kelliher, C. Wirth, C. Rebmann, B. Lühker, M. Mund, I. Milukova, W. Schulze, A. Ziegler, A. Varlagin, R. Sogachov, S. Valentini, S. Dore, O. Grigoriev, O. Kolle, and N.N. Vygodskaya, 1999: Productivity of forests in the Euro Siberian boreal region and their potential to act as a carbon sink—a synthesis of existing knowledge and original data. *Global Change Biology*, **5**, 703–722.
- Sellers, P.J., F.G. Hall, R.D. Kelly, A. Black, D. Baldocchi, J. Berry, M. Ryan, K.J. Ranson, P.M. Crill, D.P. Lettenmaier, H. Margolis, J. Chihlar, J. Newcomer, D. Fitzjarrald, P.G. Jarvis, S.T. Gower, D. Halliwell, D. Williams, B. Goodison, D.E. Wickland, and F.E. Guertin, 1997: BOREAS in 1997: Experiment overview, scientific results, and future directions. *Journal of Geophysical Research*, **102**, 28731–28769.
- Semenov, S.M., I.M. Kounina, and B.A. Koukhita, 1998: An ecological analysis of anthropogenic changes in ground-level concentrations of O₃, SO₂, and CO₂ in Europe. *Doklady Biological Sciences*, **361**, 344–347.
- Semenov, S.M., I.M. Kounina, and B.A. Koukhita, 1999: Tropospheric ozone and plant growth in Europe. Meteorology and Hydrology Publishing Center, Moscow, Russia, 208 pp. (in Russian).
- Shiller, C.L. and D.R. Hastie, 1996: Nitrous oxide and methane fluxes from perturbed and unperturbed boreal forest sites in northern Ontario. *Journal of Geophysical Research*, **101**, 22767–22774.
- Siegenthaler, U. and F. Joos, 1992: Use of a simple model for studying oceanic tracer distributions and the global carbon cycle. *Tellus*, **44B**, 186–207.
- Sombroek, W.G., F.O. Nachtergaele, and A.V. Hebel, 1993: Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio*, **22**, 817–826.
- Spiecker, H., K. Mielikäinen, M. Köhl, and J.P. Skovsgaard (eds.), 1996: *Growth Trends in European Forests—Studies from 12 Countries*. Springer-Verlag, Heidelberg, Germany, 354 pp.
- Stallard, R.F., 1998: Terrestrial sedimentation and the carbon cycle: Coupling weather and erosion to carbon burial. *Global Biogeochemical Cycles*, **12**, 231–257.
- Steele, L.P., E.J. Dlugokenky, P.M. Lang, P.P. Tans, R.C. Martin, and K.A. Masarie, 1992: Slowing down of the global accumulation of atmospheric methane during the 1980's. *Nature*, **358**, 313–316.
- Steffen, W., I. Noble, J. Canadell, M. Apps, E.-D. Schulze, P.G. Jarvis, D. Baldocchi, P. Ciais, W. Cramer, J. Ehleringer, G. Farquhar, C.B. Field, A. Ghazi, R. Gifford, M. Heimann, R. Houghton, P. Kabat, C. Körner, E. Lambin, S. Linder, H.A. Mooney, D. Murdiyarsa, W.M. Post, C. Prentice, M.R. Raupach, D.S. Schmiedl, A. Shvidenko, and R. Valentini, 1998: The terrestrial carbon cycle: Implications for the Kyoto protocol. *Science*, **280**, 1393–1394.
- Tamm, C.O., 1991: Nitrogen in terrestrial ecosystems. Questions of productivity, vegetational changes, and ecosystem stability. In: *Ecological Studies 81*. Springer-Verlag, Berlin, Germany, New York, NY, USA, and London, United Kingdom, 116 pp.
- Tans, P.P. and D.W.R. Wallace, 1999: Carbon cycle research after Kyoto. *Tellus*, **51B**, 562–571.
- Taylor, C.M.A. and P.M. Tabbush, 1990: Nitrogen deficiency in Sitka spruce plantations. *Forestry Commission Bulletin 89*, 20 pp.
- Thompson, M.V., J.T. Randerson, C.M. Malmström, and C.B. Field, 1996: Change in net primary production and heterotrophic respiration: How much is necessary to sustain the terrestrial sink? *Global Biogeochemical Cycles*, **10**, 711–726.
- Tian, H., J.M. Melillo, D.W. Kicklighter, A.D. McGuire, J.V.K. Helfrich III, B. Moore III, and C.J. Vörösmarty, 1998: Effect of interannual climate variability on carbon storage in Amazonian ecosystems. *Nature*, **396**, 664–667.
- Tisdall, J.M. and J.M. Oades, 1982: Organic matter and water-stable aggregates in soils. *Journal of Soil Science*, **33**, 141.
- Tubiello, F.N., C. Rosenzweig, B.A. Kimball, P.J. Pinter, G.W. Wall, D.J. Hunsaker, R.L. La Morte, and R.L. Garcia, 1999: Testing CERES-wheat with free-air carbon dioxide enrichment (FACE) experiment data: CO₂ and water interactions. *Agronomy Journal*, **91**, 247–255.
- Uhl, C., R. Buschbacher, and E.A.S. Serrao, 1988: Abandoned pastures in Eastern Amazonia. I. Patterns of plant succession. *Journal of Ecology*, **76**, 663–681.
- Valentini, R., G. Matteucci, A.J. Dolman, E.-D. Schulze, C. Rebmann, E.J. Moors, A. Granier, P. Gross, N.O. Jensen, K. Pilegaard, A. Lindroth, A. Grelle, C. Bernhofer, T. Grünwald, M. Aubinet, R. Ceulemans, A.S. Kowalski, T. Vesala, Ü. Rannik, P. Berbigier, D. Loustau, J. Gudmundsson, H. Thorgeirsson, A. Ibrom, K. Morgenstern, R. Clement, J. Moncrieff, L. Montagnani, S. Minerbi, and P.G. Jarvis, 2000: The carbon sink strength of forests in Europe: novel results from the flux observation network. *Nature*, (in press).
- van Noordwijk, M., C. Cerri, P.L. Woormer, K. Nugroho, and M. Bernoux, 1997: Soil carbon dynamics in the humid tropical forest zone. In: *The Management of Carbon in Tropical Soils Under Global Change Science, Practice and Policy* [Elliott, E.T., J. Kimble, and M.J. Swift (eds.)]. *Geoderma*, **79**, 187–225.
- Viglizzo, E.F., Z.E. Roberto, M.C. Filippin, and A.J. Pordomingo, 1995: Climate variability and agroecological change in the Central Pampas of Argentina. *Agriculture, Ecosystems & Environment*, **55**, 7–16.
- Vitousek, P.M. and R.W. Howarth, 1991: Nitrogen limitation on land and in the sea: How can it occur? *Biogeochemistry*, **13**, 87–115.
- Vitousek, P.M. and R.L. Sanford, Jr. 1986: Nutrient cycling in moist tropical forest. *Annual Review of Ecology and Systematics*, **17**, 137–167.
- Walker, B.H., W.L. Steffen, and J. Langridge, 1999: Interactive and integrated effects of global change on terrestrial ecosystems. In: *Implications of Global Change for Natural and Managed Ecosystems: A Synthesis of GCTE and Related Research* [Walker, B.H., W.L. Steffen, J. Canadell, and J.S.I. Ingram (eds.)]. International Geosphere-Biosphere Programme (IGBP) Book Series No. 4, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 329–375.

- Wang, Y.P., P.G. Jarvis, and C.M.A. Taylor, 1991: PAR absorption and its relation to above-ground dry matter production of Sitka spruce *Journal of Applied Ecology*, 28, 547–560.
- Wang, Y-P., A. Rey, and P.G. Jarvis, 1998: Carbon balance of young birch trees grown in ambient and elevated atmospheric CO₂ concentrations. *Global Change Biology*, 4, 797–807.
- Wechsung, G., F. Wechsung G.W. Wall F.J. Adamsen B.A. Kimball P.J. Pinter R.L. La Morte R.L. Garcia, and T. Kartschall, 1999: The effects of free-air CO₂ enrichment and soil water availability on spatial and seasonal patterns of wheat growth. *Global Change Biology*, 5, 519–530.
- Winchester, J.W., F. Song-Miao, and L. Shao-Meng, 1988: Methane and nitrogen gases from rice fields of China—possible effects of microbiology, benthic fauna, fertilizer and agricultural practice. *Water, Air and Soil Pollution*, 37, 149–155.
- Winguth, A.M.E., M. Heimann, K.D. Kurz, E. Maier-Reimer, U. Mikolajewicz, and J. Segschneider, 1994: El Niño-southern oscillation related fluctuations of the marine carbon cycle. *Global Biogeochemical Cycles*, 8, 39–63.
- Wissenschaftlicher Beirat der Bundesregierung Globale Umweltveränderungen (WBGU), 1998: Die Anrechnung biologischer Quellen und Senken im Kyoto-Protokoll: Fortschritt oder Rückschlag für den globalen Umweltschutz. Sondergutachten 1998, Bremerhaven, Germany, 76 pp. (available in English).
- Zoltai, S.C. and P.J. Martikainen, 1985: Estimated extent of forest peatlands and their role in the global C cycle. In: *Forest Ecosystems. Forest Management and the Global C Cycle* [Apps, M.J. and D.T. Price (eds.)]. NATO ASI series, Springer-Verlag, Heidelberg, Germany, 548 pp.